Optimisation of building energy retrofit strategies using dynamic exergy analysis and exergoeconomics

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Student Declaration

As the author of this thesis, Ivan Garcia Kerdan, I confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

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Abstract

Existing buildings represent one of the most energy intensive sectors in today's society, where comprehensive building energy retrofit (BER) strategies play a major role in achieving national reduction targets. Despite the efforts made in recent decades through policies and programmes to improve building energy efficiency, the building sector (which proportionally has the highest demand for heat) has the lowest thermodynamic efficiency among all UK economic sectors. As other sectors have shown, exergy and exergoeconomic analyses can be indispensable tools for the design and optimisation of energy systems. Therefore, there is a need for modification of existing BER methods in order to include thermodynamic analysis with the aim improve true efficiency of buildings and minimise its environmental impact. However, a paradigm shift represents a big challenge to common building practice as traditional methods have prioritised typical energy and economic objectives. The aim of this thesis is to develop a methodological framework for the evaluation of BER strategies under exergy analysis and exergoeconomic accounting supported with the integration of the calculation framework into a typical dynamic building simulation tool.

There are two original contributions to the knowledge of this research. First, the techno-economic appraisal of BER strategies, based on the typical energy-efficient and cost-benefit method, is enhanced by adding a whole-building exergy analysis combined with an exergoeconomic method (SPECO). Second, ExRET-Opt, a retrofit-oriented simulation tool based on dynamic exergy calculations and exergoeconomic analysis combined with a comprehensive and robust retrofit database, is developed and implemented for this research. In addition, a multi-objective optimisation module based on genetic algorithms is included within the simulation framework in order to improve BER design under different thermodynamic and non-thermodynamic conflicting cost objective functions.

Three UK non-domestic case studies implementing a wide range of active and passive retrofit strategies are presented. Results suggest that under identical economic and technical constraints, the inclusion of exergy/exergoeconomic indicators as objective functions into the optimisation procedure has resulted in buildings with similar energy and thermal comfort performance as traditional First Law methods; while providing solutions with better thermodynamic performance and less environmental impact. The approach also demonstrates to provide BER designs with an appropriate balance between active and passive measures, while consistently accounting of irreversibilities and its costs along every subsystem in the building energy system. The developed framework/tool seems like a promising approach to introduce the Second Law into typical building energy practice and for the development of policies, incentives, and taxes based on exergy destruction footprints. Such policies could help highly thermodynamically-efficient or low exergy BER designs to become widely available.

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Abbreviations and Symbols

A/C	Air Conditioning
ACH	Air Changes per Hour
AHU	Air Handling Unit
ASHP	Air Source Heat Pump
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BER	Building Energy Retrofit
CAV	Constant Air Volume
CDD	Cooling Degree Day
mCHP	Micro Combined Heat and Power
CIBSE	Chartered Institution of Building Services Engineers
CO	Carbon Monoxide
CO2	Carbon Dioxide
DECC	Department of Energy and Climate Change
DHW	Domestic Hot Water
DPB	Discounted Payback
EPS	Expanded Polystyrene
ExRET-Opt	Exergy-Based Retrofit-oriented Optimisation Tool
FiT	Feed-in-Tariffs
GHG	Greenhouse Gases
GSHP	Ground Source Heat Pump
HDD	Heating Degree Day
HP	Heat Pump
HVAC	Heating, Ventilation and Air Conditioning
kW	Kilowatt(s)
kWh	Kilowatt-Hour(s)
LCCA	Life Cycle Cost Analysis
LED	Light Emitting Diode
MCDM	Multi Criteria Decision Making
MOO	Multi-Objective Optimisation
MVHR	Mechanical Ventilation Heat Recovery
NPV	Net Present Value
NSGA	Non-Dominated Sorting Genetic Algorithm
PV/T	Photovoltaic-Thermal
RHI	Renewable Heat Incentive
SPECO	Specific Exergy Cost Method
TMY	Typical Meteorological Year
VAV	Variable Air Volume
XPS	Extruded Polystyrene

Nomenclature

A	area (m²)
COP	coefficient of performance (W/W)
$\dot{C}_D$	exergy destruction cost (£)
$\dot{C}_p$	exergy cost balance (£/kWh)
c_{Pheat}	specific heat capacity (J/K)
c_f	average cost of fuel (£/kWh)
c_p	average cost of product (£/kWh)
c_{Pheat}	specific heat capacity (J/K)
CRF	capital recovery factor (£)
DPB	discounted payback (years)
En	energy (kWh)
EUI	energy use index (kWh/m²-year)
Ex	exergy (kWh)
$\dot{E}x_D$	exergy destructions (kWh)
$\dot{E}x_F$	fuel exergy (kWh)
$\dot{E}x_P$	product exergy (kWh)
Ex_{prim}	primary exergy (kWh)
Ex_{sun}	solar exergy (kWh)
$Exec_{CB}$	exergoeconomic cost benefit factor (£/h)
f_k	exergoeconomic factor (-)
F_p	primary energy factor (-)
F_q	quality factor (-)
G	incident solar radiation (W/m²)
i	interest rate (%)
m	mass flow rate (kg/s)
N	project lifetime (years)
NPV	net present value (£)
PW	present factor (£)
R	annual revenue (£)
r_k	relative cost difference (-)
S	entropy
SV	residual cost (£)
T_0	reference temperature (K)
T_i	room temperature (K)
TCI	total capital investment (£)
Uv	heat transfer coefficient (W/m2K)
W	work (kWh)
$\dot{Z}_k$	capital investment rate (£/h)

Greek symbols

$\boldsymbol{\eta_{gen}}$	energy efficiency (-)
$\boldsymbol{\psi_{tot}}$	exergy efficiency (-)

Subscripts and superscripts

col	collector
cook	cooking
dem	*d*emand
dhw	domestic hot water
elec	electricity
gen	generation system
hvac	Heating, ventilation, and air conditioning
i	i zone equipment or energy source
k	building subsystem or component
prim	primary energy
PV	photovoltaic
sun	sun
$\boldsymbol{t_k}$	time step
therm	thermal demand

Publications arising from this Thesis

***Peer-reviewed journals*[*]:**

- **Garcia Kerdan, I**., Raslan, R., Ruyssevelt, P., Morillón Gálvez, D. (2017). A comparison of an energy/economic-based against an exergoeconomic-based multi-objective optimisation for low carbon building energy design, *Energy*, In Revision

- **Garcia Kerdan, I**., Raslan, R., Ruyssevelt, P., Vaiciulyte, S., Morillón Gálvez, D. (2017). Thermodynamic and exergoeconomic analysis of a non-domestic Passivhaus retrofit, *Building and Environment*, 117, 100-117.

- **Garcia Kerdan, I**., Raslan, R., Ruyssevelt, P., Morillón Gálvez, D. (2017). The role of an exergy-based building stock model for exploration of future decarbonisation scenarios and policy making, *Energy Policy*, 105, 467-483.

- **Garcia Kerdan, I**., Raslan, R., Ruyssevelt, P., Morillón Gálvez, D. (2017). ExRET-Opt: An automated exergy/exergoeconomic simulation framework for building energy retrofit analysis and design optimisation, *Applied Energy*, 192, 33-58

- **Garcia Kerdan, I**., Raslan, R., Ruyssevelt, P., Morillón Gálvez, D. (2016). An exergoeconomic-based parametric study to examine the effects of active and passive energy retrofit strategies for buildings, *Energy and Buildings*, 133, 155-171.

- **Garcia Kerdan, I.**, Raslan, R., Ruyssevelt, P. (2016). An exergy-based multi-objective optimisation model for energy retrofit strategies in non-domestic buildings, *Energy*. 117(2):506–522.

- **Garcia Kerdan, I**., Morillón Gálvez, D., Raslan, R., Ruyssevelt, P. (2015). Modelling the energy and exergy utilisation of the Mexican non-domestic sector: A study by climatic regions, *Energy Policy*, 77, 191-206.

Peer-reviewed conferences:

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- **Garcia Kerdan, I.,** Raslan, R., Ruyssevelt, P. (2014). Dynamic exergy simulation coupled with thermoeconomic analysis to support retrofit decisions in non-domestic buildings, *The 9th International Conference on System Simulation in Buildings (SSB2014)*, December 10th-12th, 2014. Liege, Belgium

- **Garcia Kerdan, I.,** Raslan, R., Ruyssevelt, P. (2014). An exergy-based simulation tool for retrofit analysis in school buildings, *Building Simulation and Optimization (BSO14),* June 23-24th, 2014, London, UK

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Chapter 1 Introduction

1.1 Rationale for the study: Research Background

Energy represents the force to move almost every activity in today's modern societies. Energy generation and supply is a fundamental part in producing goods, services, and jobs at a rate that modern and future generations demand. Countries depend on this process on a daily basis to keep modern economy moving, causing irreversible environmental degradation. The constant raise of anthropogenic emission of greenhouse gases (GHG) is causing today's society to face its greatest threat: global warming. There is high confidence among the scientific community that the increase of temperatures is due to anthropogenic activities (Metz et al., 2007). The fifth Climate Change Assessment report from the Intergovernmental Panel on Climate Change (IPCC, 2014) showed that back in 2010, GHG emission stood at 49 $GtCO_2eq$, almost twice as in 1973 (27 $GtCO_2eq$). A great part of these emissions are caused by the processes of extraction, production, transformation, and energy utilisation among all economic sectors. Despite the implementation of several climate change mitigation policies in the past three decades, the average emissions growth hit a historical maximum annual rate of 2.2%.

The UK Government, through the Climate Change Act (2008), has created a long-term framework by establishing the world's first legal climate change target. The document established that UK's GHG emissions, compared to the 1990 levels (809.4 $MtCO_2$), have to be reduced by at least 80% by 2050. In 2014, UK's GHG net emissions were estimated at 568.3 $MtCO_2$, 8.4% lower than the previous year, and 29% lower than 1990 levels (DECC, 2015a); however, only a small share (~1%) resulted from implementing emissions reduction measures. The reductions have been mainly achieved due to changes in the energy generation mix by including more renewable-based energy generation and combined with the introduction of more efficient energy conversion technologies. However, to achieve the desired goals in the next 30 years and to move to an energy efficient and low carbon economy, actions along all productive sectors of the economy are required. Positive side effects can arise from these measures as the country can become less dependent on imported fossil fuels and consequently less exposed to higher energy prices in the future. In this sense, the building sector could play a major role for the achievement of the aforementioned target.

In industrialised countries, buildings are responsible for approximately 20-40% of the national primary energy utilisation (Pérez-Lombard et al., 2008) and 25-30% of the global CO_2 emissions (Metz et al., 2007, UNEP-SBCI, 2009). In particular, the non-domestic sector, which accounts for public and commercial buildings, regardless of its high variability, represents a significant opportunity for GHG reduction. At present, the UK non-domestic building sector is composed of 1.8 million buildings and with high dependency on fossil fuels (>90%). The sector is responsible for 18% of the country's total carbon emissions (DECC, 2012), resulting in high contribution to atmospheric pollution, with damage to the environment and public health (CIBSE, 2012). Particularly, only in England and Wales, the non-domestic sector final energy utilisation in 2013 was estimated at 840.9 PJ, with a primary energy input of 1,576.9 PJ. From an end-use perspective, about 50% of all sector's energy demand was due to space heating, followed by lighting (17%), DHW (10%) and catering (10%) (DECC, 2014a).

As the majority of buildings were built before energy regulations were implemented, this resulted in poor fabric characteristics, inefficient HVAC equipment and controls, and poor occupant energy awareness and comfort levels (Clarke et al., 2008). Also, the expansion of HVAC systems in existing buildings represent higher energy use rates each year, mainly driven by the constant increasing demand for cooling and IT systems (Hammond and Stapleton, 2001). In addition, the building replacement rate is typically low (<2%), and although it is expected that by 2050 the building footprint will increase by a third, 80% of existing buildings will still be in use (CarbonTrust, 2012). Therefore, the sector holds a great opportunity for energy reduction and carbon abatement by delivering cost-effective building energy retrofit (BER) strategies. BER can postpone shortages of energy resources, reduce environmental damage, and provide economic benefits (Dincer and Zamfirescu, 2012)

To address the current UK building energy demand and the dependency on high quality energy sources, such as natural gas and coal, recent energy policies and regulatory shifts have aimed to improve cross-sectoral efficiency. These include policies to drive down energy demand and decarbonise the heating supply. As the energy issue is becoming more evident in the building sector, developing techniques for designing efficient and cost-effective energy systems is still a challenge that practitioners and researchers face in today's building industry. On the one hand, this constitutes exceptional opportunities, such as creation of a more robust market for optimal energy retrofit projects, as well as the improvement of internal conditions for the diverse range of occupants. On the other hand, academic research has the opportunity to redesign typical approaches, where the consideration of the fundamental Second Law of thermodynamics appears to hold some promise. From a macroscopic perspective, the Second Law of thermodynamics states that in every process, where energy or matter is dispersed, entropy is inevitably generated; leading to irreversibilities. Any real process is irreversible, which means that it cannot return to its original conditions because of the constant increase of entropy in the environment, with buildings and their systems being no exception.

Deriving from the Second Law principles and combining it with the First Law, the concept of '*Exergy'* arises, where unlike energy, which is always conserved, exergy is exposed to consumption and destructions. The simplest example in buildings is found in the heating process, where the thermal exergy content of 'hot water' or 'hot air' that is finally delivered by the space conditioning system (radiator, fan coil, etc.) is intrinsically lower than the exergy content contained in the primary energy source (e.g. gas, electricity). The largest exergy destructions or irreversibilities occur when the energy flow passes through the different subsystems located in the energy supply chain, with the largest destructions found in processes such as fuel combustion and high temperature heat exchange. By destroying exergy, useful work is being wasted that could be useful for other higher quality processes such as industrial, transport, or chemical. From using resources inefficiently and unwisely, a significant detriment on national energy security can be expected (Dincer, 2002).

A recent low carbon strategic framework from the UK government mentions the importance of considering energy quality or exergy values in the analysis for low carbon strategies (DECC, 2012); thus, implying its importance for buildings' energy efficiency design. In the past decades, an increase in the utilisation of exergy analysis methods in real practice can be tracked. Many researchers and engineers consider exergy methods as the most powerful tool for designing, improving, and optimising energy systems, demonstrating exceptional capabilities for energy efficiency improvement and resolution of energy economic issues (Rosen, 2002b). Although widely used in other productive sectors such as power generation and chemical industry, exergy analysis appears to be a neglected method among buildings' energy design practice. The main reason appears to be the lack of a properly defined economic component. For example, exergy is more difficult to evaluate in an 'open system' such as building energy systems. This is because its final products, such as final heat, cold, and hot water, are not as tangible as those found in 'closed system' processes (e.g. a polymer from a chemical plant or electricity from a power generation plant). Other main barriers are: unfamiliarity with the concept, complexity of methods, difficulty to interpret outputs, and lack of appropriate tools and evidence in real case studies (Rosen, 2002b).

Exergy analysis provides an appropriate link between the demand and supply analysis, which is often performed separately. This disengagement has led the decision makers to assume that systems, such as electric-based heating, are the most efficient way to deliver heat as it has an 'energy efficiency' of 100%. The problem is that the delivery of electricity to cover a low quality demand, such as space heating/cooling, can be considered as irrational because the qualities of the demand and supply do not match. Thereby, as a result of a notorious lack of thermodynamic awareness among buildings' energy design, the building sector presents the worst thermodynamic performance amongst all the UK economic sectors (Figure 1-1) (Hammond and Stapleton, 2001, Gasparatos et al., 2009).

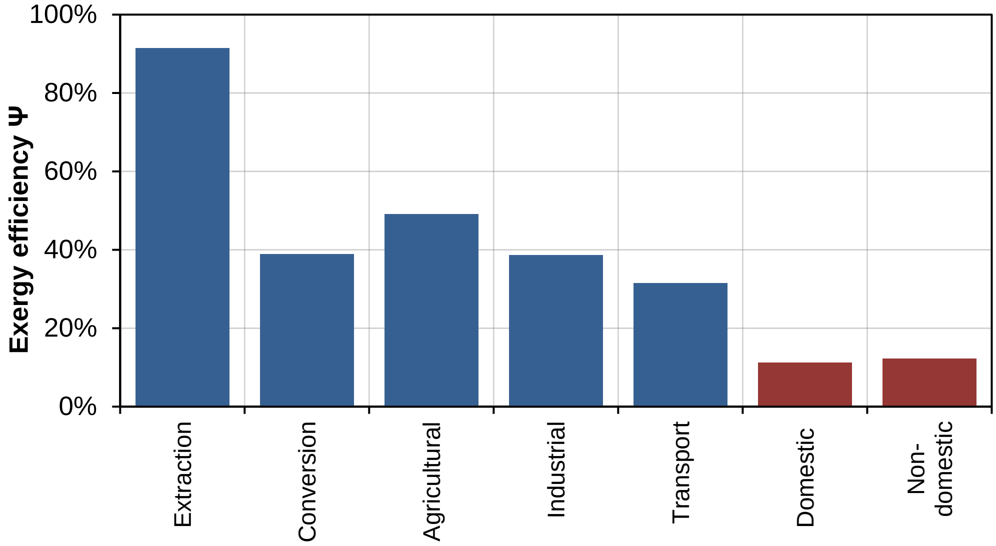


Figure 1-1 Exergy Efficiency in different UK sectors. Source: Gasparatos et al. (2009).

Current BER practice bases the evaluation, assessment, and decision making process on simulation tools. However, this represents a big challenge for the introduction of exergy analysis, since traditional tools lack the evaluation prioritising calculation of energy and economic objectives. Another limitation is the absence of a framework that allows design teams to asses and optimise BER under an exergetic paradigm. Notwithstanding, one example that is worth mentioning was found in Geneva, Switzerland. Since 2001 the local government mandates to building practitioners involved in large-scale new developments or refurbishment projects, to include exergy indicators into the assessments. The experience of this regulation showed major complications since no calculation framework was defined beforehand. It was not until 2008 where a simple methodology along with a calculation spreadsheet was developed (Favrat et al., 2008).

In BER practice, it is intended that projects minimise global costs while also maximising energy efficiency. Although energy and economics is a mature field that is commonly accepted by practitioners, the problem is that energy does not hold any relationship with the energy content of a commodity, whereas the concept of exergy does (Rosen, 2002c). Combining typical microeconomic methods, such as NPV or IRR, with life cycle exergy cost accounting, gives place to ‘exergoeconomics’. This branch of physical science and economic science was created with the aim to minimise an objective function usually composed of capital, operation, maintenance, and inefficiencies’ costs. As exergy is directly related to the physical state of the system, any negative impact would have an exergy cost which leads to a more realistic appraisal than solely based on monetary costs. Therefore, it can be said that exergoeconomics, and not simple economics (monetary cost), relates better to the environmental impacts. In addition, exergoeconomics may hold the key to bring down the barrier of limited building-oriented exergy evaluation. Yet, buildings are designed to the primary objective of providing a comfortable environment for its occupants. Therefore, the optimal selection of BER should be a trade-off between the thermodynamic efficiency, capital costs, and most importantly, occupant thermal comfort.

1.2 Research motivation

Considering the constant depletion of fossil fuels and the increase of global temperatures, improving current buildings' energy performance with low environmental impact designs is crucial in order to meet the national emission reduction targets. Recently, retrofit-oriented optimisation methods have received significant attention in building energy practice; however, exergy methods have not managed to keep up with the same trend. From a theoretical point of view, exergy and exergoeconomic analysis presents a perfect case for building energy renovation. For this purpose, frameworks and practical tools have to be investigated and developed. At present, existing exergy methods and tools are often complex where outputs seem 'illegible' or difficult to interpret, leading to unconvinced practitioners about the benefits of its application (Rosen, 2002b).

A broader appreciation and understanding of the exergy concept in buildings could come from developing a framework showing its strengths and connections with typical economic appraisal of investment projects. As the majority of BER projects' implementation mainly depends on its cost-effectiveness, by showing the strengths of exergoeconomics for energy and cost optimisation, building practitioners could realise the benefits and 'hidden' potential of thermodynamic accounting. By utilising popular buildings' simulation tools as the foundation, practical exergy and exergoeconomics theory could become more accessible, reaching a wider audience of industry decision makers as well as academic researchers. Combined with other methods, such as multi-objective optimisation and multi criteria decision making, exergy finally could hold a good chance to find a place in the everyday practice.

By having a poor understanding of exergy utilisation in buildings, current policies misapply physical resources. The development of such framework and tool could also lead to the support of policies, incentives, and exergy-based taxation, by providing specific subsidies, funding, and taxation relief to exergy efficient technologies. By determining exergy based financial subsidies and taxes, the building industry would be encouraged to provide more low carbon and exergy efficient projects.

1.3 Research Aims and Objectives

The main aim of this research is to develop a systematic methodological framework that integrates exergy and exergoeconomic analyses into buildings' energy retrofit optimisation design, showing the relationship between energy use, exergy destructions, occupant thermal comfort, cost-effectiveness, exergoeconomic factors, and carbon emissions. Added to this, the specific objectives are:

1. Review of up to date BER optimisation methods and tools, and thermodynamic and thermoeconomic approaches applied to buildings. (Chapter 2 and 3)
2. Improving typical BER design by integrating a holistic exergy analysis method and the enhancement of typical cost-benefit approach with the addition of exergoeconomic-based indicators. (Chapter 4)
3. Integration of dynamic (time-dependant) exergy calculations and exergoeconomic analysis into a retrofit-oriented building energy simulation tool with multi-objective optimisation capabilities. (Chapter 5)
4. Exergy and exergoeconomic performance evaluation of typical UK non-domestic buildings and the thermodynamic assessment of a wide range of active and passive BER technologies. (Chapter 6)
5. Effect of different reference environments on the building's exergy and exergoeconomic indicators. (Chapter 6)
6. Evaluation of a building energy retrofit (BER) optimisation problem under a large search space using an exergy-based multi-objective optimisation approach based on evolutionary algorithms. (Chapter 7)
7. Application of a Multi-Criteria Decision Making (MCDM) method to rank optimal Pareto solutions provided by the optimisation model. (Chapter 7)
8. Conduct an energy/economic-oriented (First Law) optimisation and an exergy/exergoeconomic-oriented (First and Second Law) optimisation on a recently retrofitted 'Passivhaus' non-domestic building, to demonstrate strengths and limitations of either approach. (Chapter 8)

1.4 Research Structure and Chapter Layout

The rest of the dissertation is structured into seven more chapters (Figure 1-2) that can be described as follows:

Chapter 2 presents a state-of-the-art review about relevant literature concerned with typical BER design by identifying and connecting relevant research areas and locating knowledge gaps. The review is focused on a brief overview of buildings' energy simulation modelling, typical economic analyses, and optimisation procedures, particularly in the context of non-domestic buildings.

Chapter 3 presents a continuation of the literature review by locating major research gaps in the wider thermodynamic field. Exergy and exergoeconomic research, theories, and its application to buildings will be presented. A discussion on the reasons of its limited application in building research and the necessity of including exergy and exergoeconomic assessment in BER practice is presented. The opportunity to be integrated with other methods, such as optimisation and multi-criteria decision making, is also discussed.

Chapter 4 presents a holistic exergy-based framework integrated into typical building energy retrofit practice by considering all energy streams found in buildings and its systems. In addition, an effort is made to enhance typical economic analysis by integrating exergoeconomic theory into BER cost-benefit analysis. A discussion of the framework usefulness is included.

Chapter 5 illustrates the integration of the developed calculation framework into a dynamic simulation tool (ExRET-Opt) by explaining the pre-processing, processing, and post-processing modules as well as the modelling environments involved at each step. The particularities of the modules such as building calibration, retrofit database, economic and exergoeconomic appraisal, multi-objective optimisation procedure, and multi-criteria decision making are presented in detail. In addition, the modelling tool is verified with an established steady-state building exergy tool and other exergy-related research.

Chapter 6 illustrates the framework and tool application on two UK non-domestic archetype building case studies. A series of active and passive measures are simulated under energetic, exergetic, and exergoeconomic analysis, providing novel baseline thermodynamic results. By following a typical scenario by scenario approach, deep energy retrofit packages are defined based on energy, exergy and exergoeconomic variables.

Chapter 7 explores the application of a genetic-based multi-objective optimisation algorithm module by considering all the possible combinations of retrofit technologies integrated within the modelling tool (ExRET-Opt) that were individually assessed in the previous Chapter. This is applied to the same building archetype case studies, where optimisation outputs are compared against the previously obtained baseline values. The application of the model seeks to show the strengths of exergy-based multi-objective optimisation over typical energy practice by exploring the trade-off between energy, exergy, life cycle cost, exergoeconomics, and occupant thermal comfort variables.

Chapter 8 presents the application of the model in a different context by conducting a study in a recently retrofitted non-domestic building under *Passivhaus* standards. Although the *Passivhaus* approach and the *Low-exergy* approach could have some similarities among their strategies, fundamental differences exist in the calculation procedure. To explore these differences, first, an exergoeconomic evaluation is performed on the pre and post retrofitted building. Later, with the intention of challenging the established methodology for passive building energy design, a comparison between an energy/economic-based optimisation and exergy/exergoeconomic-based optimisation is conducted. Although it is expected that both optimisation approaches provide better outcomes than the real case, it is foreseen that the exergy approach will provide better performance under similar economic constraints, suggesting a paradigm change for sustainable building design.

Chapter 9 presents the discussion of the individual studies as well as concluding remarks focusing on the key findings and contributions of the research. This is followed by the explanation of the current research limitations and provides recommendations for the future enhancement of the particular field study.

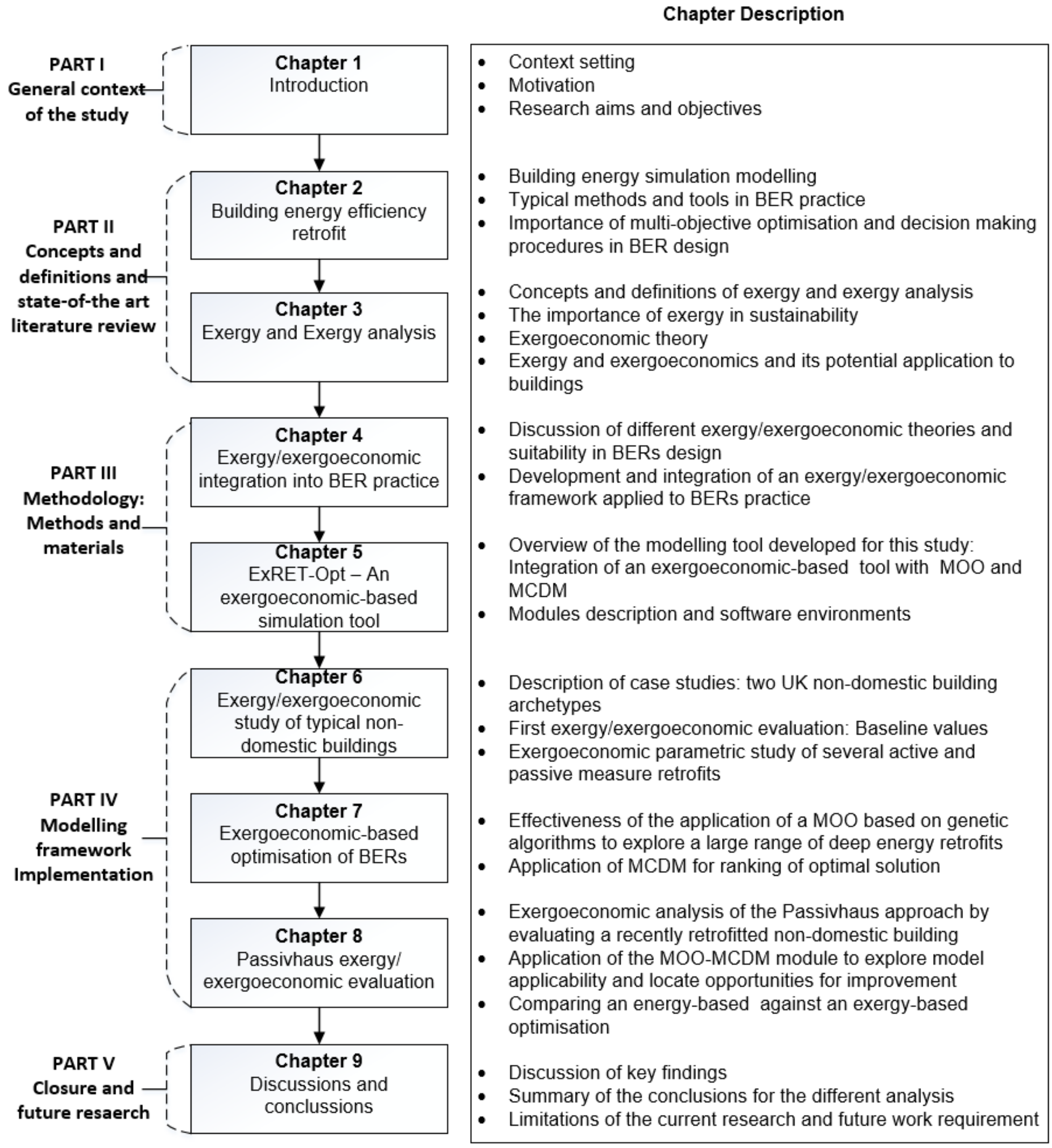


Figure 1-2 Dissertation structure

Chapter 2 Building energy efficiency retrofit (BER)

The following two chapters provide an understanding of how the proposed research fits into a wider field of study, in particular the two main research fields to which it relates: a) building energy performance and optimisation, and b) applied thermodynamics and thermoeconomic analysis for building energy design. The state-of-the-art and current literature on buildings' energy retrofit (BER) design is presented, dividing it into two main topics: energy performance and retrofit optimisation. Firstly, building energy use and the importance of energy conservation in existing buildings is showed. Following this, current literature on existing BER methods, tools, and typical optimisation approaches are discussed.

2.1 Energy use in non-domestic buildings

Worldwide, the resources required for the construction, maintenance, and operation of buildings account for 40% of the annual primary energy use and 30% of GHG emission (UNEP-SBCI, 2009). In Europe, non-residential buildings represent 25% of the total buildings' stock (BPIE, 2011), where in the last two decades an increase in electricity use, due to the introduction of cooling processes and IT equipment, can be seen (Figure 2-1). As a result, electricity currently accounts for the largest share of the final energy mix with 48%; followed by gas (29%) and oil (15%).

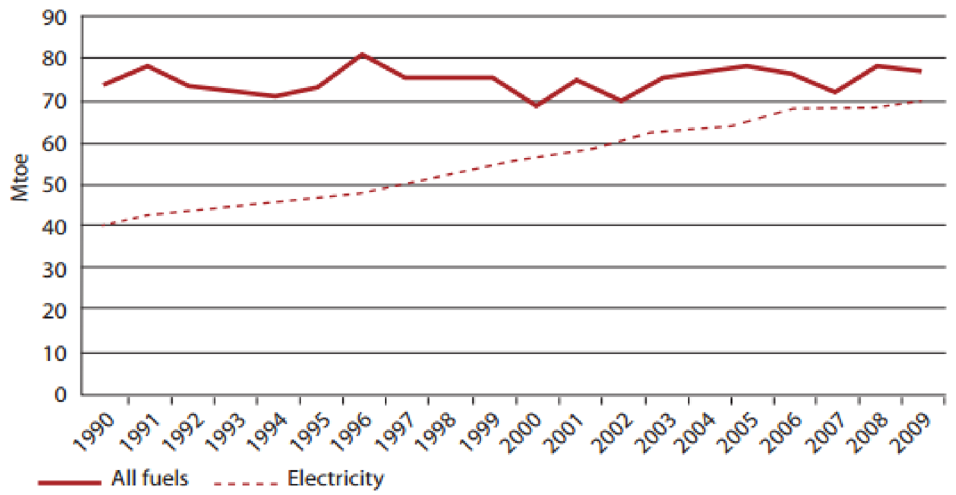


Figure 2-1 Final energy utilisation of the European non-domestic sector from 1990 to 2009. Source: BPIE (2011)

Particularly, the UK non-domestic building sector is responsible for 17% of the country's total energy use; equivalent to an annual primary energy use of 1,576.9 PJ (DECC, 2014). As more than half of the energy used in the UK is for heating purposes, the sector is still dependant on gas (60%), oil (10%), and non-renewable electricity. However, special attention has to be put on electric-based end-uses where lighting represents around 16% of the final energy use (Mortimer et al., 2000b, Pérez-Lombard et al., 2008) (Figure 2-2).

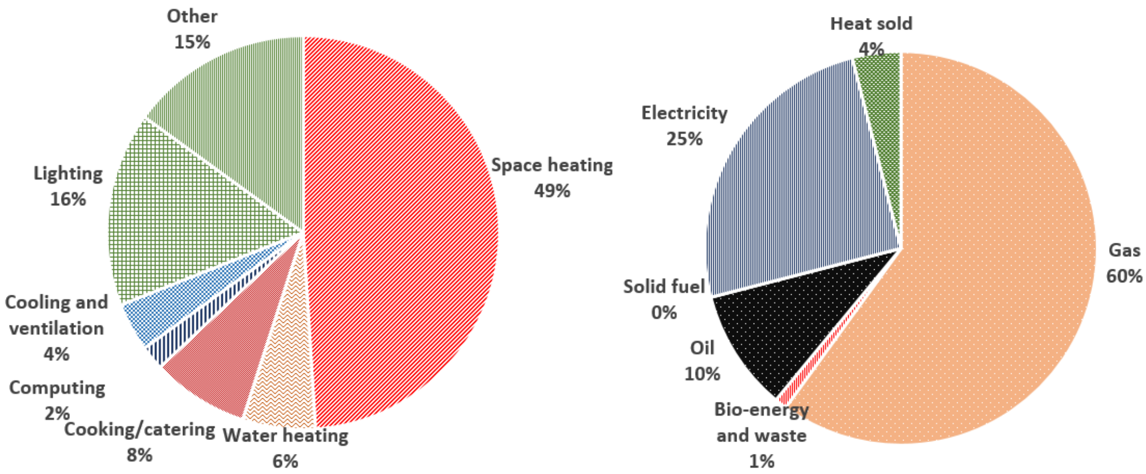


Figure 2-2 Energy utilisation by end-use and by fuel type in the UK non-domestic building (commercial only) in 2011. Source: DECC, 2013

2.1.1 Characteristics influencing energy use in UK non-domestic buildings

The non-domestic sector is complex and presents high levels of heterogeneity among building types, where a wide range of shapes, sizes, materials, and activities is found. Added to this, end-uses, such as lighting, ventilation, heating, cooling, refrigeration, IT equipment, and electric appliances vary greatly from one building type to another. Lack of comprehensive data and classification of these determinants are a great limitation to conducting robust studies (Bruhns, 2007).

Nevertheless, at the beginning of the last decade, a UK research group (Brown et al., 2000, Rickaby and Gorgolewski, 2000, Bruhns et al., 2000, Mortimer et al., 2000a, Mortimer et al., 2000b, Pout, 2000) combined a series of investigations that helped to develop the '*National Non-Domestic Buildings Energy and Emission Model*' (N-DEEM). The intention of the model was to provide an assessment of the potential for reducing emissions attributed to energy use. To develop the model, 3,350 buildings were surveyed covering almost 4 million m². Characteristics from building forms, glazing types and areas, HVAC systems, construction materials, and energy use patterns were analysed. Figure 2-3 presents the baseline energy utilisation values by end-use for different UK non-domestic buildings (ARUP, 2013)

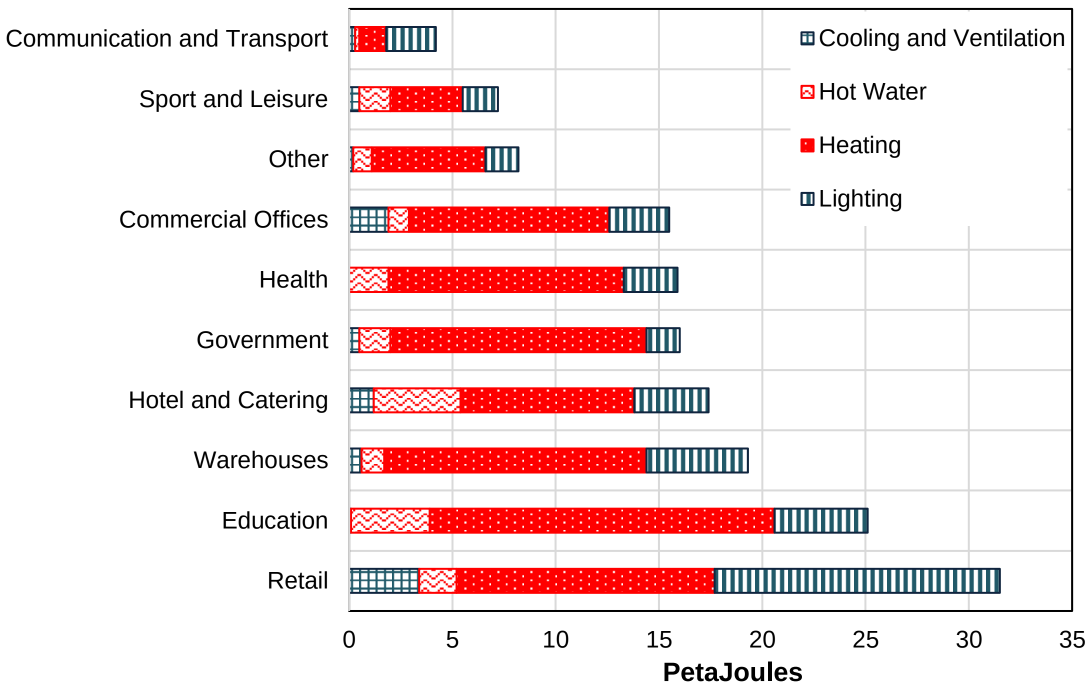


Figure 2-3 Contribution by end use for different buildings in the UK non-domestic stock. Source: ARUP (2013)

Research has demonstrated that the most influential parameters in building energy use are built form, glazing ratio, building envelope characteristics, building services, internal heat gains, schedules, solar shading and control, and factors related to the actual use of the building, such as occupant behaviour and presence (Menassa, 2011, Famuyibo et al., 2012, Korolija et al., 2013a, DECC, 2013).

2.1.2 Building energy conservation and efficiency

Improving buildings' energy efficiency is one of the most effective ways to reduce energy use and associated pollutant emissions. Although both energy conservation and energy efficiency could imply actions to reduce energy use in any process, the former refers to a behavioural change which results in energy savings, such as turning off the lights or reducing thermostat set-points. On the other hand, energy efficiency refers to a technological approach that results in minimising energy use and delivering the same service without compromising the occupants' comfort.

From an economic and environmental perspectives, energy conservation and efficiency measures could hold greater potential than deployment of renewable energy technologies (Dincer and Zamfirescu, 2012). Since the oil crisis in the 1970s, energy efficiency has been an international focus, being a matter of policy concern, with governments intensively promoting it across all economic sectors (Aydinalp et al., 2003). According to the International Energy Agency, there are three types of policies that could address energy efficiency:

- Regulatory instruments (e.g. energy codes)
- Information instruments (e.g. labelling)
- Incentive schemes (e.g. complementary policies, fiscal and financial incentives).

Although many of the energy policies focus on the supply side at a macro scale, demand side regulations have been actively promoted in the last decades. To tackle the growing concerns of buildings' implications on the environment, the EU implemented the European Directive 2002/91/EC on Energy Performance of Buildings (European Parliament, 2002). The directive seeks to reduce buildings' energy use by including energy performance certificates (EPC), establishing inspection schemes for HVAC systems, and setting minimum energy performance requirements for new and retrofitted buildings. Almost a decade later, a recast of the directive was published (European Parliament, 2012), strengthening the energy performance requirements, and clarifying some of its provisions to reduce the large differences between the member states' practices (Dascalaki and Sermpetzoglou, 2011). The recast took effect in 2013, and for retrofit projects it sets minimum energy performance requirements (Article 7), as well as the minimum energy performance on retrofitted energy systems (Article 8), seeking BER projects to achieve a trade-off between energy saving and cost-effectiveness.

2.1.2.1 UK building regulations and programmes

In the UK, building regulations started back in 1965, when minimum building envelope U_{values} requirements were introduced with the objective to reduce energy heat losses through the elements of the fabric of new constructions. Following the oil crisis, these thermal values have been tightened several times as novel and cheaper materials have become available. The majority of these standards are derived from an extensive technical analysis of materials, building's physics modelling, demonstration projects, and statistical studies of the building stock (Verbruggen et al., 2011). A review of buildings' maximum allowed U_{values} set by UK regulations in the past five decades is shown in Table 2-1. Nowadays, regulations also set minimal envelope insulation levels when retrofit actions are implemented in existing non-domestic buildings, delivered through the Part L2B document (DCLG, 2010).

Table 2-1. Historical review of maximum allowed U-values in building envelope by UK regulations. Source: Korolija et al. (2013a)

Building envelope element	U_{value} (W/m²K)						
	1965	**1976**	**1985**	**1990**	**1995**	**2002**	**2010**
External wall	1.70	1.00	0.60	0.45	0.45	0.35	0.35
Roof	1.42	0.60	0.60	0.45	0.45	0.25	0.25
Ground floor	1.42	1.00	0.60	0.45	0.45	0.25	0.25
Glazing	n/a	5.70	5.70	5.70	3.30	2.2	2.20

Furthermore, the Climate Change Act 2008 (UK-Government, 2008) pursues an 80% CO_2 emissions reduction target for 2050 with interim targets of 34% by 2020 (based on 1990 levels). The non-domestic sector has been highlighted as a sector that has a significant potential for energy conservation, with three main action areas: a) building envelope, b) building services, and c) occupant behaviour.

Moreover, a number of financial mechanisms have been introduced in an aim to drive down the demand and improve efficiency. Cost-optimality of measures strongly depends on factors, such as energy prices and government subsidies or incentives that encourage the installation of efficient technologies. In this context, policies to support the implementation of renewable and low carbon systems have been developed, where technologies such as photovoltaic panels, cogeneration systems, biomass boilers, heat pumps, and solar thermal equipment are widely supported. Table 2-2 shows the main policies and programmes oriented to improve energy utilisation in the UK non-domestic sector.

Table 2-2 Policies and programs to support energy conservation and energy efficiency in UK non-domestic buildings (DECC, 2013)

Policy/Programme	Aim	Start Date	End Date	Description
Climate Change Levy (CCL)	Drive down demand and improve efficiency	2001	Ongoing	A tax on energy delivered to non-domestic users, charged at the time of supply. Energy delivered refers to electricity, gas, liquid petroleum gas, and solid fuel. Its aim is to provide an incentive to increase energy efficiency and to reduce carbon emissions.
CRC Energy Efficiency Scheme, formerly known as the Carbon Reduction Commitment	Drive down demand and improve efficiency	2010	Ongoing	A mandatory carbon emissions reporting and pricing scheme to cover large public and private sector organisations in the UK (excluding state funded schools in England from April 2013), that use more than 6,000 MWh per year of electricity and have at least one half-hourly meter settled on the half-hourly electricity market.
Energy Saving Advice Service	Drive down demand and improve efficiency	2012	Ongoing	Telephone-based service offered by the Energy Saving Trust (EST) on behalf of DECC offering impartial energy saving advice to homes and businesses in England and Wales, with Energy Saving Scotland advice centres run by the EST in Scotland. The Service supports the Green Deal and ECO as those schemes develop.
European Union Emissions Trading System (EU ETS)	Uptake of low carbon technologies	2005	Ongoing	Puts a price on greenhouse gas emissions to create financial incentives for industry and businesses to reduce emissions. It also limits emissions from electricity generation and the main energy-intensive industries.
Green Deal	Drive down demand and improve efficiency	2012	2015	The Green Deal lets businesses and other non-domestic organisations pay for some or all of the cost of energy-saving property improvements through savings on their energy bills over time. Update (24 July 2015): The UK Government has decided to stop funding the Green Deal Finance Company (GDFC).
Building regulations	Cross cutting	1965	Ongoing	Building regulations implement the Energy Performance of Buildings Directive. They ensure that buildings are constructed to a high standard by setting out requirements for specific aspects of building design and construction.

Table 2-2 Cont. Policies and programs to support energy conservation and energy efficiency in UK non-domestic buildings (DECC, 2013)

Policy/Programme	Aim	Start Date	End Date	Description
Enhanced Capital Allowance (ECA)	Uptake of low carbon technologies	2001	Ongoing	ECA let businesses that invest in certain energy-saving equipment write off the total cost of the equipment against their taxable profit as a 100% first-year capital allowance. This means the company can write off the cost of the new plant or machinery against the business's taxable profits in the financial year the purchase was made. An ECA is claimed through a business's income or corporation tax return in the same way as any other capital allowance. HM Revenue and Customs is responsible for the tax-related aspects of the ECA scheme.
Feed-in-Tariffs (FiT)	Uptake of low carbon technologies	2010	Ongoing	A UK Government scheme designed to encourage uptake of a range of small-scale renewable and low-carbon electricity generation technologies. The scheme requires some suppliers to make tariff payments on both generation and export of renewable and low carbon electricity. Generation and export tariff rates are index-linked which means that they will increase or decrease with inflation. Technologies such as photovoltaic panels, wind turbines, and combined heat and power are supported
Renewable Heat Incentive (RHI)	Uptake of low carbon technologies	2011	Ongoing	A UK Government environmental programme that provides financial incentives to increase the uptake of renewable heat. For the non-domestic sector, it provides a subsidy payable for 20 years to eligible non-domestic renewable heat generators and producers. Technologies such as biomass boilers, air source heat pumps, ground source heat pumps, water source heat pumps, solar collectors are supported.

2.2 Research, methods and tools dedicated to improve existing buildings energy performance

Energy policies are systematically developed, supported, complemented, and further analysed through comprehensive research, which considers the complex interactions of building physics and building systems. Great efforts from the scientific community can be seen from the last three decades. A large number of research has been developed by the International Energy Agency's Energy in Buildings and Communities Programme (IEA-EBC[†]). The programme has undertaken several studies, dedicated to improving the energy performance of new and existing buildings, by developing joint research projects that support technology application in practice. The outcomes are generally used as the basis for the developments of energy-based financial mechanisms, standards, and policies. These projects, also called 'Annexes', are developed through the period of 3-4 years, where usually multiple research groups from different institutions are involved.

Several Annexes are focused on BER. As part of the IEA EBC Annex 36, Erhorn et al. (2008) presented the development of the Energy Concept Adviser (ECA) for energy and financial retrofit measures. The tool is applicable during the entire retrofitting phase to ensure that savings and financial success is achieved. The authors showed that considering both the thermal envelope and the building services installations in the design process, could lead to more cost-efficient solutions. As part of the IEA EBC Annex 56, Ott et al. (2015) outlined a methodology to asses and evaluate buildings, undergoing a retrofit process. A framework, considering cost optimality, as well as energy efficiency and the deployment of renewables' strategies within the building, was considered. The main studied objectives were the minimisation of cost, primary energy use, and carbon emissions during the whole building life cycle. In addition, the identification of relevant co-benefits and methods for its integration into the retrofit assessment process were studied.

Similar projects under the IEA have been developed, are currently undergoing, or are projected for the future, where many are specifically dedicated or at least consider non-domestic buildings. Appendix A presents a review of IEA Annexes that consider both topics: building energy retrofits and non-domestic buildings.

Worldwide, several other research groups have carried out a wide range of studies evidencing the importance of studying the existing building stock to unlock opportunities for energy performance improvement. Ma et al. (2012) reviewed existing literature regarding BER, providing a systematic approach for the optimal selection and identification of retrofits options.

[†] International Energy Agency, The EBC Research Programme, http://www.iea-ebc.org/ebc/. Accessed: 23 October 2015

Among the possible retrofit measures, these can be catalogued into three different types: a) demand-side management, b) supply-side management, and c) occupant behavioural change.

2.2.1 Energy performance tools for Building Energy Retrofit (BER)

With the current range of available technologies and measures, the identification of the most appropriate of these is a critical aspect of the early design phase. In order to improve the selection of appropriate measures, practitioners require robust tools for effective design, where building simulation play a major role in the design of energy efficient buildings (Siddharth et al., 2011). Building performance modelling and simulation is a fast flourishing field, focusing on reliable reproduction of the physical phenomena of the built environment (Miller et al., 2013), where in BER design it becomes a critical method to predict outcomes, based on past or current trends. Crawley (2008) provided an up to date comparison of 20 different simulation programs/engines for energy balance calculation. The author sees much ambiguity in all the compared tools, suggesting that the user should have the knowledge of a wide range of tools in order to know which suits them better, depending on the characteristics of the project.

Simulation tools must represent the complex physical interactions as reliably as possible. Its use for BER represents a quick and cost-effective method to estimate pre and post-retrofit energy use of a building, as it is impossible to get information about the impact without actually testing it in real life. Also, simulations can be conducted faster than real-time analysis, allowing efficient 'if-then-else' analyses of different retrofit alternatives. Several retrofit oriented simulation tools have been developed in the last two decades, and researchers have categorised retrofit tools by their simulation approach (Coakley et al., 2014, Lee et al., 2015, Chidiac et al., 2012):

a. *Data driven or Black-box approach*
b. *Normative calculations or Grey-box approach*
c. *Physics-based or detailed model calibration approach*

Data driven or Black-box methods can be regarded as simple benchmarking processes or complex regression models, relying on real, measured data. Regression equations can be more useful and less time consuming than complex simulation tools, if the data behind their development is robust enough (Korolija et al., 2013a). *Normative calculations* are based on reduced models using simple inputs for quick evaluation. Models such as resistor-capacitance (RC), degree-day method, and the bin method can be considered as reduced order models. Although these models could deliver rougher estimates, their outputs are normally accepted by building regulations or certification methods such as BREEAM (Building Research

Establishment Environmental Assessment Method) and LEED (Leadership in Energy and Environmental Design). Finally, *Physics-based* retrofit tools can provide the highest accuracy and fidelity. These tools commonly use, as the main energy calculation engine, open source tools such as DOE 2.2 (LBNL and USDOE, 2015) and EnergyPlus (EnergyPlus, 2012). However, these tools present higher complexity because of the need for larger input data and longer simulation times. Among the most recent developments using EnergyPlus are ROBESim (Chuah et al., 2013), CBES (Hong et al., 2015) and SLABE (Mauro et al., 2015). Lee et al. (2015) provided a review of eighteen retrofit toolkits categorised by simulation engines (Figure 2-4).

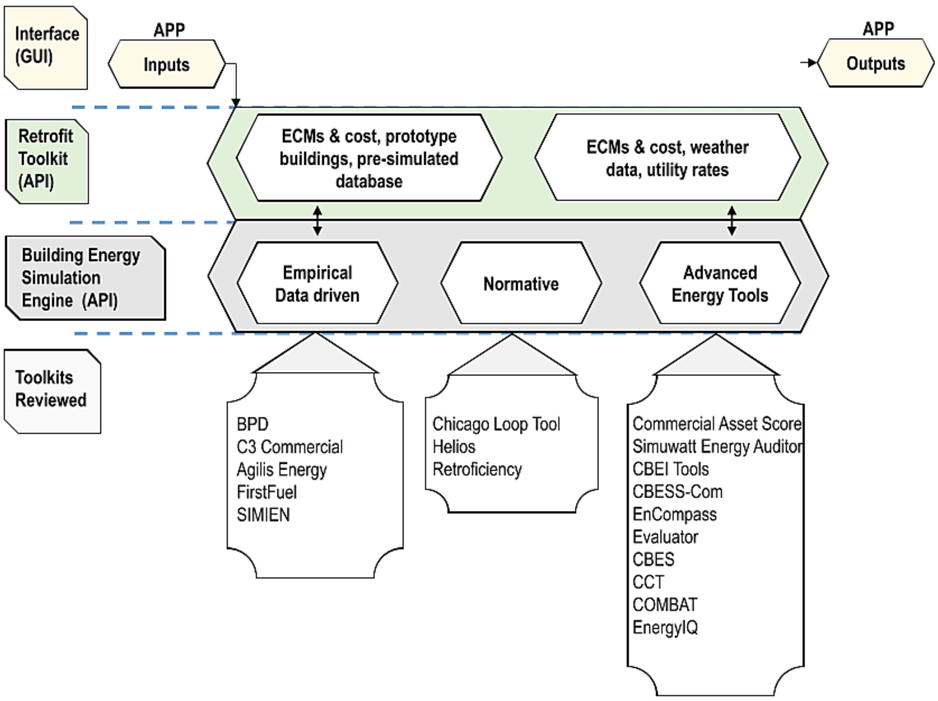


Figure 2-4 Types of existing retrofit tool kits separated by simulation engine. Source: Lee et al. (2015). **Image reproduced with permission of the rights holder, Elsevier.**

2.2.2 Economic methods for Building Energy Retrofit (BER)

On the one hand, inefficient systems use more primary energy resources resulting in higher energy bills. On the other hand, high efficiency systems usually involve higher investment costs, resulting both cases in different lifetime cycle costs (Dincer and Zamfirescu, 2012). In practice, it is intended that BER projects minimise global costs while also maximising energy savings. For this, appropriate quantification methods are required. As the problem becomes a trade-off between the capital investment and energy benefits, economic analysis methods play an important role in the decision making process, facilitating the comparison among alternative measures, and providing an indication of whether the retrofit alternatives are energy-efficient and cost-effective (Ma et al., 2012). One of the most important decision factors is the money savings or additional income from a particular project. Several authors have been using multiple techniques and methodologies to achieve better and more reliable results with the objective of giving more certainty to investors.

Among typical cost-benefit methods in BER practice are: Simple Payback Period (SPP), Discounted Payback (DPB), Profitability Index (PI), Net Present Value (NPV), and Internal Rate of Return (IRR). As future cash flow is essential for the analysis, and despite some limitations derived from the uncertainty of the future, DPB and NPV are identified as the most widely used cost-benefit techniques for general economic appraisal (Remer and Nieto, 1995, Ashuri et al., 2011). Both methods consider all the future cash flow and convert it into present value of money. Virtually, DPB and NPV are based on the same concept, but are providing slightly different answers. NPV shows the present value of an investment based on expected energy savings costs minus the cost of the project. It helps the decision makers to assess whether or not a strategy is financially viable. Contrary, DPB provides the number of years that the project will break even by also considering the future value of money.

2.2.2.1 Life Cycle Cost Analysis

The Life Cycle Cost Analysis (LCCA) method, strongly linked to the two aforementioned economic techniques, has been used recently to deliver and support decision makers with more accurate results by considering the future cash flow of planning, designing, supporting and operating costs (Wang et al., 2014, Ott et al., 2015, Bull et al., 2015). LCCA is generally used in figuring out if future savings justify high investment costs (Kneifel, 2010), and help in decisions regarding an implementation of a conservation measure versus the demolition of the entire building. In BER design, the LCCA indicator of a given project is then contrasted with the baseline building LCCA as well as other BER solutions, showing usefulness for design comparison with similar energy performance but with disparate economic indicators. If energy performance is similar, a lower life cycle cost indicates a more cost-effective solution.

Marshall and Ruegg (1977) were amongst the first researchers to introduce LCCA into BER practice describing state-of-the-art techniques. They defined its application in a wide range of conservation projects promoting a broader awareness of the method among practitioners. A big limitation in those years was the difficulty in obtaining the life cycle data on performance, durability, and maintenance cost, leading to high uncertainty in the results. Feasibility of BER has to be calculated carefully as the uncertainties in future energy prices, interest rates, and equipment degradation are just some of the variables that could have major influence on the outputs (Papadopoulos et al., 2002). The LCCA outputs from a wide range of BER solutions can be graphically represented, first by defining the reference scenario, and then by plotting the alternative BER solutions based on the energy use and Life Cycle Costs (Ferreira et al., 2014). Solutions are expected to draw a quadratic function as shown in Figure 2-5.

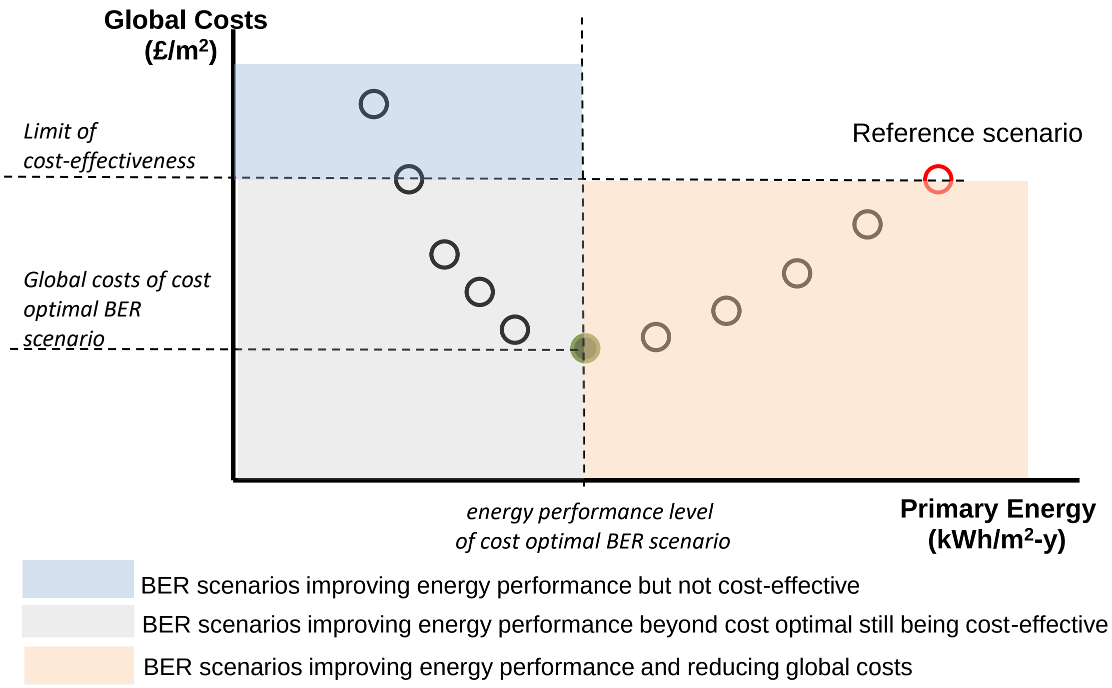


Figure 2-5 Graphical representation of BER solutions by considering LCC and energy performance. Source: Ferreira et.al., 2014

Studies have shown that the most energy efficient retrofit measures are not always cost-effective solutions (Gustafsson, 2000, Ouyang et al., 2009, Chidiac et al., 2011a). Typically, solutions can improve either energy or economic performance while deteriorating the other objective (located in the blue and orange areas). In addition, solutions improving both objectives could also be achieved providing benefits in both energy performance and global LCCA (located in the grey area). Yet, the cheapest solution can be located at the bottom of the curve, while the most energy efficient solution will be located at the curve's left end.

However, LCCA (and consequently NPV and DPB) can present several limitations. The biggest is in the inability to calculate future techno-economic uncertainty. Still, economic uncertainty is one of the most influential parameters to decide whether to invest in a project or not. By quantifying the probability of certain economic or technical scenarios occurring in the future, it provides the decision maker with the option to choose the best design under uncertainty. Verbruggen et al. (2011) discussed the general anatomy on investing in energy efficient buildings treating the aspect of time in the NPV method. The author suggests that typical NPV technique could provide misleading information by lacking accounting of concepts such as irrevocability and preclusion, arguing that timing to implement a BER is dependent mainly on the building's construction year. Ashuri et al. (2011), knowing the limitations of NPV for investment decision, developed an investment analysis framework to evaluate BER based on 'Real Options Theory'. The developed model can decide between immediate or delayed implementation of BER as it considers different components, such as fluctuations in future energy price and decrease in the future cost of new technologies. The financial framework receives input from external modelling components given by building energy simulation modelling, provided by EnergyPlus and TRNSYS (Klein, 2010). Later, it calculates the savings by focusing on characterizing the equipment performance degradation and future energy price fluctuations. By using this method, it is possible to find the optimal time for the project implementation, showing that delayed BER decision making can enhance the future value of project and improve the LCC.

As shown by the literature, LCCA can be used with building simulation tools in order to justify upgrades. Nevertheless, the integration of economic analysis in building energy performance tools is still limited. Rysanek and Choudhary (2013) developed a retrofit oriented simulation tool capable of using non-probabilistic decision rules, applied to assess largely uncertain scenarios. However, the tool was developed for research purposes lacking implementation in real world practice. Also, in the last versions, EnergyPlus has incorporated a LCCA methodology based on the NIST Handbook 135 'Life Cycle Costing Manual' (Fuller and Petersen, 1995). Although EnergyPlus is not directly oriented to assess retrofit measures, external toolkits could be developed. This could provide a valuable tool, as EnergyPlus is one of the most widely used building performance simulation tools both in research and in practice.

2.2.3 Simulation-based optimisation and application in Building Energy Retrofit (BER) design

Thanks to the development of powerful simulation tools in the last years, BER research and practice have been capable to improve multiple and conflicting objectives at a time. The reduction of building energy uses alongside the maximisation of occupants' comfort conditions, while managing constraint budgets, is an issue that the architecture, engineering, and construction industry faces on a daily basis. However, in practice, designs rarely reach or even get close to the optimal solution. Naboni et al. (2013) categorised building design in three approaches:

a) *Scenario by Scenario*
b) *Parametric Full-Factorial*
c) *Optimisation Algorithms*

The most common approach is the '*Scenario by Scenario'*, where the practitioner models several solutions based only on personal experience. The main limitation associated with this approach is that the number of analysed scenarios is typically very low due to time constraints, which often leads to solutions that can be far from optimal (considering actual potential). In recent years, '*Parametric Full-Factorial'* studies have been developed (Molinari et al., 2013), where a large number of simulations is carried out in order to assess all the possible combinations, usually having a search space of thousands of solutions. This method has the strength of providing a large amount of data that, for example, can be used to train artificial neural networks (ANN) (Asadi et al., 2014). Although theoretically the method gives the certainty of reaching the optimal scenario; however, in practice it presents the limitation that is computationally and time expensive. That is, depending on the number of parameters or retrofit measures to explore, in some cases several years or hundreds of years would be required to simulate all the possible combinations.

'Optimisation' is a technique that is commonly used in research and engineering applications. During the last three decades many mathematical linear and non-linear programming methods have been developed for solving optimisation problems; however, no single solution exist that fits all problems. When optimisation is made of only one objective, the optimisation problem can be considered as one dimensional; however, optimisation procedures become more complex as the number of objectives increases, often involving multiple and conflicting objectives.

2.2.3.1 Multi-objective optimisation and algorithms

Some traditional methods scalarise multiple objectives into a single objective ('method of objective weighting'), where the obtained solution could be highly sensitive to the weight vector used in the scalarisation (Srinivas and Deb, 1994). Other classical approaches include 'method of distance functions', and 'min-max formulation'. To overcome its sensitivity towards the objective function, researchers have developed tools and algorithms based on evolutionary algorithms, where several approaches can be found.

An approach that has shown potential to explore large search spaces in an efficient manner is the multi-objective optimisation (MOO). MOO minimises a function *F*(x) subject to a range of decision variables, constraints, and objectives. The selected algorithm has to minimise the components of the vector *F*(*x*), where *x* is a n-dimensional decision variable vector, from all the possible universe Ω (Veldhuizen and Lamont, 2000) (Figure 2-6).

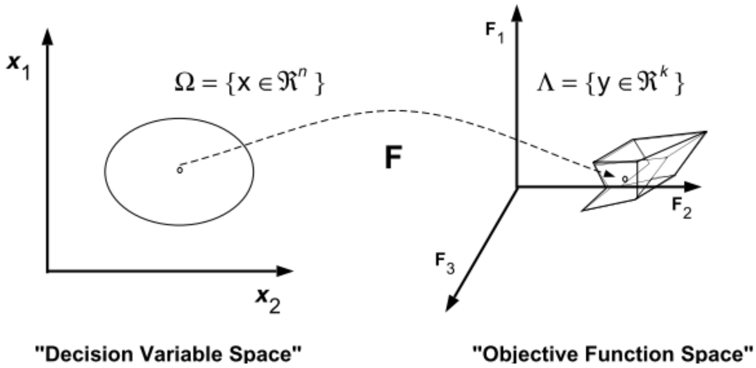


Figure 2-6 Multi-objective optimisation evaluation mapping. Source: Veldhuizen and Lamont, 2000

In buildings' research and practice, Attia et al. (2013) found that MOO methods are normally used during early designs as practitioners, who use optimisation techniques, applied 93% of the cases for new buildings. However, some studies have also demonstrated the strength of MOO for retrofit projects (Siddharth et al., 2011, Asadi et al., 2012a, Malatji et al., 2013). Improvement of the envelope, HVAC equipment, renewable generation, controls, etc., while optimising objectives, such as energy savings, occupant comfort, total investment, and life cycle cost have been investigated. Evins (2013) conducted a comprehensive review of 74 buildings' optimisation research, providing a list of the most typical objectives used in sustainable building design. He found that the most common objective was energy use (found in 60% of the studies), followed by costs and occupants' comfort (Figure 2-7).

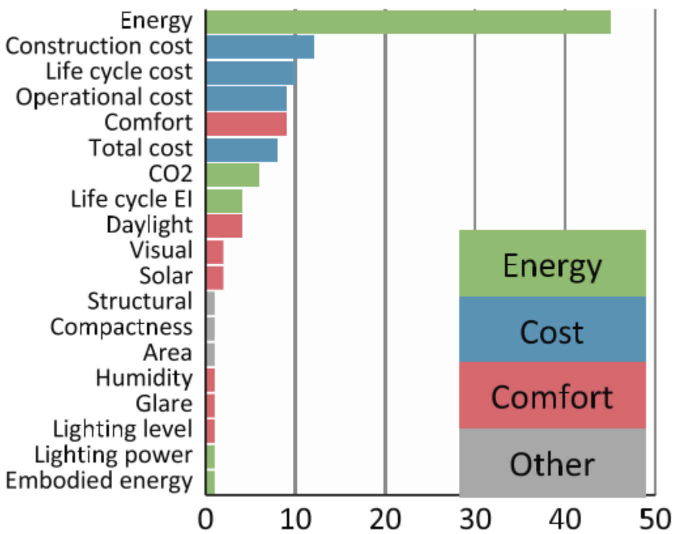


Figure 2-7 Typical objective in building optimisation research. Source: Evins, 2013.
Image reproduced with permission of the rights holder, Elsevier.

Three basic types of algorithms are used in optimisation problems applied to buildings: enumerative, deterministic, and stochastic (Attia et al., 2013). Enumerative and deterministic algorithms present several limitations when implemented in the building design, such as sensitivity to the initial guess, design variables, and the characteristics of the objective function (Alajmi, 2006). Stochastic methods based on genetic algorithms (GA) can be regarded as the most popular method for building optimisation. Other popular algorithm methods are 'Direct Search', 'Simulated Annealing', and 'Particle Swarm optimisation' (Evins, 2013).

The concept of GA was first developed by Holland (1975), inspired by Darwin's theory of evolution and the natural law of the survival of the fittest. GA is a global search procedure that progressively improves the objective functions in future populations by using a range of natural evolution operations such as reproduction, crossover, and mutation. Every individual in the population gets an evaluation of its adaptation to the environment or fitness. Some, by elitism, are passed to the next generation automatically, others go to the crossover phase and some of the crossover individuals pass through mutation. When the entire population is analysed, the collected information is randomly exchanged to create superior off-springs (Haupt and Haupt, 2004). GA is a flexible approach that can be applied to a wide range of learning and optimisation problems. It becomes useful where traditional optimisation techniques break down or are computationally intractable McCall (2005).

Konak et al. (2006) provided an extensive review of different genetic algorithms. The first GA used was the 'vector evaluated genetic algorithm '(VEGA) developed by Schaffer (1985). The method vectorises performance feedback for the successful GA selection process. The author made heuristic modifications to the traditional methods to give preference to non-dominated solutions. From this method, several versions have been developed such as Niched Pareto Genetic Algorithm (NPGA), Weight-based Genetic Algorithm (WBGA), Non-dominated Sorting Genetic Algorithm (NSGA), among others. Unfortunately, energy system models have a number of characteristics which make them difficult to optimise as these are usually non-linear. To overcome this, researchers usually simplify models by linearising it. Also, other strategy for simplification is reducing the search space. Algorithms such as NSGA-II have demonstrated to work perfectly for linear and non-linear problems while handling three or more objective functions, thus maintaining a stable and uniform reproductive potential across non-dominated individuals (Srinivas and Deb, 1994).

However, GA has some limitations. The parameters for the selection of population size, crossover and mutation, can affect the location of the optimal value and the rate of convergence. Studies have demonstrated that population size could have the most significant effect among the control parameters (Roeva et al., 2013, Alajmi and Wright, 2014), especially where the appropriate parameter selection becomes essential. Still, even though crossover and mutation rates could appear to be less sensitive, authors provided evidence suggesting that the optimisation problem performs at its best with high crossover probability (1.0) and a low mutation rate (>0.2). Another limitation of GA is that only operates in a discrete search space, meaning that continuous variables have to be discretised. Finally, because of its stochastic nature, it does not guarantee that the designer will find the best solution but instead provides a way to reach a reasonable solution in a time-effective manner (Nguyen et al., 2014).

2.2.3.1 BER-based studies using MOO and MCDM

As it is difficult to locate only one optimal solution in MOO, since the algorithms provide a range of different optimal outputs, one approach for analysis is to combine individual objectives into a single composite objective, returning a single optimal solution with the drawback that cannot be examined for trade-offs. A different approach is to determine an entire 'Pareto optimal' solution set by examining the objective functions individually. Pareto optimal solutions are defined as non-dominated (in respect to each other), admissible, and efficient. When the entire search space is shown in a graph, these non-dominated vectors are known as 'Pareto front' (Figure 2-8).

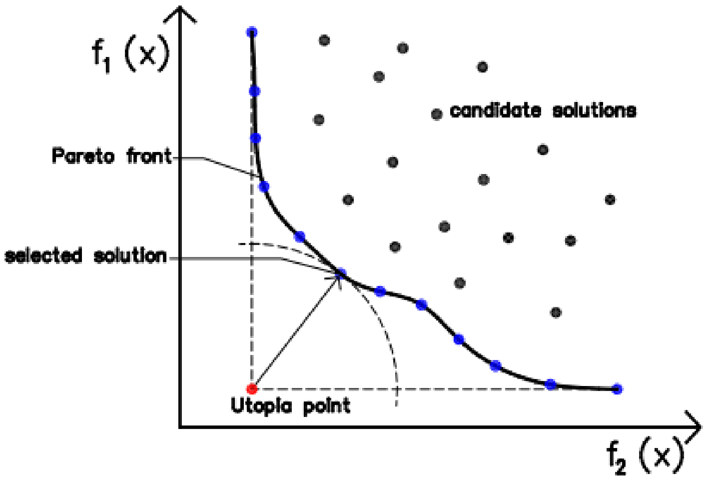


Figure 2-8 Graphical representation of a Pareto front. Source: Nguyen et al., 2014. Image reproduced with permission of the rights holder, Elsevier.

For most implementations, it is not vital to find every Pareto optimal solution, but identify Pareto optimal solutions across each objective function (Konak et al., 2006). When the Pareto set is defined, each point can represent the optimised point where the selection of the optimum solution is dependent on the preferences and criteria of the decision maker (Ahmadi et al., 2011).

Nevertheless, in building practice a particular design has to be selected for implementation. The issue of selecting the best solution from the Pareto set is not trivial as it depends on a number of aspects (e.g. the significance of objective functions, the demand of building investors, etc.). Multi-criteria decision making (MCDM) is a method that provides decision makers with a technique capable of analysing attributes, when multiple conflicting objectives are analysed. However, consideration must be given to different groups of decision makers, each with own point of view and different criteria (Pohekar and Ramachandran, 2004).

Buildings' design optimisation is an inherently complex, multi-disciplinary technique, which involves many disciplines such as mathematics, engineering, environmental science, economics, and computer science (Nguyen et al., 2014). In the last years, the application of MOO and MCDM has become more frequent for new building energy design practice for both domestic and non-domestic buildings. However, retrofitting or renovating existing buildings introduces design challenges beyond those found in new construction (Evins, 2013).

There are various classifications of MCDM. First, depending on the nature and on the type of alternatives or objectives, these can be categorised as discrete or continuous, quantitative, qualitative and mixed methods. On a second level of discrete MCDM, a further distinction can be made between weighting and ranking (Zavadskas et al., 2014). Pohekar and Ramachandran (2004) found that AHP, PROMETHEE, and ELECTRE are the most popular techniques used in energy systems planning. Figure 2-9 presents a general division of the most common MCDM methods.

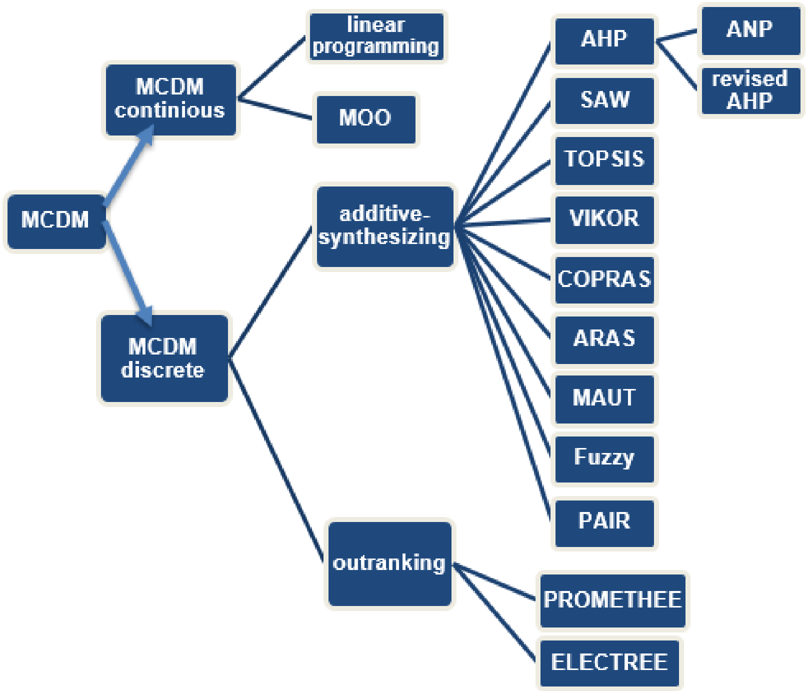


Figure 2-9 General classification of MCDM methods

Among the most notable contributions and pioneers in applying MOO-MCDM to BER design was Diakaki et al. (2008). First, the authors applied optimisation techniques to obtain energy-efficient and cost-effective solutions, with the objective of including the maximum possible number of measures and variations in order to facilitate the project decision making. Although the interaction of a great variety of technologies could represent a challenge for a practitioner, the study showed the strength in applying a MOO technique to reach an optimal or close to optimal solution in a time-effective manner. Finally, the author showed the application of three MCDM methods (compromise programming, global criterion method, and goal programming) to scan through all the solutions obtained in the Pareto front and locate an optimal solution depending on the weighted criteria given to each objective.

Asadi et al. (2012b) further explored the use of building simulation tools and MOO by developing a framework using TRANSYS, GenOpt and MatLab (The MathWorks, 2012). The tool was used to optimise retrofit investment cost, energy savings, and thermal comfort in a Portuguese residential building. After generating the Pareto solutions, compromise programming, based on the Chebyshev optimisation technique, was applied to help with the decision-making process.

As MOO-MCDM studies have been increasing in number, different software tools have been developed, mainly with the enhancement of typical building energy simulation tools. The most common building performance software used in optimisation are TRNSYS and EnergyPlus, covering almost 80% of the developed tools until 2014 (Nguyen et al., 2014). Optimisation toolboxes from high-performance tools such as MatLab or R have been typically coupled with TRNSYS and EnergyPlus; other tools, based on programming languages such as Java, Python, or C++ have also been developed. Figure 2-10 shows a relationship between simulation tools and optimisation tools combined in the last decade.

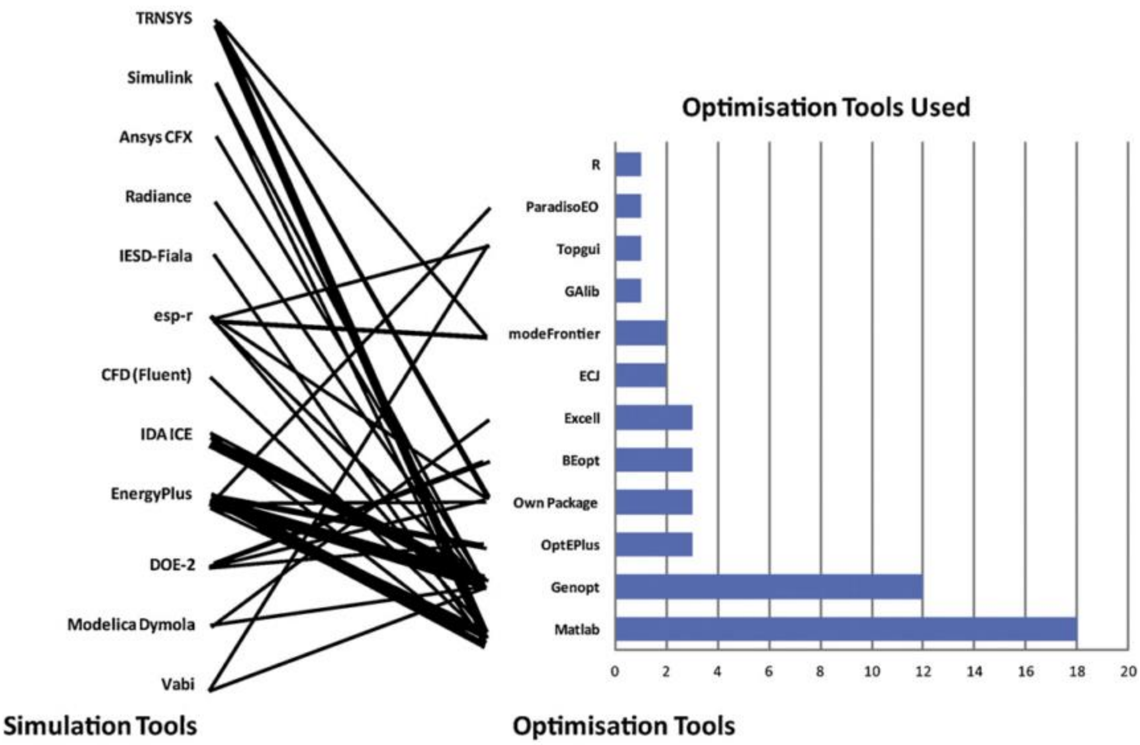


Figure 2-10 Studies frequency of combination between building energy simulation tools and optimisation tools. Source: Attia et al. (2013). **Image reproduced with permission of the rights holder, Elsevier.**

To date, the most popular available MOO final products are GenOpt, jEPlus, modeFrontier, Tpgui, Opt-E-Plus, BEOpt. Taking the advantages from these tools, retrofit-oriented optimisation studies have become more common in the last decade, considering different decision variables (retrofit measures), objective functions, and constraints, while also investigating other mathematical algorithms. The most notable contributions can be seen in Table 2-3. However, optimisation is mainly applied to research, where its limited introduction into real practice is a result of poor planning from stakeholders and a lack of standards for integrated optimisation methods, where more research on the practitioners’ experience with optimisation is needed (Attia et al., 2013).

Table 2-3 Comparison of several multi-objective optimisation studies applied to building energy retrofit (BER)

No.	Author	Case study	Location(s)	Simulation engine	Decision variables or measures	Objective functions	Constraints	Optimisation algorithm	MCDM method
1	Diakaki et al. (2008)	Single-zone dwelling (100 m2)	Athens, Greece	LINGO	Windows, insulation type, wall insulation thickness	• Initial investment cost • Building load coefficient	Insulation thickness	Mixed-integer combinatorial optimisation problem	Compromise programming and goal programming
2	Diakaki et al. (2010)	Single-zone dwelling (100 m2)	Athens, Greece	LINGO	HVAC and DHW systems, Solar collectors, and building envelope characteristics	• Primary energy use • Carbon emissions • Initial investment cost	Capital investment	Mixed-integer combinatorial optimisation problem	Chebyshev programming
3	Siddharth et al. (2011)	Office building (3721 m2)	Chennai, India. Maryland, USA. Arkansas, USA	DOE-2.2	HVAC systems, envelope characteristics	• Energy use • Initial investment cost	Non-defined	NSGA-II	N/A
4	Asadi et al. (2012b)	Semi-detached dwelling (97 m2)	Coimbra, Portugal	TRNSYS, GenOpt, and MatLab	Envelope characteristics (windows, walls, and roof) and solar collectors	• Initial investment cost • Energy savings • Thermal comfort	Non-defined	Mixed-integer combinatorial optimisation problem	Chebyshev programming
5	Diakaki et al. (2013)	Single-zone dwelling 50m2	Iraklion, Greece	TRNSYS and LINGO	Envelope characteristics and HVAC systems	• Primary energy use • Carbon emissions • Initial investment cost	Technological and budget constraints	Mixed-integer multi-objective combinatorial optimisation problem	Chebyshev programming

Table 2-4 cont. Comparison of several multi-objective optimisation studies applied to building energy retrofit (BER)

No.	Author	Case study	Location(s)	Simulation engine	Decision variables or measures	Objective functions	Constraints	Optimisation algorithm	MCDM method
6	Gossard et al. (2013)	Single-zone dwelling (112 m2)	Nancy, France Nice, France	TRNSYS, GenOpt, and ANN	Envelope thermo-physical values	• Energy use • Thermal comfort	Comfort conditions	NSGA-II and Particle swarm optimisation (PSO)	Weighted-sum method
7	Malatji et al. (2013)	Facility building (--- m2)	Pretoria, South Africa	N/A	Insulation, lighting, controls, and HVAC systems	• Energy use • Payback period	NPV, initial investment, energy target, and payback period	Integer programming GA	Weighted-sum method
8	Asadi et al. (2014)	School building 9850 m2	Coimbra, Portugal	TRNSYS, GenOpt, and ANN	Envelope characteristics (windows, walls, and roof), solar collectors, and HVAC systems	• Energy use • Retrofit cost • Thermal comfort	Non-defined	NSGA-II	N/A
9	Murray et al. (2014)	University building (--- m2)	Cork, Ireland	Degree-days and BeOpt	Envelope characteristics (windows, walls, and roof)	• Simple payback • Carbon emissions • Energy Cost	Capital investment	NSGA-II	N/A
10	Shao et al. (2014)	Office building (400 m2)	Aachen, Germany	Visual Basic energy model	Envelope characteristics (windows, walls, and roof), and HVAC systems	• Initial capital investment • Energy use, • Carbon emissions	Envelope physical values, annual energy use and envelope air leakage	NSGA-II	Multiple-attribute value theory (MAVT)
11	Wang et al. (2014)	Facility building (--- m2)	Pretoria, South Africa	N/A	Lighting and HVAC systems	• Energy savings • NPV • Evaluation period	% energy use, expected payback period, initial investment	Differential evolution (DE) algorithms	Weighted sum method

Table 2-4 cont. Comparison of several multi-objective optimisation studies applied to building energy retrofit (BER)

No.	Author	Case study	Location(s)	Simulation engine	Decision variables or measures	Objective functions	Constraints	Optimisation algorithm	MCDM method
12	Ascione et al. (2015)	Apartment flats (110 m2 per flat)	Naples, Italy	EnergyPlus and MatLab	Setpoints, envelope insulation, and HVAC systems	• Initial investment cost • HVAC energy requirement • Thermal comfort	Investment costs	NSGA-II	N/A
13	Dahlhausen et al. (2015)	Office building (6968 m2)	Philadelphia, USA	Open Studio, EnergyPlus, and R	Building enclosure, solar control, plug load/lighting control, and HVAC equipment	• Energy use • NPV	Investment costs	mixed-integer multi-objective combinatorial optimisation problem	N/A
14	Lu et al. (2015)	Office building (1520 m2)	Hong Kong, China.	TRNSYS and MatLab	Envelope and HVAC systems	• Investment costs • Carbon emissions • Grid interaction index.	Zero energy use	NSGA-II	N/A
15	Penna et al. (2015)	Single-zone dwelling (100 m2)	Milan, Italy. Messina, Italy	TRNSYS and MatLab	Envelope and HVAC systems	• Energy use • NPV • Thermal comfort	Investment costs	NSGA-II	N/A
16	Delgarm et al. (2016)	Single-zone dwelling (9 m2)	Tehran, Iran. Kerman, Iran	EnergyPlus, jEPlus and MatLab	Insulation, glazing, and solar shading	• Annual heating • Cooling • Lighting	N/A	Particle swarm optimisation (PSO)	Weighted sum method
17	Schwartz et al. (2016)	Council house complex (--- m2)	Sheffield, England	EnergyPlus, jEPlus and jEPlus EA	Envelope characteristics, insulation, windows	• Life cycle cost • Life cycle carbon	N/A	NSGA-II	N/A

2.3 Summary

Building energy retrofit (BER) is a strategy that has the potential to significantly reduce sectoral emissions. A wide range of policies, programmes, incentives, simulation tools, and techno-economic appraisal techniques, oriented to assess BER, seems to be in place. In addition, a large body of research regarding BER and optimisation procedures combined with decision support tools based on multi-criteria decision making is available in the literature. However, despite strong efforts made in the past decades, energy utilisation and carbon emissions from the building sector are still at high levels. Thus, typical approaches do not seem to improve the overall sectoral performance at a desired rate, required to achieve emissions' reduction goals.

The concepts and research presented in this chapter has its basis in the First Law of thermodynamics or the 'conservation of mass and energy' principles. Energy analysis typically shows similar efficiencies between different system configurations, so it has significant limitations when it comes to assessing the characteristics of energy conversion systems. Driven by current building regulations, common BER practice is still largely reliant on maximising thermal efficiency of the building's envelope before HVAC system improvements are introduced. Although widely accepted at scientific and practical levels in building energy design, the application of the First Law can have its limitations for an in depth understanding of energy systems. Its current use in established building methods and tools for sustainable building design could have an effect on reaching the maximum performance potential. Few researchers mention the intrinsic low thermodynamic efficiency of the current buildings, where it should be a matter of concern and should be explored in depth. With the current high dependency on high-quality energy sources, such as natural gas, oil, and off-site generated electricity, combined with the low thermodynamic efficiency of current building system technologies, new approaches to improve the selection of optimal BER measures are required.

Chapter 3 Exergy and Buildings

After discovering the lack of thermodynamic integration into typical BER practice, this chapter has the intention to give the reader a general understanding about the exergy concept and its potential implementation in the design of energy efficient buildings. The objective is not to present an exposition of the theory of the Second Law of Thermodynamics; instead a general basis to justify its application for the design of building energy systems is presented. In the second part of this chapter, an introduction to exergoeconomic analysis and its importance in delivering energy efficient and cost-effective energy systems is provided. As exergoeconomics is not a typical method in building energy research, links have to be established showing its potential implementation into BER practice. The theory and formulation revealed in this chapter will pave the way for the introduction of the developed methodological framework in Chapter 4.

3.1 Concepts and definitions

3.1.1 Brief history of exergy and differences with the First Law

The main limitation of the First Law is that it does not account for energy quality, where thermal, chemical, and electrical energy sources, should not be valued the same, since they all have different characteristics and potentials to produce work. For example, an energy analysis of a CHP could consider 1 kW of thermal energy product the same as 1 kW of electricity produced by the system, while in reality both products have a different utility. A useful categorisation in energy analysis is that a kW (or kWh) can be expressed as thermal energy (kW_{th}) and electrical energy (kW_e) (Chapman, 1975). Nevertheless, this ambiguity can be amended by using the concept of energy availability or exergy. To explain the concept, first we have to briefly introduce the Second Law of thermodynamics.

Traditionally the Second Law has its origins from the work of Sadi Carnot (1796-1832). Carnot's main interest was studying heat engines' efficiencies under ideal conditions (null piston mass, null friction, null heat loss, etc.), with a main focus on locating the maximum theoretical efficiency. Carnot stated the following: "*No heat engine operating between two heat reservoirs can be more efficient than a reversible heat engine operating between the same two reservoirs"*. (Figure 3-1).

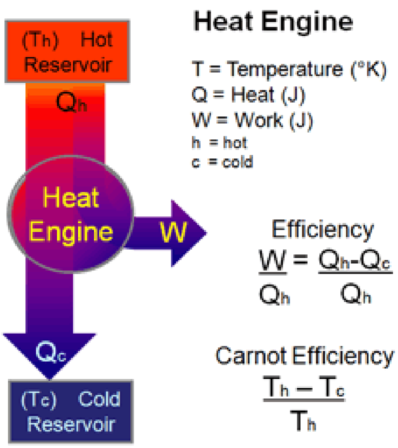


Figure 3-1 Conceptualisation of the Carnot engine

where *W* is the work done by the system, *Qh* is the heat put into the system, *Qc* is the heat out from the system, *Th* is the absolute temperature of the hot reservoir, and *Tc* is the absolute temperature of the cold reservoir. Carnot's main findings established that engine's theoretical efficiencies depend only on the temperature difference and not on the working fluid (either gas or liquid). Although Carnot did not directly provide an interpretation of the Second Law, his work established the foundations by influencing the works from Lord Kelvin (1824-1907) and Rudolf Clausius (1822-1888). Through separate work in the 1850s, both authors provided equivalent statements for what is known today as the Second Law of Thermodynamics.

Kelvin-Planck statement, based on the fact that a heat engine is never 100% efficient, states the following: "*It is impossible to construct an engine, which operating in a cyclic manner extract an amount of heat* Q_h *from a hot reservoir and use it all to do work W. Some amount of heat* Q_c *must be exhausted to a cold reservoir*"

Clausius's statement, based on the fact that energy will not flow spontaneously from a low temperature object to a higher temperature object, states: "*It is impossible for a self-acting machine working in a cyclic process without any external force, to transfer heat from a body at a lower temperature to a body at a higher temperature*". This statement gave the first understanding of the concepts of refrigerators and heat pumps, which basically are heat engines running in reverse

Although it is not evident how both statements could be related, their equivalence is demonstrated by the fact that the violation of each statement implies the violation of the other (Moran and Shapiro, 1988). The key aspects of the Second Law are the prediction of the direction of any process, the establishment of equilibrium equations and maximum theoretical efficiencies, and evaluation of factors that limit ideal behaviour.

3.1.1.1 *Entropy and Irreversibilities*

It was Clausius's intuition about how spontaneous processes are governed by a 'Law' that rules the direction of an event, which gave place to the 'Clausius inequality' (Ben-Naim, 2007), thus providing the definition of the 'entropy' (S) concept. Like mass and energy, entropy is also an extensive property that can be transferred through the system's limits. In every process where energy or matter is dispersed, entropy is inevitably generated; leading to irreversibilities. Irreversibilities can happen in any form of energy transfer (heat exchange, gas or liquid expansion to a lower pressure, spontaneous chemical reaction, friction**,** flow of an electrical current through a resistance, etc.) (Moran and Shapiro, 1988). Any real process is irreversible, which means that it cannot return to original conditions because of the constant increase of entropy in the environment. By locating irreversibilities, a clear indication of the thermodynamic improvement potential of a given energy system can be obtained.

Entropy changes or irreversibilities produce a loss of capability to do work, in other words, 'energy availability' is being lost in the process. The main contributors to the concept of 'energy availability' were J.W. Gibbs (1839-1903) and J.C. Maxwell (1831-1879) (Gaggioli Richard, 1983). Later, separated works from Louis Gouy (1854-1926) in 1889, and Aurel Stodola (1859-1942) in 1910, provided a relationship between entropy and energy availability deriving from the formulation of the Gouy-Stodola theorem. The statement establishes that: "*the rate of energy availability loss in a process is proportional to the product of the reference temperature* T_0 *and the rate of entropy generation S; thus minimizing loss of available energy is equivalent to minimizing entropy production*". This statement shows that any thermodynamic process must have a minimum amount of irreversibility generation. It is expressed with the following formula:

$$\dot{I} = T_0 \dot{S} \tag{3.1}$$

3.1.1.2 *From 'Energy Availability' to 'Exergy'*

Nowadays, energy availability is also called 'exergy'. The term was suggested for the first time by a chemist Zoran Rant (1956), referring to a combination of Greek words *ex* and *ergos*, which means 'external work'. Based on Gibbs's work, Rant gave his own definition for exergy stating the following: "*the maximum work obtained while bringing the system into thermodynamic equilibrium within an "infinite" reference environment."* As Hermann (2006) mentioned, all activity in the universe derives from the matter and energy becoming more disorganised, as expressed by the Second Law of thermodynamics. This Law can quantify the work potential of a substance relative to a reference state. This reference state has to be specified by giving temperature values, pressure or chemical composition of the reference environment. For example, a cup of hot water has more exergy in winter than in summer simply because of the larger difference in temperature. Because of the complexity that represents the exergy concept, a uniform definition does not exist in the literature (Table 3-1).

Table 3-1 Exergy definitions provided by several authors

Researcher	Definition of exergy
Szargut (1957)	• Amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of its surrounding nature by means of reversible processes, involving interaction only with the above mentioned components of nature.
Gallo and Milanez (1990)	• Amount of work obtained when a piece of matter is brought to a state of thermodynamic equilibrium with the surroundings by means of reversible processes.
Dincer (2002)	• Measure of a system potential or a flow to cause change, as a consequence of not being completely stable equilibrium relative to the reference environment.
Asada and Boelman (2004)	• Concept that shows the usefulness or quality of energy and matter; this in addition to the quantity of energy consumption in a course of an energy conversion process, where this provides a holistic view of how a system really works by analysing in which part of the chain energy is degraded.
Gasparatos et al. (2009)	• The maximum work that can be extracted from a system, when this system moves toward a thermodynamic equilibrium with a reference state; in a dead state exergy is equal to zero and no more entropy is generated.
Torío et al. (2009)	• The maximum theoretical work that might be extracted from the system, where exergy is a measure of the potential of a given energy flow to be transformed into high quality or high grade energy.
Müller et al. (2011)	• Ability of an energy carrier to perform work and can be seen as a core indicator of measuring its quality.

From all the different definitions, we can infer that exergy is an indication of energy quality. Therefore, the main difference between the First and the Second Law is the capabilities of the latter to account for the different amount of exergy of every energy source and also calculate irreversibilities or exergy destructions. Exergy of a system can be composed of different types of exergy: mechanical exergy, thermal exergy, and chemical exergy. A more detailed visual classification can be seen in Figure 3-2.

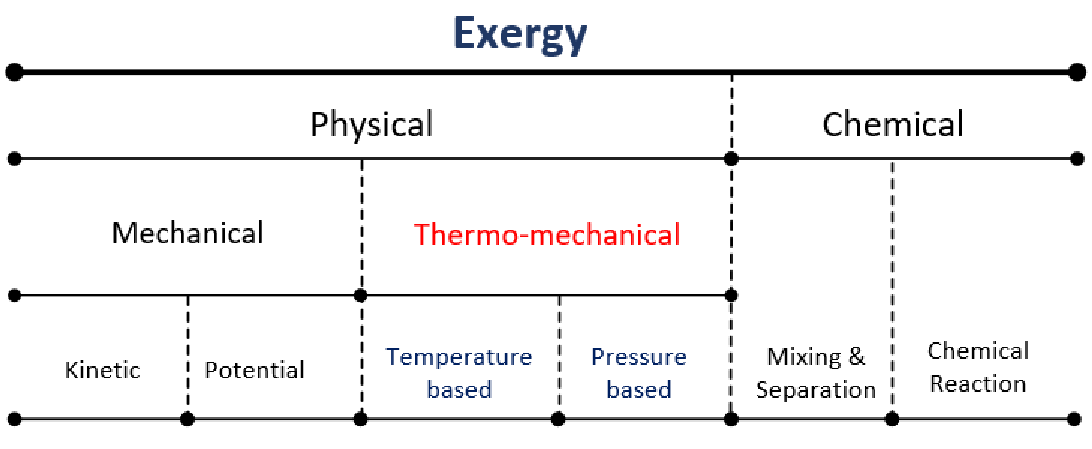


Figure 3-2 Classification of different types of exergy forms. Source: Gundersen, 2011

In order to avoid confusion with traditional energy methods, it is important to distinguish between the energy and exergy concepts (Dincer and Zamfirescu, 2012) (Table 3-2).

Table 3-2 Main differences between energy and exergy. From Dincer (2002)

Energy	Exergy
• Is dependent both on the parameters of matter or energy flow and on the environment parameters.	• Is dependent on the parameters of matter or energy flow only, and independent of the environment parameters.
• Has values different from zero (equal to mc^2 in accordance with Einstein's equation).	• Is equal to zero (in a dead state by equilibrium with the environment).
• Is guided by the first law of thermodynamics for all the processes.	• Is guided by the first law of thermodynamics for reversible processes only (in irreversible processes it is destroyed partly or completely).
• Is limited by the Second Law of thermodynamics for all processes (incl. reversible ones).	• Is not limited for reversible processes due to the Second Law of thermodynamics.
• Is motion or ability to produce motion.	• Is work or ability to produce work.
• Is always conserved in a process, so can neither be destroyed nor produced.	• Is always conserved in a reversible process, but is always consumed in an irreversible process.
• A measure of quantity.	• Is a measure of quantity and quality due to entropy generation.

Since the 70s, exergy analysis is typically applied in power plants, diesel engines, combined cycle operations, combustion processes, as well as in the chemical industry and some industrial processes (Agazzani and Massardo, 1997). Rosen (2002b) described how researchers and engineers refer to exergy analysis as a powerful tool for analysing, assessing, and improving systems and processes, however its utilisation is still not widespread. The biggest barriers to using exergy analysis are:

a. methods are too complex for some users (because of the necessity to choose a reference environment),
b. the results of exergy are regarded by some as difficult to interpret, understand and utilise,
c. many potential users are simply unfamiliar with exergy, and
d. practitioners have simply not found exergy methods to lead to tangible, direct results.

With regards to the actions that can be performed to overcome these barriers, Rosen (2002b) lists the following:

a. practitioners must be educated about exergy methods and their applications through college programs and employment training,

b. efforts should be made to point out clearly to industry the benefits of using exergy methods, and

c. these efforts should be supplemented by cases studies where exergy has been applied beneficially.

3.1.2 Exergy and sustainability

Exergy can be useful in explaining sustainability of different energy sources and technologies. Rosen and Dincer (2001) considered exergy as the confluence of energy, environment and sustainable development (Figure 3-3), suggesting that exergy analysis provides an effective measurement for reducing environmental problems and achieving sustainable development.

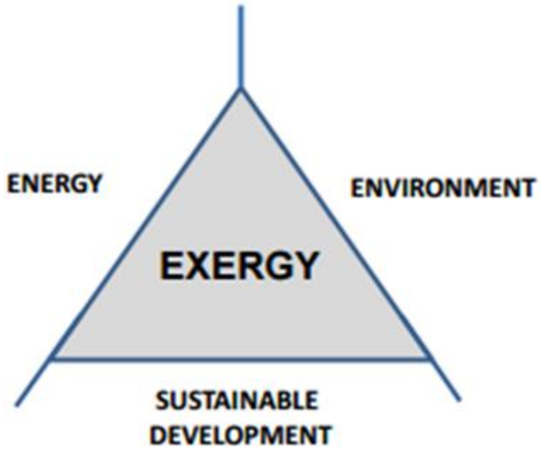


Figure 3-3 Interdisciplinary triangle covered by the field of exergy analysis. Taken from Rosen and Dincer (2001). Image reproduced with permission of the rights holder, Elsevier.

Rosen (2002a) explained the importance of the exergy concept in understanding environmental problems. The author showed how exergy analysis focused on systems' and processes' optimisation lead to lesser depletion of environment's energy resources, such as fossil fuels and uranium. Therefore, improvements in a system's exergy efficiency can directly minimise air pollution, liquid waste, and solid waste problems. As exergy analysis can identify the losses from using non-renewable sources, it can therefore provide more information for a sustainable design. Rosen et al. (2008) expresses a sustainability index based on exergy as an inverse of the depletion rate or rational exergy efficiency. It can be expressed as follows:

$$SIx = \frac{1}{\Psi rat_{sys,th}} \tag{3.2}$$

A relationship among the index, exergy efficiency, and carbon emission for a traditional fossil-fuel driven HVAC system can be seen in Figure 3-4.

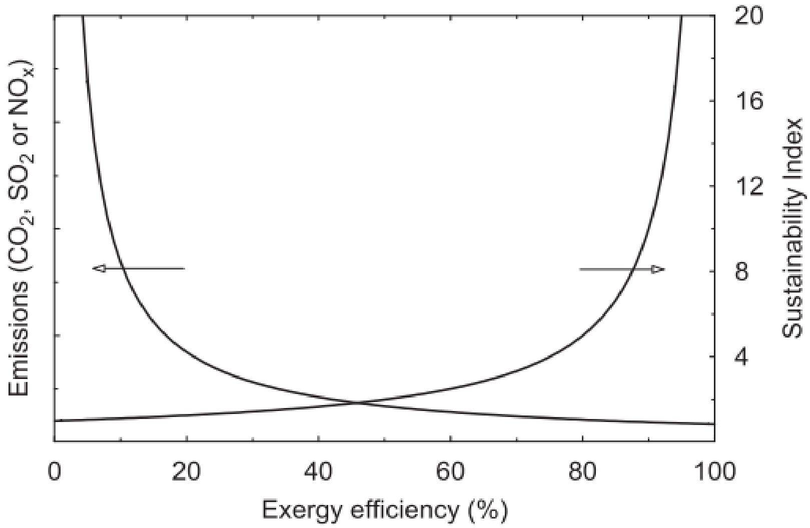


Figure 3-4 Relation between exergy efficiency, environmental impact and exergy-based sustainability. Source: Rosen et.al (2008). **Image reproduced with permission of the rights holder, Elsevier.**

Cambel (1980) pointed out the following: *"the solution to the conflict between energy and environment must not be curtailing energy supply, but in reducing the irreversibilities and dissipative effects when we convert and consume energy"*. Nowadays, it is rare to find an 'energy efficiency program' focused on reducing inefficiencies throughout the supply chain; instead, programs are focused on how to save energy. From a policy perspective, rather than focusing only on the energy utilisation, a well-grounded energy/exergy policy could speed up the progress towards a more sustainable society by ensuring the exergy of resources is used in a rational way providing governments with an improvement in its energy and resource security (Rosen, 2002d).

3.2 Exergy and buildings

Most buildings demand four types of products: a) heating energy, b) cooling energy, c) domestic hot water (DHW), and d) electricity to run appliances. Exergy demand in buildings is regarded as the minimum amount of work necessary to provide the energy to cover these demands. When energy flows pass throughout the building's energy supply chain, energy is not being consumed, instead the conversion processes are converting the energy to a less useful energy source. The main problem lies in the ineffective match between the potential of the sources and the demand of the building. Energy demand for heating, cooling, and DHW are low quality demands that are commonly satisfied by high quality sources. In this context, Hammond and Stapleton (2001) calculated exergy efficiency for different UK building end-uses, considering a reference temperature of -1°C (272.15 K). Exergy efficiency can be considered as the ratio of exergy output to the exergy input. The authors found that space heating true thermodynamic efficiency was 0.12 (12%), 0.17 for water heating, 0.25 for electric catering, and 0.05 for lighting and appliances. Gasparatos et al. (2009) showed that the overall building sector exergy efficiency stands at roughly 0.12 (12%), thus being the most thermodynamically inefficient economic sector in the UK.

Nevertheless, exergy as a concept is arising among buildings' energy researchers, and most importantly, among policy makers. A valuable example is the UK government's report "*The Future of Heating: A strategic framework for low carbon heat in the UK*" (DECC, 2013), where for the first time exergy is mentioned in order to establish a difference between 'energy' and 'energy quality' and is considered as a useful indicator in the development of low carbon systems. The report considers heat pumps as the best alternative for decarbonisation of the building sector, especially working with low temperature emission systems, such as large surface wall or underfloor systems. However, Lowe (2011) demonstrated that CHP systems can be regarded as virtual heat pumps, showing how the CHP steam cycle plus an additional virtual steam cycle is thermodynamically equivalent to a conventional heat pump cycle. This analogy demonstrates that CHPs can be more efficient than heat pumps, as the practical performance of CHP is higher than conventional heat pumps using grid electricity. CHPs are able to achieve COP of 9.0, while heat pumps commonly achieve COP of around 3.0. Despite the evidence, depending on current energy prices, it could be more cost-effective to produce heat with the aid of heat pumps rather than install a CHP or connect the building to a district heating network (Dincer, 2002). Nevertheless, other studies (Olivier and Simmonds, 2012) have demonstrated that state of the art district heating distribution systems could be more economically attractive than individual heat pumps even in low density communities, demonstrating the importance of studying energy systems at a larger scale. Müller et al. (2011) presented a study of energy prices for typical energy sources used in buildings in four European countries. It postulates that energy prices reflect the exergy content of the fuels, since customers are looking for the part of energy that can be converted to work and is able to cover the final demand. It also shows how the share of technological investment increases when low exergy sources are required, since the lower the exergy factor, the higher the investment and capital needs are for making use of low exergy carriers.

3.2.1 Exergy analysis methods applied to buildings

In some sectors, exergy methods count with a certain degree of maturity that makes the analysis useful (Streich, 1996, Lior, 2002, Montelongo-Luna et al., 2007, Querol et al., 2011, Ayres et al., 2011, Ghannadzadeh et al., 2012, Suleman et al., 2014 , and Caliskan, 2015), while in others, exergy analysis is still in an initial stage and more investigation is required. This happened through the research methodology switch from an entropy-based approach to an exergy-based approach, since exergy is a more tangible measure. Its implementation overcomes the limitations of the First Law by indicating locations, causes, and magnitudes of energy degradation and calculating meaningful efficiencies (Dincer and Zamfirescu, 2012). Exergy analysis does not have to be seen as a replacement of typical energy analysis, but instead as a supplement, which aids in the design and optimisation of energy systems. An efficient system design will be achieved when destructions and losses are minimised.

However, in building energy research, exergy analysis has been implemented at a slower rate, and it is almost non-existent in the industry. For example, to date, exergy has had a very low influence on professional design where it does not appear neither in ASHRAE handbooks nor in CIBSE guides (Fisk, 2014). However, as Torio (2012) explained, methods of exergy analysis are not completely transferable between energy systems. For example, exergy analysis for a power generation plant has different objectives than those found in the buildings' energy design. The objective of a power plant is to increase outputs (electricity production) while minimising irreversibilities. The aim of building exergy analysis is to keep (or improve) occupant's comfort conditions by decreasing irreversibilities (Figure 3-5).

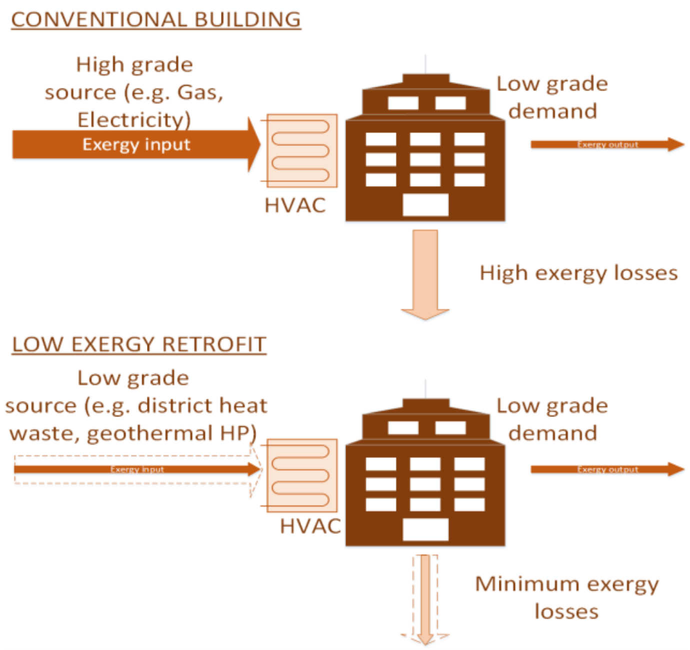


Figure 3-5 Schematic exergetic flow comparison between a conventional building and an exergy-efficient building (Modified from IEA-Annex 49, 2009)

The majority of exergy research in the built environment, dedicated to improve energy performance, has been applied to large scale technologies, especially in the assessment of district networks and community supply power generation systems (Verda et al., 2001, Molyneaux et al., 2010, Bagdanavicius et al., 2012, Li and Svendsen, 2012, Verda et al., 2012a, Verda et al., 2012b, Rezaie et al., 2015, Nilsson, 1997). The research has mainly focused on defining criteria for network design, sizing energy generation plants, optimising water flow pressure and temperatures (inlet and return), pipe diameter sizing and insulation thickness, selection of heat and energy storage equipment, as well as selecting optimal energy source. However, some researchers have considered that exergy interactions at a building level play a fundamental part in improving exergy efficiency in the buildings' sector.

3.2.1.1 The reference environment for buildings

The most important concept that has to be considered in order to perform exergy analysis, is the establishment of a reference environment (which is somewhat subjective); this is because exergy is not a property only of the system, but of the system and the environment. The thermodynamic environment in exergy analysis represents a large system that is in constant equilibrium where the temperature, pressure, and chemical components remain constant when a thermodynamic process occurs within its boundaries. The thermodynamic environment can be distinguished between reference environment and immediate environment (Figure 3-6). In this case external irreversibilities occur in the immediate environment, and internal irreversibilities occur in the analysed system. The reference environment does not suffer irreversibilities as a consequence of the system operation.

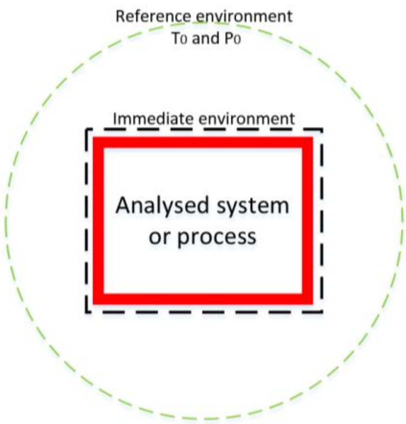


Figure 3-6 Reference environment, immediate environment, and energy system

When the two interacting bodies reach a state of equilibrium it is called a 'dead state', meaning that no potential to do any work exists anymore. In this sense, the system and the environment possess energy but the exergy value is zero. The reference environment, used in the majority of macro systems' analysis, is composed of a T_0 = 25 ºC (289 K) and P_0 = 1 atm, with a chemical composition of air saturated with water vapour (Gaggioli Richard, 1983). In this sense, the European Commission (2010) proposed the use of exergy to calculate emissions generated from CHP products. The analysis is performed assuming a reference temperature of 0 °C (273 K). Orchard (2012) finds this assumption impractical because of the natural operation of CHP plants, where normally heat rejections occur above the ambient temperatures. The author recommends a reference temperature of 30 °C (303 K) for the analysis mainly due to the impractical nature of condensing high steam volumes at a low temperature such as 0 °C.

However, contrasted with the power plants or chemical processes, where the choice of the reference environment is not very influential towards the final results as the working temperatures can achieve values well above 1000 ºC, the reference environment in the building's exergy analysis is of vital importance because the building works very close to the reference temperature. As surroundings' properties, such as temperature, pressure, and chemical composition are in constant change, it represents a difficult characterisation. The selection has to be determined with a preliminary analysis, locating which environment could act as entropy-disposal sink. From the buildings' perspective, the following four options for entropy sink have been discussed in the literature: a) *universe, b) building indoor air, c) undisturbed ground, and d) outside air*. Torío et al. (2009) explained the following characteristics for each option:

1) <u>Universe</u>
    a) *radiative energy transfers from the earth*
    b) *discarding of entropy generated by energy processes on earth*
    c) *receives energy flux from the sun – high quality solar radiation, tidal energy from celestial bodies (moon) and nuclear processes within the earth crust. (First Law)*
2) <u>Indoor air inside the building</u>
    a) *is neither an infinite sink or in thermodynamic equilibrium*
    b) *the temperature greatly varies as a result of energy processes*
3) <u>Undisturbed ground</u>
    a) *can be an infinite sink*
    b) *can remain uninfluenced by building energy processes*
    c) *the limitation is that it is not always directly available in the built environment*
4) <u>Ambient air surrounding the building</u>
    a) *can be regarded as the ultimate sink*
    b) *the air volume that surrounds the building is big enough for it not to have any big changes due to energy processes.*
    c) *naturally available and ready to use*

The biggest debate has been between the 'undisturbed ground' and the 'outside air' surrounding the building. Both can be considered as an infinite sink for entropy disposal and its exergy contents are available for use, but the ground has the limitations that is not always available for the building; on the other hand, outside air has the quality that is always available and it does not suffer any changes in its physical properties (thermal, chemical, mechanical) due to interaction with the building's energy processes. Accordingly, the majority of the research considers the outdoor air as the most appropriate reference environment for the analysis (IEA EBC-Annex49, 2011).

3.2.1.2 Steady-state or dynamic reference environment

Currently, prevailing discussion is concerning whether the static or dynamic temperatures should be chosen for exergy analysis. According to Pons (2009), considering the dynamism of the reference environment and the time-dependency may not be the best choice for the reference environment; therefore, suggesting the use of a static reference temperature as more appropriate for the analysis. The author considers that the analysis must be robust enough to not be biased towards the fluctuations in ambient temperatures. The author demonstrated that the 'dead state' contains some amount of exergy, demonstrated by a night ventilation application, where the cold exergy of air contained in the reference environment is used to lower the building's cooling demand. He also showed that a linear combination between entropy generations multiplied by a constant temperature can be the basis for exergy calculations. This presents an advantage, as entropy does not depend on temperature but only on the state of the system.

Other authors consider that the dynamism of the reference environment has to be accounted for, where the use of dynamic temperature values is more appropriate, especially, if dehumidification and cooling processes exist within the building (Alpuche et al., 2005, Angelotti et al., 2009, Sakulpipatsin et al., 2010, Zhou and Gong, 2013). Studies based on quasi steady-state or dynamic analysis use hourly external temperatures provided by weather files allowing to perform time step calculations. Steady-state calculations might be reasonable for an estimation of exergy flows for heating applications, particularly in colder climates. The error increases when milder climates are analysed. A quasi-steady-state approach is suitable, if there are no systems with large energy storage capacities (IEA EBC-Annex49, 2011). In this sense, a dynamic exergy analysis implies the assessment of all storage processes within the regarded energy systems (Angelotti et al., 2009). Nevertheless, more evidence is still required in order to reach a consensus on the most appropriate reference temperature for building exergy analysis.

3.2.1.3 Exergy analysis for thermal-based equipment

The exergy depends on the temperature at which the heat is available (T_i) and the temperature level at which the rejected heat can be disposed (T_0, reference temperature). With the support of the Second Law and the Carnot factor (quality factor), the useful part of energy to produce power from heat can be obtained. The Carnot factor is calculated as follows:

$$F_q = 1 - \frac{T_0}{T_i} \quad (3.3)$$

Therefore, exergy of heat can be obtained by multiplying the Carnot factor by the heat energy. This can be expressed as follows:

$$Ex_{heat} = Q\left(1 - \frac{T_0}{T_i}\right) \quad (3.4)$$

The remainder of the heat is transferred to the reference environment T_0. From the formula it can be seen that when T_i approaches infinity the quality factor is close to 1, which means that all heat can be converted to work. When T_0 is greater than T_i, the quality factor is negative, meaning that exergy has an opposite value of heat transfer. The advantage of this analysis is that magnitudes and direction of processes can be accounted for.

Nieuwlaar and Dijk (1993) were one of the first researchers to advocate the use of exergy analysis at a building level. The authors provided a basic Second Law calculation to account for exergy consumption and irreversibilities along the buildings' systems. While the authors consider that envelope thermal insulation can only reduce heat demand efficiently up to a certain level, energy strategies should focus on more advanced supply options, as these may be more cost-effective and environmentally-friendly. A thermodynamic performance of different supply side equipment, such as CHP, heat pumps, and district heat waste was conducted, concluding that a great potential exists to reduce current inefficiencies, given favourable technical, political, and market conditions. Figure 3-7 provides a general abstraction of the building's energy supply chain made in the study.

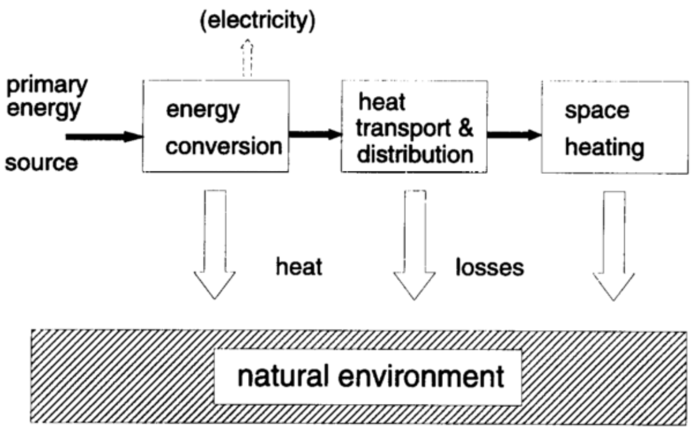


Figure 3-7 General scheme of a typical energy supply chain. Source: Nieuwlaar and Dijk, 1993. **Image reproduced with permission of the rights holder, Elsevier.**

Another pioneer of the building exergy analysis was Shukuya (1994). The author stated that the systems in a building work as an 'exergy-entropy' process, explaining that a working building system basically feeds on exergy, consumes exergy, generates entropy, and finally, the generated entropy is disposed to the environment by disposing of the generated entropy from the system and making new room for feeding on exergy and consuming it again, thus the process cycle. Shukuya showed that characteristics of the building envelope have a strong influence on the exergy demand and exergy consumption of the building, where special attention has to be put on parameters such as insulation, thermal mass, and windows' performance. Shukuya's approach, although similar to Nieuwlaar's and Dijk's (1993), suggests that rational passive design is a prerequisite to realise exergy efficient systems before focusing on designing low carbon generation systems.

Later, Shukuya and Hammache (2002) developed a more robust methodology for analysing exergy flows of heating and cooling systems in buildings. This work was also part of the IEA-EBC Annex 37 '*Low Exergy Systems for heating and cooling of buildings*' (IEA EBC-Annex37, 2007). In addition to the mathematical formulation, different exergy indicators were introduced. The 'irreversibility rate', based on the Guoy-Stodola relation, shows that exergy destructions are the product of the entropy generation for all systems located in the building, and the temperature of the environment. Also, three definitions of exergetic efficiencies were analysed: a) simple/conventional exergetic efficiency, b) rational exergetic efficiency, and c) utilisable exergy coefficient. In the context of space heating and cooling in buildings, it is obvious that the use of either a conventional or a rational exergetic efficiency is sufficient to compare different heating and cooling systems, since no chemical reactions are involved.

Schmidt (2004) in his doctoral thesis, developed the fundamentals of the building exergy methodology that is commonly applied in the majority of 'LowEx' exergy research nowadays. The author's main objective was to obtain a practical and reliable model of thermally activated building components as a way to reduce exergy consumption through the utilisation of lower temperature differences between the building's demand and the energy sources. It was demonstrated how losses, produced by ventilation systems, which also account for a significant portion of building energy demand, can be reduced by using highly efficient heat recovery systems. The author acknowledges that by using heat recovery systems, a loss in pressure can be significant (provoking negative pressure), therefore an optimisation process to calculate air exchanges for natural ventilation was proposed. The developed exergetic method, based on an input-output approach, is similar to the analysis applied to other thermodynamic systems (power plants). The system thermodynamic abstraction made by the author, in accordance to a modified DIN 4701-10 method, is presented in Figure 3-8.

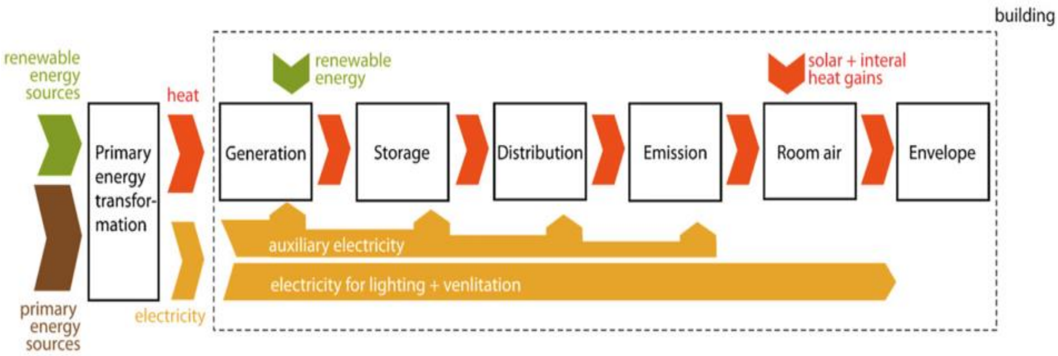


Figure 3-8 Heating chain and subsystems for exergy calculations. Source: Schlueter and Thesseling (2009) via Schmidt, 2004. **Image reproduced with permission of the rights holder, Elsevier.**

Although a single component analysis can be done, the potential of the method is to perform an overall optimisation. The demand of each subsystem must be satisfied by the subsystem before. The primary energy transformation subsystem is located outside the building's boundary and the calculation has to be performed in the opposite direction, starting from the envelope and finishing in the conversion of primary energy. The method was further developed on the IEA Annex 49 '*Low Exergy Systems for High-Performance Buildings and Communities*' (IEA EBC-Annex49, 2011). The calculation method has been widely used by other researchers (Hepbasli, 2012, Schlueter and Thesseling, 2009, Sakulpipatsin et al., 2010).

In parallel, a different exergy method was developed by Favrat et al. (2008). Its development was due to the implementation of a legal framework in Geneva, Switzerland, which required practitioners, involved in large development and retrofit projects, to submit exergy indicators within the required planning documentation. The aim of Favrat's approach was to simplify the thermodynamic calculations for architects and engineers, concerning electricity use, heating, air conditioning, and refrigeration. Following the traditional exergy methods of providing an abstraction of the energy system by separating subsystems in different blocks, the author separated the building energy supply chain in four subsystems: 1) power plant, 2) cogeneration/heat pump district system, 3) building plant or district system heat exchanger, and 4) room convector or radiator. The abstraction of this model can be seen in Figure 3-9.

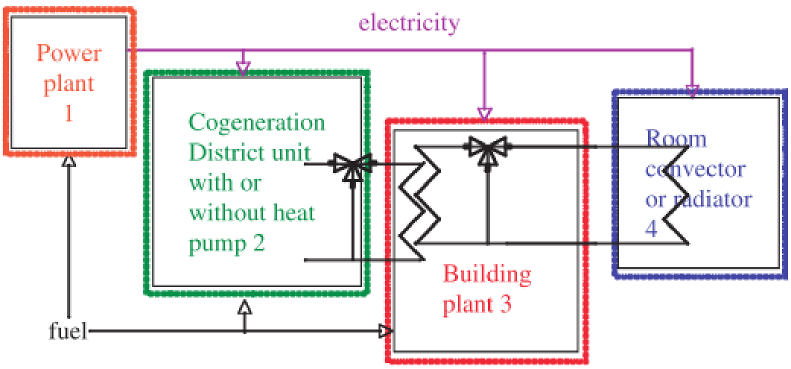


Figure 3-9 Building energy system decomposition by Favrat et.al. 2008. **Image reproduced with permission of the rights holder, Elsevier.**

This methodology simplifies the analysis by calculating energy inputs and outputs, and efficiencies at each process. A limitation of this method is that it does not identify the impact of renewable sources, and although some renewable technologies have lower exergy efficiencies than fossil-based equipment, this should not be quantified in the same manner. This can be dealt with by the use of an additional and separate indicator.

3.2.1.4 Exergy analysis for electrical equipment

Exergy can be applied to electrical systems in the same way as to general thermodynamic systems. As there are fewer energy forms, analysis is much simpler and straightforward. Because electricity is pure exergy, efficiencies of energy and exergy tend to be the same ($\psi_{elec} \approx \eta_{elec}$), thus electrical equipment energy use and exergy consumption will be the same. Nevertheless, exergy destructions have to be quantified, as several electric equipment, such as pumps and fans, are necessary to run HVAC equipment.

Rosen and Bulucea (2009) stated that a big reason for exergy analysis not to be commonly employed in electrical engineering studies is because thermodynamic analysis often deals with different forms of energy at a time (electric, work, heat, chemical, etc.), while electric engineering commonly focuses on electricity only. Notwithstanding, a demonstration of the potential of exergy analysis for electrical systems by identifying potentials to reduce exergy destructions and improve efficiencies, was provided in the study. The authors pointed out two benefits of using exergy analysis for electric-based equipment: a) losses are identified in terms of cause and located more accurately, and b) in systems where non-electrical quantities are involved, efficiencies in energy and exergy bases differ. For example, lighting as an end-use is very inefficient, as it converts high quality work (electricity) into visible light (fluorescent lamps convert 20% of electricity into light with waste heat emissions at 30 ºC). For exergy analysis, the electromagnetic radiation has similar energy and exergy contents, thus First Law and Second Law efficiencies are similar. Lighting has one of the biggest potential for energy and exergy conservation due to its large demand in current buildings.

In buildings, electric demand for fans, pumps, motors, and other devices could also represent high exergy consumptions (Sakulpipatsin et al., 2010). Some authors have demonstrated that accounting for electrical exergy in the building's system represents an important task. For example, Verda and Kona (2012) in an exergetic study in a district heating network, showed that exergy destructions due to electric pump devices operating within the plan, represented 10% of the total overall exergy destructions. Considering thermal processes as well as electric processes in buildings provides with comprehensive means to understand the interactions between the building envelope and the building energy services.

3.2.1.5 Exergy analysis for renewable energy systems

Exergy analysis can also provide a fundamental tool in the evaluation of renewables-based systems, as these can provide with configurations capable of optimising destructions and redirecting energy sources according to the demand's quality. Still, the literature demonstrates that there are no common methods to explore and analyse renewable systems. Hepbasli (2008) and Torío et al. (2009) provided a review of exergy analysis with focus on renewable systems for space heating in buildings. While solar energy can be considered as a purely renewable source, other 'renewable sources', such as biomass, cannot be put in the same category, since renewability depends on consumption rate compared to the regeneration time. In addition, renewable sources are not necessarily low exergy sources, as both solar energy and biomass should be considered as high exergy sources, due to its intrinsic energy quality values. Based on Torio et. Al. (2009), exergy efficiencies for typical renewable systems can be seen in Table 3-3.

Table 3-3 Exergy efficiencies from renewable-based systems. Source: Torio et.al (2009)

Renewable-based systems	Exergy efficiency (Ψ)
Solar thermal collector	0.021
Photovoltaic panel	0.112
Solar-assisted GSHP	0.015-0.035
Biomass boiler	0.055
Evaporative cooling	0.380
Desiccant systems	0.025-0.063

Depending on the chosen exergy methodology, some would suggest the use of as much renewable energy as possible, without considering the end-use equipment (e.g. use of renewable electricity for heating), thus resulting in poor thermodynamic efficiency. Other methods would suggest the use of renewable sources in an optimal way, redirecting its use to appropriate end-uses (e.g. use of electricity exclusively for electric-based appliances). Many of the calculation methods differ, providing different efficiencies for similar technologies, as some methods account for exergy outputs and exergy inputs with different qualities. For example, some methods analysing a GSHP consider renewable exergy from ground at the same level as exergy provided by electricity; thus, the obtained exergy efficiency will be smaller than the method that considers ground exergy as free exergy with no value for the calculation.

3.2.1.6 Exergy losses/destructions

Unlike energy, exergy is not subject to a conservation law (Dincer and Cengel, 2001). Exergy loss in a system/component can be associated with the transfer of thermal exergy from the system to the environment (Tsatsaronis and Park, 2002). Phenomena, such as friction, chemical reaction (burning gas), heat exchange, fluid compression, etc., generate entropy which eventually destroys exergy. Exergy destructions can be calculated from the entropy production or from the exergy balance, which can be calculated by analysing the lost work potential. From a system consisting of *n* subcomponents, the total exergy destructions are equal to the sum of exergy destructions in all subcomponents (Tsatsaronis, 1993), as shown in Eq. 3.5.

$$E_{D,tot} = \sum_{k=1}^{n} E_{D,k} \quad (3.5)$$

Figure 3-10 shows a simplified exergy balance through a Grassmann diagram for a generic energy system. As can be seen, exergy input will always be higher than the exergy output (or useful work) due to irreversibilities within the system/components (named internal losses) and exergy accompanying energy losses (e.g. dissipation of waste heat).

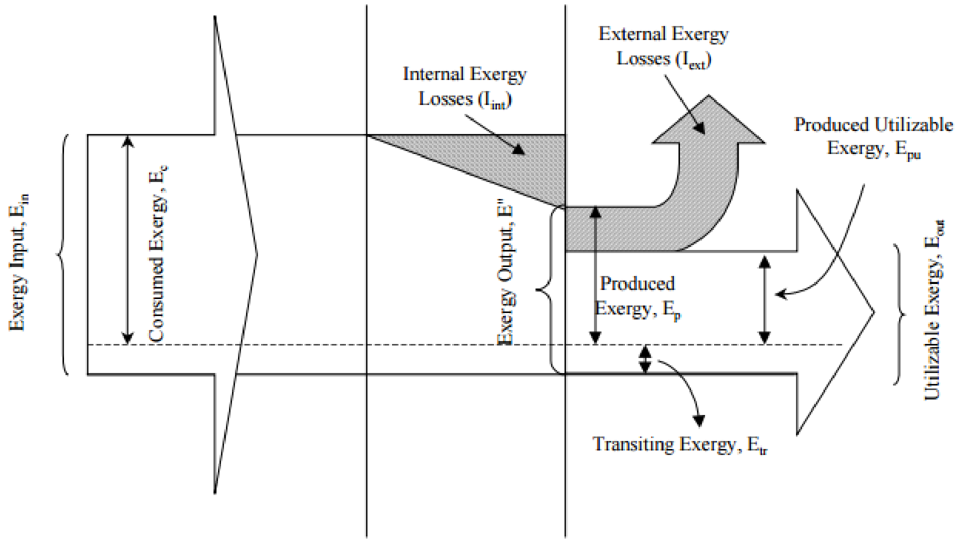


Figure 3-10 Grassmann diagram of an overall exergy balance (Shukuya and Hammache, 2002).

Exergy analysis is a powerful tool to study interdependencies, and it is common that exergy destructions within components are not only dependant on the component itself but on the efficiency of the other system components. These destructions can be endogenous or exogenous exergy destructions. Endogenous destructions occur when the analysed component operates under ideal conditions, while exogenous occur due to non-ideal operation of external components. In addition, avoidable and unavoidable exergy destructions can also be quantified, where although components may have a large potential of thermodynamic improvement, this can be limited by unavoidable irreversibilities, commonly due to technical limitations. This analysis is known as the '*extended exergy method'*, and has the potential to facilitate optimisation procedures (Tsatsaronis and Park, 2002).

3.2.1.7 Exergy efficiency

Energy efficiencies based on the First Law only detects possible losses and cannot indicate how far the process is from the theoretical ideal performance (reversible process). A main objective of exergy analysis is to identify meaningful (exergy) efficiencies. Exergy efficiency or *'Second-Law efficiency'* evaluates the true performance from a thermodynamic point of view. In its simplest form *can be expressed as follows:*

$$\Psi = \frac{Exergy\ demand}{Exergy\ supply} = 1 - \frac{Exergy\ destructions}{Exergy\ supply} \quad (3.6)$$

However, exergy efficiencies from heat engines, heat pumps, and refrigerators can also be expressed as the performance of a device, relative to the performance under reversible conditions for the same reference environments (expressed by the Carnot factor), as shown in the next equation.

$$\Psi_{th} = \frac{\eta_{th}}{\eta_{th,rev}} = \eta_{th}\,(1 - \frac{T_0}{T_i}) \quad (3.7)$$

For heat pumps or refrigerators, true thermodynamic efficiency can be calculated as the relationship between real operation conditions and maximum theoretical efficiency:

$$\Psi_{HP} = \frac{COP_{real}}{COP_{rev}} \quad (3.8)$$

COP_{rev} can be established on a Carnot cycle working between a hot reservoir and a cold reservoir, which can be the internal temperature and the reference environment.

$$COP_{heating,rev} = \frac{T_h}{T_h - T_c} \quad (3.9)$$

Box 1 Exergy efficiency of a heat pump

For example, let's consider an air-source heat pump (ASHP) supplying thermal energy at 20 ºC (T_h) at an outdoor temperature of 5 ºC (T_c) and working with an 'energy efficiency' of 300% (COP_{real} = 3.0). This means that for each W of electricity, 3 W of thermal energy is supplied. To calculate the real thermodynamic efficiency, we have to draw on the Carnot efficiency. Therefore, the maximum theoretical performance is obtained from:

$$COP_{rev} = \frac{293.15}{293.15 - 278.15}\,(K) = 19.53$$

Thus, the true thermodynamic efficiency is not 3.0 (300%), but:

$$\Psi_{HP} = \frac{3.0}{19.53} = 0.1536$$

A comparison between energy and exergy efficiencies for typical building energy systems, working under the same environmental conditions, can be seen in Figure 3-11.

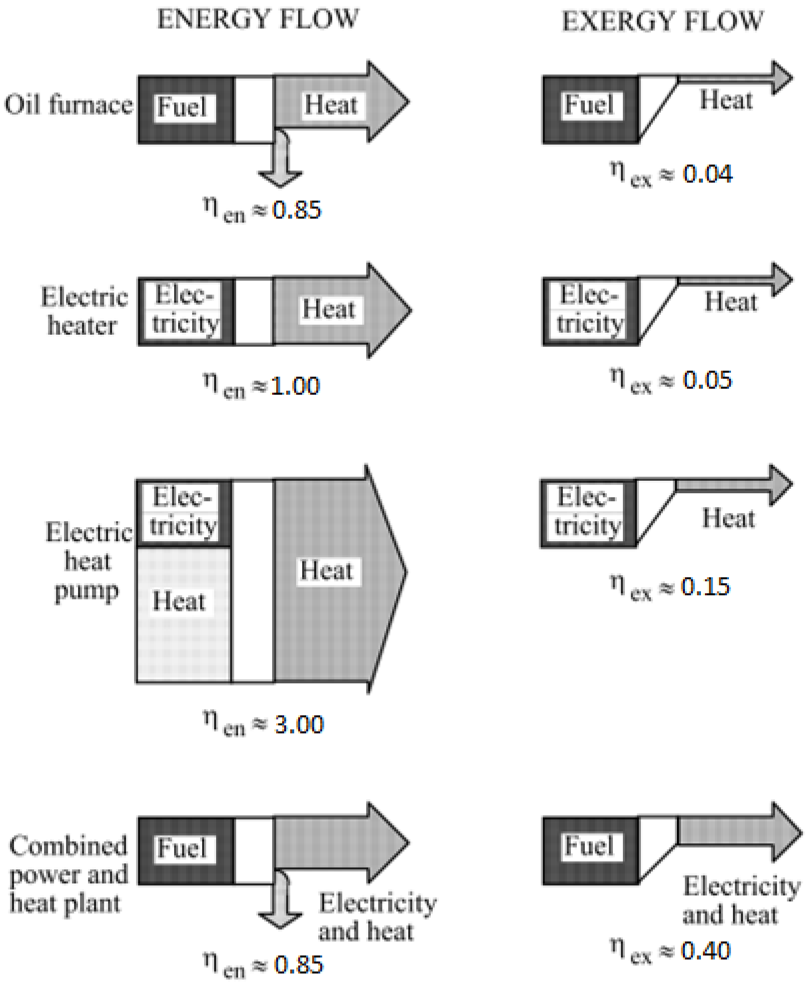


Figure 3-11 Energy and exergy efficiency of different systems (T_i=20 ºC, T_0= 5 ºC). Source: Wall (1977)

3.2.2 Exergy-based studies in buildings

The extent of research and application of exergy analysis in buildings has significantly increased in the last years, mainly supported by the creation of the two aforementioned IEA EBC Annexes (IEA EBC-Annex37, 2007, IEA EBC-Annex49, 2011) and the 'LowEx - COSTeXergy' research group (Ala-Juusela et al., 2014). Moreover, in the last ten years, several doctoral theses have provided a state-of-the-art research that led to a deeper understanding of using exergy analysis and its potential application in the built environment.

Sakulpipatsin (2008) applied the exergy concept in the design of buildings and buildings' services. A new calculation framework based on steady-state equations was developed by merging building envelope and HVAC systems exergy analyses. The model was tested in different system configurations (heat recovery systems, district heating systems and cooling machines, heat exchangers and heat pumps) with the aim to develop knowledge into the potential added value of exergy analysis in the built environment. Later, Molinari (2012) presented an exergy-based parametric analysis to improve ground source heat pump designs. The research provided a method to assess the potential reduction of energy demand and exergy input and to evaluate the cost-efficiency of renovation measures. Optimal configurations dependant on envelope insulation and GSHP's boreholes characteristics were identified. This method ensured more flexibility in the energy supply, making the building more resilient to changes in energy prices.

Torio (2012) developed a suitable dynamic exergy analysis method to optimise the quality level match between the supply and demand of heating in buildings. The method was applied to a solar thermal collector and a district heating network, both connected to low temperature underfloor systems. The outputs highlighted that the exergy performance of a system is strongly influenced by the high-quality inputs present in the supply. Cooper (2013) provided a thermodynamic modelling framework to dynamically simulate air source heat pumps (ASHPs) and mCHP units used in buildings, showing the potential of both technologies to yield important energy savings. The aim of this research was to provide a robust framework for the assessment of the aforementioned HVAC systems operating under different conditions and characteristics.

El shenawy (2013) proposed a new exergy-based index framework to account for building sustainability. Similar to methods such as LEED or BREEAM, the developed framework is an attempt to help guide decision making towards thermodynamically efficient and sustainable building practice. Jansen (2013) developed a new calculation methodology for cooling processes as well as a new detailed dynamic approach for calculating exergy demand for heating and cooling. The method was tested in Dutch and Spanish dwellings. The results show the importance of reducing energy demand, increasing system efficiency, and the use of renewable sources to reduce and eliminate negative impact on the environment. A reduced need for exergy input means less high-quality energy is needed, and low-quality energy sources can be used to fulfil the need. Finally, Ferreira Goncalves (2013) research aimed to make the exergy concept more familiar and accessible for building professionals and to encourage its wider use in engineering practice, by showing the strength of the analysis in the performance improvement of real domestic and non-domestic buildings' case studies. Results showed that exergy analysis revealed meaningful information, especially when CHP units and other energy generation systems provide heat under different temperature conditions.

Additionally, Table 3-4 shows an extensive chronological literature review of the main exergy-based studies applied to single buildings and their systems.

Table 3-4 Exergy-based research applied to buildings and building systems

No	Author	Building/system type	Calculation and analysed end -uses	Location	Observations and main results
1	Tozer et al. (1996)	CHP system with absorption chiller	Steady-state exergy analysis (heating and cooling)	London, UK	Exergy and thermoeconomic analysis has been applied to determine destructions within the system and optimise operation. The Chiller COP varied between 0.639 to 0.693
2	Bilgen and Takahashi (2002)	Dwelling/Air Source Heat Pump	Steady-state exergy analysis (heating)	Tokyo, Japan	Exergy destructions within the ASHP components were determined. COP based on First Law varied between 3.85 to 7.40 while exergy efficiencies (Ψ) between 0.25 and 0.37
3	Asada and Boelman (2004)	Office/Air source Heat Pump and low temperature ceiling radiant system	Dynamic exergy analysis (heating)	De Bilt, Netherlands	A low temperature radiant system is assessed. Results show that the total amount of exergy consumed during the heating season are larger than the total amount of exergy supplied during the same period, as a result of exergy consumption of solar radiation that initially was stored in the building thermal mass.
4	Alpuche et al. (2005)	Hospital/Packaged Air Cooling desiccant system	Dynamic exergy analysis (cooling)	Tabasco, Mexico	Analysed the influence of desiccant cooling on a hot humid location. Exergy efficiencies (Ψ) varied between 0.01 and 0.04 depending on outside temperature
5	Itard (2005)	Dwelling and Office/Gas boiler and ASHP	Steady-state exergy analysis (heating, cooling, and electric appliances)	Delft, Netherlands	The paper proposes a simplified exergy method for comparison with traditional energy analysis. The results show that the exergy uses for heating and cooling accounts for approximately 25% and 18% when a boiler and a heat pumps is used respectively. However, the majority of exergy destructions come from electrical equipment, suggesting reducing its demand or improving electrical efficiencies.
6	Sakulpipatsin and Schmidt (2005)	Dwelling/Gas boiler	Steady-state exergy analysis (heating)	Delft, Netherlands	The authors presented a simulation tool. The example presented energy and exergy consumed in different sub systems of the building energy supply chain, considering heat supply, distribution, emission and final dissipation through room air and the building envelope. Exergy efficiency (Ψ) was found at 0.05
7	Kalmar and Kalmar (2008)	Detached dwelling/ Gas boiler working at 90 and 70 C and air source heat pumps	Steady-state exergy analysis (heating)	Budapest, Hungary	The study presents the analysis of retrofit effects on the exergy consumption on houses built from different materials. Considering the baseline values, the exergy savings are between 69-88.1%.
8	Angelotti et al. (2009)	Dwelling/Air source heat pump	Dynamic exergy analysis (heating and cooling)	a) Milan, Italy b) Palermo, Italy	A comparison between a steady-state and a dynamic exergy analysis is presented. Result show the importance of using dynamic analysis, especially if cooling is studies. The dynamic efficiencies showed for Milan: COP_{heat}: 2.71, COP_{cool}: 2.82, Ψ_{heat}= 0.16, Ψ_{cool}= 0.02 Palermo: COP_{heat}: 3.17, COP_{cool}: 2.89, Ψ_{heat}= 0.10 Ψ_{cool} = 0.01

Table 3-4 cont. Exergy-based research applied to buildings and building systems

No	Author	Building/system type	Calculation and analysed end -uses	Location	Observations and main results
9	Xydis et al. (2009)	Hotels/Electric based air conditioner	Steady-state exergy analysis (electric heating and electric based equipment)	a) Rethimno, Crete b) Thessaloniki, Greece	Exergy analysis is performed to four hotels. As electricity has the lowest exergy factor, as it is directly convertible, gives the highest energy and exergy efficiency compared to other energy forms such as gas or oil. Exergy efficiencies (Ψ) were found around 0.55 for all cases.
10	Yildiz and Güngör (2009)	Office/ a) Gas Boiler b) Condensing boiler c) Air source heat pump	Steady-state exergy analysis (heating)	Izmir, Turkey	Using the Annex 49 method, exergy analysis is performed to different heating systems. The largest exergy destructions are found at the combustion process when boilers burn gas. For heat pumps, the largest destructions in the primary energy transformation in the electricity generation plant. Total exergy efficiencies of systems using LNG condensing boiler, LNG conventional boiler and external air–air heat pump (exergy demand room/total exergy input) were 0.087, 0.086 and 0.066, respectively. Although the heat pump appears to have the lowest thermodynamic efficiency, it has the lowest greenhouse gas emissions among analysed systems.
11	Dovjak et al. (2010)	Dwelling/Gas boilers	Steady-state exergy analysis (heating)	a) Koper, Slovenia b) Ljubljana, Slovenia c) Ratece, Slovenia	Exergy analyses were done for three cases of exterior walls located in three different Slovenian climatic zones during heating season. Different configurations of boilers and different levels of insulations were assessed. Without economic consideration, the most effective solution was the holistic approach, by improving boiler efficiency together with t well-insulated envelope. Exergy efficiencies (Ψ) ranged between 0.033 and 0.052.
12	Sakulpipatsin et al. (2010)	Office/Low temperature district heating and chiller	Steady-state exergy analysis (heating and cooling)	Delft, Netherlands	Exergy analysis to an HVAC system is applied. In the heating case, the district heating at 90 ºC improved overall exergy efficiency from 0.033 to 0.172. For the cooling case, the overall exergy efficiency was found at 0.068, due to the use of electricity to produce low quality thermal energy.
13	Yucer and Hepbasli (2011)	School/Gas boiler	Steady-state exergy analysis (heating)	Izmir, Turkey	Exergy analysis is performed by using the Annex 49 LowEx method. The largest exergy destructions are in the power generation and generation subsystems (79.8%). Exergetic efficiencies of the conventional boiler and fan coil unit were calculated to be 0.134 and 0.376, respectively. The overall exergy system efficiency (Ψ) was found at 0.027.

Table 3-4 cont. Exergy-based research applied to buildings and building systems

No	Author	Building/system type	Calculation and analysed end -uses	Location	Observations and main results
14	Caliskan et al. (2011)	Dwelling/Evaporative cooling systems	Steady-state exergy analysis (cooling)	Izmir, Turkey	Four air cooling systems were investigated. Exergetic and sustainability performance assessments are done at twelve different dead state temperatures varying from −5 ºC to 50 ºC. Exergy efficiencies (Ψ) between 0.358 and 0.603
15	Hepbasli (2011)	Greenhouse/ a) GSHP b) Wood biomass boiler c) Gas boiler	Steady-state exergy analysis (heating)	Riyadh, Saudi Arabia	Using the Annex 49 method, the study analyses the performance of various systems connected to a greenhouse building. The overall exergy efficiency values were found at 0.033, 0.115, and 0.032 for the solar assisted vertical ground-source heat pump, natural gas boiler and wood biomass boiler respectively at a reference temperature of 0 ºC. A new exergetic-based indicator is proposed, the exergetic renewability ratio which is a ratio of useful renewable exergy to the total exergy input to the system.
16	Gonçalves et al. (2012)	Hotel/Gas boiler and chiller	Steady-state exergy analysis (heating, cooling, and electric appliances)	Coimbra, Portugal	A new exergy-based performance indicator for heating, cooling, DHW, ventilation and other hotel's electric equipment is proposed (PER). PER is defined as the ratio of useful energy at demand (and primary energy supplied. For the case study PER was found at 0.49 and exergy efficiency at 0.17. Is intended that legislative framework used this indicator to improve building energy performance.
17	Caliskan et al. (2012)	Dwelling/Thermochemical and sensible thermal storage	Steady-state exergy analysis (heating)	Izmir, Turkey	Energy and exergy analyses of thermochemical TES systems at various reference temperatures (8C, 9C and 10C) were performed. The exergy efficiencies of the charging and discharging process of thermochemical TES were found at 0.217 and 0.324, respectively. Maximum efficiencies were found at a reference temperature of 8 ºC.
18	Jansen et al. (2012)	Dwelling/ASHP and CHP with various configurations of heat recovery and solar collectors	Steady-state exergy analysis (heating, cooling, and electric appliances)	Bilbao, Spain	Exergy analysis is performed to explore different energy systems and propose innovative configurations. Three cases are investigated. First the typical house with no insulation. Secondly, the application of typical retrofits (mainly insulation). Finally, improving scenarios based on exergy principles. The overall exergy efficiency of the two reference cases is 0.10 and 0.16, respectively. New configurations based on exergy theory were able to reduce significantly primary energy input, lowering by almost 80%.

Table 3-4 cont. Exergy-based research applied to buildings and building systems

No	Author	Building/system type	Calculation and analysed end -uses	Location	Observations and main results
19	Meggers et al. (2012)	University/GSHP with PV/T panels and heat recovery system	Steady-state exergy analysis (heating)	Zurich, Switzerland	An implementation of Low exergy technologies is investigated in a real case study. These technologies are being implemented in integrated systems that minimise the temperature-lift for a high COP heat pump. By reducing the temperature lift of a heat pump, COP were increased from 3-6 to 6-13, bringing the system closer to the maximum Carnot efficiency. Low exergy systems provide an alternative perspective from 'Passivhaus' designs by eliminating the design restrictions and minimizing the barrier between the building shell and the environment.
20	Yucer and Hepbasli (2013)	House residence/Steam boiler	Steady-state exergy analysis (heating)	Izmir, Turkey	The study evaluates a convention steam boiler system connected to a block of residences. Steam boiler presented the largest exergy destructions. Exergetic efficiencies of the steam boiler, heat exchanger, and radiator were 0.194, 0.370 and 0.310, respectively, providing an overall system efficiency of 0.032.
21	Bojić et al. (2013)	Dwelling/Low radiant systems connected to a gas boiler	Steady-state exergy analysis (heating)	Kragujevac, Serbia	The paper compares four different types of radiant heating systems: floor, wall, ceiling and floor-ceiling. It was found that although the floor–ceiling heating system has the lowest exergy efficiency, it has the lowest energy consumption, exergy consumption, destroyed exergy, CO_2 emissions, operation costs, and the nominal boiler power. Wall heating system also presented good results. The classical ceiling heating has the worst performance.
22	Cooper et al. (2013)	Dwelling/Air source heat pump and CHP	Dynamic exergy analysis (heating)	United Kingdom	Several ASHP and CHP are modelled and analysed with energy and exergy analysis. The results showed that current ASHP and mCHP have comparable performances with a condensing boiler with grid supplied electricity. In exergy terms electricity is more notable due to the low quality of thermal energy The analysis showed that the largest energy losses are in converting primary energy to electricity and to the low exergy value of the heat flow, having a larger impact on ASHP and favouring mCHP installations. For the mCHP, the main exergy losses are in the generation of electricity and the creation of heat.
23	Terés-Zubiaga et al. (2013)	Dwelling/ ASHP and CHP in various configurations of heat recovery, thermal storage, and solar collectors	Dynamic exergy analysis (heating)	Bilbao, Spain	Based on the previous study from Jansen et al. (2012), five different energy scenarios for a social dwelling have been analysed. In this case a dynamic exergy calculation has been used. The analysis servers to improve and design new systems configurations. Configuration based on CHP, thermal storage, and heat recovery systems presented the best energy/exergy performance, able to reduce primary energy input as well as exergy destructions by 15%

Table 3-4 cont. Exergy-based research applied to buildings and building systems

No	Author	Building/system type	Calculation and analysed end -uses	Location	Observations and main results
24	Zhou and Gong (2013)	Residential building/Air Source heat pump	Dynamic exergy analysis (heating and cooling)	Ningbo, China	Three cases of improvements together with a standard case were analysed. The study showed that improving HVAC efficiency is more effective than increasing insulation thickness for this particular case study in China. 80% of exergy destructions occur at the primary generation and heating/cooling production subsystems. The author advocates to not ignore chemical exergy composition of room air, as it stands at 12%. The exergy efficiency of the standard case was improved from 0.051 to 0.079.
25	Açıkkalp et al. (2014)	House residence/Steam boiler	Steady-state exergy analysis (heating)	Izmir, Turkey	An advanced exergy analysis is performed for the first time in a building study. The endogenous and exogenous exergy destructions of the system were 27% and 73% while the avoidable and unavoidable exergy destructions were 26.2% and 73.8%, respectively. This shows new insight, as improvement potential of systems such as the generation is much lower than typical analysis show, due to the calculation of unavoidable exergy destructions. In this particular case, distribution systems have the biggest improvement potential, a subsystem often neglected in the analyses.
26	Kim et al. (2014)	Office/Air source heat pump with AHU and ceiling panels	Dynamic exergy analysis (heating)	Singapore	With the aid of a simulation tool, energy and exergy analysis to evaluate three air-cooling systems in in a hot and humid climate was conducted. The chilled ceiling panel with a centralised AHU system presented the best thermodynamic performance of all analysed cases. The system had a higher cooling impact ratio, and presented lower temperature difference between the cooling source and the ambient conditions. Exergy efficiencies (Ψ) ranged between 0.04 and 0.13
27	Khalid et al. (2015)	a) Natural gas boiler with absorption chiller b) PV and solar thermal system with heat pump c) PV and solar thermal system with vapour refrigeration chiller	Steady-state exergy analysis (heating and cooling	Ontario, Canada	Energy and exergy analysis is performed in three stand-alone systems. The best thermodynamic performance was found for the PV and solar thermal operated system with a vapour compression chiller with an exergy efficiency of 0.039. The poorest performance was for the PV and solar thermal operated system with heat pump with an efficiency at 0.012.
28	Suárez-López et al. (2015)	Dwelling/Solar chimney	Steady-state exergy analysis (heating and cooling	Gijon, Spain	Energy and exergy analysis applied to solar chimneys used for building ventilation was studies. A CFD simulation model was employed to gather data. The results how that the thermal exergetic efficiency is only 0.0055, and the useful exergetic efficiency is 0.00006. This low value is due to the small increase in temperature with respect to the reference or dead state values.
29	Mert and Saygın (2016)	Building blocks/architectural optimisation	Steady-state exergy analysis (heating and cooling	Izmir, Turkey	Exergy analysis method into the field of urban planning is employed for the first time. The analysis is focused on the design and orientation of a building block. Exergy analysis for individual building and building blocks were performed. The results show that the exergy efficiency of the existing designs is about 0.02, with a potential to be around 0.10-0.11. Thermodynamic performance at a city level can improve when energy efficient design parameters are considered during planning and design steps in an urban area

3.2.3 Exergy-based building simulations tools

As a result of the aforementioned research, a number of exergy-based simulation tools have been developed with the intention to promote the concept of exergy to a broader audience, especially directed towards educational purposes, common practitioners, and decision makers. The first exergy-based building simulation tool can be traced back to the work of the IEA EBC-Annex37 (2007), where an analysis tool capable of calculating exergy flows for the building energy supply chain was developed. The tool is based on a spreadsheet built up in different blocks of sub-systems representing each step of the building energy supply chain. A steady-state energy demand calculation was integrated, where the user has to define different indoor/outdoor conditions and typical building's physical parameters to calculate the building's exergy demand. The calculation is done in the direction of the development of demand; this means that the tool calculates exergy destructions through every step of the supply chain until it reaches the primary energy transformation subsystem adding exergy inputs throughout every subsystem. Heat losses in the different components are taken into account, as well as the auxiliary electricity required for pumps and fans. On the primary energy side, the inputs are differentiated between fossil and renewable sources. Based on this development, Sakulpipatsin and Schmidt (2005) included a GUI oriented towards engineers and architects. The aim of the tool was to compare exergy flows for different buildings and HVAC systems. One of the main characteristics of the GUI is the input interface that allows building designers to automatically select building services' components along the energy supply chain (Figure 3-12).

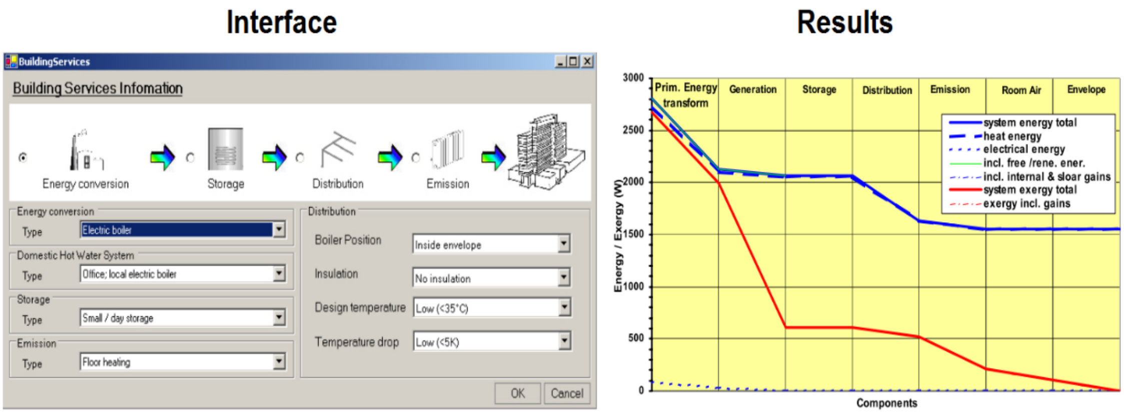


Figure 3-12 GUI building exergy simulation tool (Right) and results showing energy and exergy flows through components. Source: Sakulpipatsin and Schmidt (2005)

Later, for the IEA EBC-Annex49 (2011), the tool was improved along with the creation of other modules (S.E.P.E. and DVP). The tool, called the 'LowEx pre-design tool', is also an excel-based spreadsheet, but enhanced with the use of macros and a more robust database for the analysis of more system options. As its previous version, the tool is based on the same steady-state calculation method, but integrating concept from the German energy saving standard (EnEV, 2009). Thereby, the field of application is focusing mainly on buildings with normal and low internal temperatures such as residential buildings and simple office buildings. The objective of the tool was to develop a simple and transparent method, which is easy to understand and comprehensible for its users, requiring as few inputs as possible. In this occasion, Schlueter and Thesseling (2009) developed the GUI, with a focus on the analysis integration into the architectural design process. Therefore, the tool was incorporated into a Building Information Modelling (BIM) software with the intention to integrate exergy analysis into the multi-disciplinary capabilities of this type of software. The integrated software was called the 'Design Performance Viewer' (DPV) (**Figure 3-13**), where Revit is used to determine performance factors and visualisation.

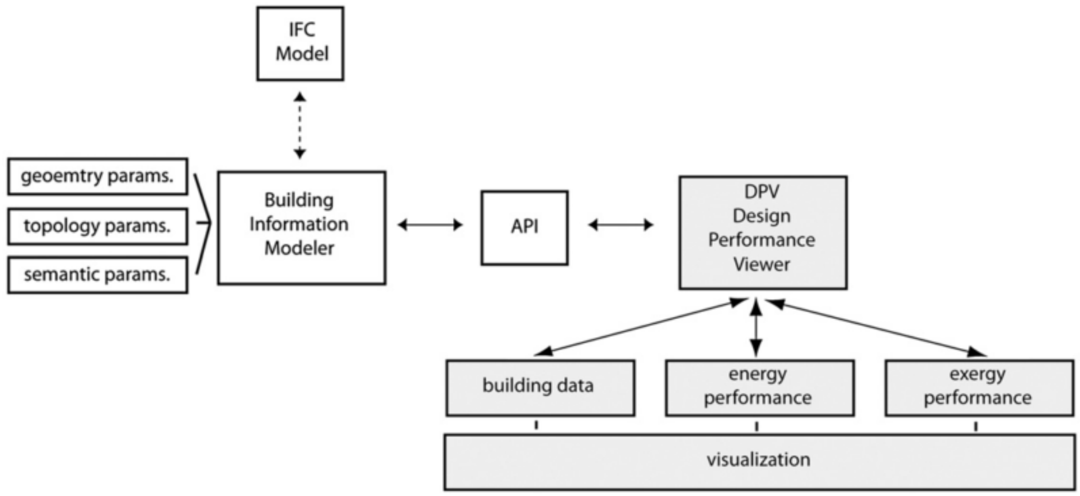


Figure 3-13 Exergy-based tool: Design Performance Viewer implementation framework. Source: Schlueter and Thesseling 2009. **Image reproduced with permission of the rights holder, Elsevier.**

Other modelling tools have been developed for research purposes, where quasi-steady state or dynamic calculations have been applied mainly with the support of TRANSYS simulation software (Sakulpipatsin et al., 2010, Angelotti et al., 2009, Jansen, 2013). However, these tools were developed to cover specific research questions and were not capable of rapidly reproducing their capabilities for different designs. In addition, exergy-based metrics have not yet been included in any retrofit-oriented simulation tools. This suggests a great opportunity for expanding on typical tools and providing a different paradigm for the assessment of retrofit strategies in existing buildings.

3.3 Exergy and economic theory: exergoeconomics

3.3.1 Basic concepts and fundamentals of exergoeconomics

After decades of exergy research in non-building sectors, the Second Law and exergy concepts can be considered well established. Therefore, a natural next step was to find their space in the economic theory (Tsatsaronis, 2014). Benedict (1948) was the first researcher to couple exergy with cost streams (Valero and Torres, 2006). Later, Georgesçu-Roegen (1971) established the foundations for the relationship between the entropy generation and economics. As mentioned earlier, the irreversibilities encountered in energy systems generate entropy (or destroy exergy) which in turn provoke the consumption of natural resources; therefore, these inefficiencies would have some economic implications. The exergy input into a system will depend on the irreversibility accumulation through the whole energy supply chain. This means that the inefficiencies in single subsystems highly influence the fuel demand in all upstream subsystems. Valero et al (2005b) states that the more irreversible the process, the higher the required investment and the higher the economic cost.

According to Dincer (2002), energy analysis has been characterised as unable to determine process's optimal design due to association with normal cost-benefit analysis. Rosen (2002c) showed a relationship between exergy and economics, noting the importance of developing research referred to exergy and economics or entropy and economics, especially in developing simplified tools for industry and decision makers. In recent years, research based on a combination of mixed economic methods and thermodynamic methods, has been developed to meet industry requirements. In this approach, apart from considering energy cost and 'non-energetic cost' such as financial, labour, and environmental remediation costs, costs due to thermodynamic inefficiencies calculated via exergy analysis, are also considered. The method is commonly known as 'thermoeconomics'. Thermoeconomics deals with the value of energy streams within an energy system, where several conversion processes occur. The aim is to find a trade-off between the fuel cost and capital investment cost of energy systems. Thermoeconomics can be an effective method for making technical systems efficient by finding the most economical solution within the technically possible limits (Wall, 1977).

However, thermoeconomics has also been criticised, but it was modern engineering rather than physics that adopted the methodological framework to optimise and improve systems, suggesting that some economic sectors have already recognised the Second Law as a self-evident and practical concept (Fisk, 2011). Thermoeconomics, based on exergy, helps to perform analysis of a system by breaking it down into individual components, where each can be analysed separately. To clearly characterise the combination of exergy analysis and economic theory, Tsatsaronis (1984) coined the term '*exergoeconomics'*. As thermoeconomics can be categorised as any thermodynamic analysis combined with any economic appraisal, therefore, it can be said that exergoeconomics belongs to the broader field of thermoeconomics (Tsatsaronis, 2014). The difference with thermoeconomics, is that

$\dot{C}_j$

exergoeconomics specifically uses the exergy-costing principle with the use of the 'Fuel-Product' concept. Exergoeconomics considers not only the inefficiencies but also the costs associated with these inefficiencies, and the investment expenditure required to reduce them (Tsatsaronis, 1999).

In any energy system, each component within the system experiences the flow of an exergy stream, where an exergy input is introduced to generate a desired exergy output or product. This output could be the final product or a different exergy input for the next component in the energy supply chain (Valdimarsson, 2011). As it was mentioned before, exergy destructions or irreversibilities within the components have some cost implications, therefore, would have an environmental and economic effect on the output streams. Also, as the components have inherent investment, and operation and maintenance (O&M) costs, these have to be considered when assessing the final product costs. Therefore, exergy cost accounting distinguishes between exergy cost and monetary costs. Exergy cost refers to the exergy used to produce a stream or an energy flow, representing the amount of energy resources needed to obtain one unit of exergy. Monetary cost considers the market price of the consumed fuel as well as the cost of installation and the operation of the system, representing the amount of money spent to obtain one unit of exergy (Tsatsaronis et al., 1993). Thus, each component within an energy system will have associated exergy input cost (fuel), exergy output cost (product), and component capital investment, and O&M cost. This cost relation can be seen in Figure 3-14.

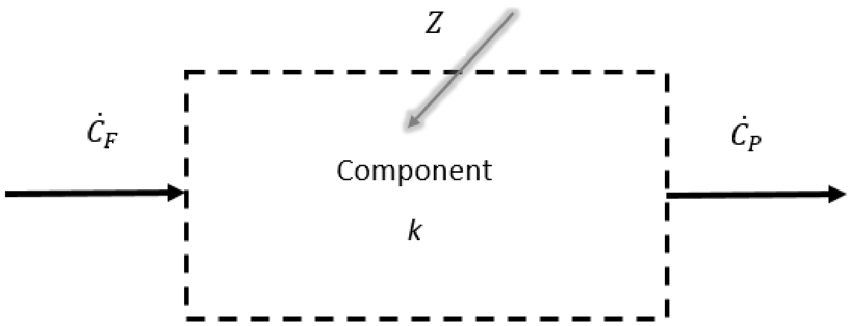


Figure 3-14 Component thermoeconomic cost balance

In addition, in exergoeconomics, a distinction between exergy cost of streams and exergy cost of components has to be made. Exergy cost of an exergy stream (heat, hot water, electricity, etc.) is the amount of exergy required to produce the stream. The cost associated with an exergy stream $\dot{C}_j$ can be obtained as follows:

$$\dot{C}_j = c_j \, \dot{E}x_j \qquad (3.10)$$

where c_j is the average cost of exergy unit supplied to the stream j and $\dot{Ex}_j$ is the exergy contained in the stream j. In Figure 3-14, $\dot{C}_F$ and $\dot{C}_P$ are the fuel and product streams of the component k. For exergy cost $\dot{C}_k$ contained within a component, a similar formula is used:

$$\dot{C}_k = c_k \, \dot{Ex}_k \tag{3.11}$$

where c_k is the average unitary exergy cost and $\dot{Ex}_k$ is the exergy contained in the component *k*. It is in this step, where thermodynamic inefficiencies and irreversibilities have to be accounted for. Similarly, to an energy/exergy balance, the cost balance shows the sum of entering exergy stream costs, and the capital investment will reflect the cost rates associated with the output streams. Cost associated with irreversibilities is hidden in the cost-balance equation, as this is finally charged to the product price. For that reason, exergy cost of products is commonly larger than exergy cost of fuels, producing an inevitable cost accumulation, demonstrating its non-conservative property. Also, to complete the thermoeconomic balance, non-exergy costs have to be accounted for. Thus, a thermoeconomic cost balance for the component *k* can be written as follows:

$$c_P \dot{Ex}_P = c_F \dot{Ex}_F + \dot{Z}_k \tag{3.12}$$

where c_P is the unitary exergy cost of the product, $\dot{Ex}_P$ is the exergy content of the product, c_F is the unitary exergy cost of the fuel, $\dot{Ex}_F$ is the exergy content of the fuel, and $\dot{Z}_k$ represents all the non-exergy costs of the component k. These are calculated as follows:

$$\dot{Z}_k = \dot{Z}_{CI} + \dot{Z}_{OM} \tag{3.13}$$

where $\dot{Z}$ is the fixed cost rate, $\dot{Z}_{CI}$ is the capital investment, and $\dot{Z}_{OM}$ is the O&M cost.

In energy systems some components could also generate multi-products. As exergoeconomics has the ability to calculate exact exergy destructions costs needed to produce each product, it can give an appropriate specific economic value to each. Figure 3-15 graphically represents exergy and economic streams, encountered in a CHP plant, producing two product streams (electricity and heat).

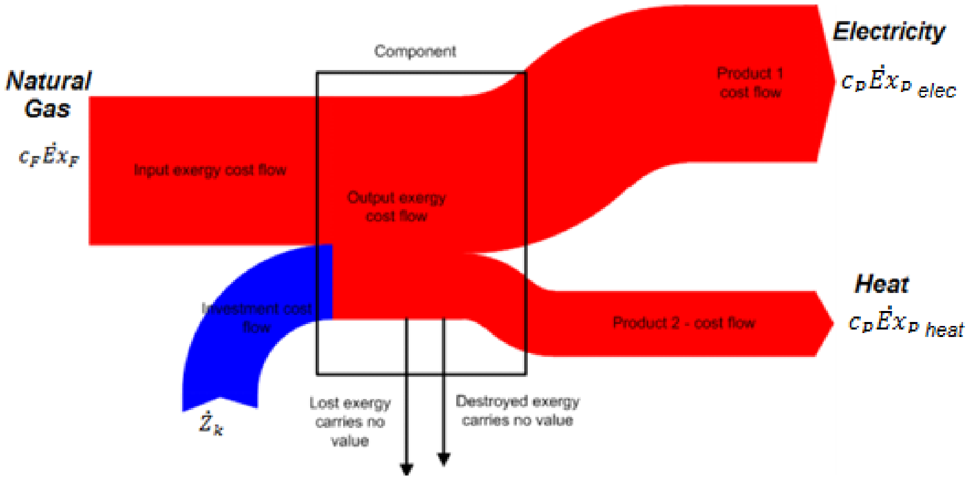


Figure 3-15 Thermoeconomic cost balance of a multi-product component. Source: Valdimarsson (2011)

It can be said that a considerable similarity exists between the exergy and costs, as both are non-conservative values. While exergy is consumed/destroyed due to different energy conversion processes and component inefficiencies, cost is generated due to investment and operation cost of devices. Cost has to be allocated properly in order to locate cost-effectiveness of a device and to appropriately define the process for products and commodities (Rosen, 2008).

3.3.2 Exergoeconomic methods

Many exergy-based analysis methods integrated with economics have been developed. The biggest setback for thermoeconomics/exergoeconomics to be accepted as a robust accounting method is its differing presentation in models, methods and nomenclatures, making it difficult for the practitioner to get a grasp of the concept. A structural theory was proposed by Valero et al. (2005b) in order to merge several optimisation and cost accounting thermoeconomic methods. However, different approaches still persist within the research community. These methods recognise exergy as a property of value, and aim to combine thermodynamic accounting with economics, in order to achieve exergetic and economic objectives. According to Tsatsaronis (1993), two types of thermoeconomic/exergoeconomic methods exist:

a) Cost accounting methods based on average costs, which allow assessment of multi-product systems or evaluation of different design alternatives
b) Optimisation methods that employ marginal costs in order to minimise the cost of a system or component

Rosen (2008) provided with a more concise review of the relationship between exergy and economics leading to the exploration of different exergy-based economic analyses. The author recognised the following methods as the most widely used:

a) EXCEM analysis
b) Loss-cost ratio analysis
c) Exergy and environmental economics
d) Exergy cost accounting (SPECO)

The '*EXCEM'* method (Rosen and Dincer, 2003) requires an examination of exergy, cost, energy and mass flows throughout the whole system. It also requires the application of the necessary balance to each property. In this sense, mass and energy are conserved, while exergy and cost are consumed, with exergy quantities being the most informative. The authors developed the analysis code in a process simulator (Aspen Plus). The method can also aid in design and optimisation of the processes. On the other hand, the '*loss-cost ratio*' analysis focuses on the rate between thermodynamic loss and capital cost. The outputs help identify where the efforts should be made to improve design, either in increasing efficiencies or reducing component capital investment. '*Exergy and environmental economics*' (Meyer et al., 2007) locates a relationship between exergy destruction and environmental degradation. It consists of three steps: a) exergy and exergoeconomic analysis of the system, b) life cycle analysis of each component and energy stream within the system, and c) environmental impact assignment to exergy streams. Although these techniques are quite sophisticated and powerful, their application in practical problems is still limited.

The most widely used exergy cost accounting method is the *'specific exergy cost method'* (SPECO). SPECO uses principles from business administration as cost balances are explicitly formulated and resources are valued at the costs at which they were purchased (Lazzaretto and Tsatsaronis, 2006). Based on the previous work from Tsatsaronis (1993), the method is based on the calculation of specific exergies and cost per exergy unit. A fuel-product-loss definition of the system's components is required to show each flow entering or leaving the components. The approach (**Figure 3-16**) can define the following thermoeconomic variables for the component and for the entire system:

- Exergy efficiency
- Exergy destructions and exergy losses
- Exergy ratios (destructions/inputs)
- Capital cost (Z) associated with capital investment and operation and maintenance expenses
- Cost of exergy destructions
- Relative cost difference
- Exergoeconomic factor

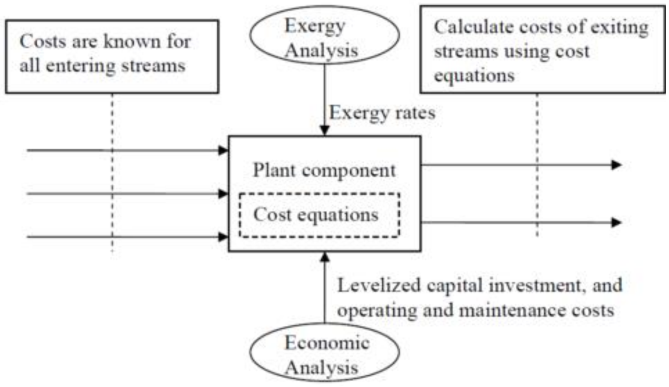


Figure 3-16 SPECO framework. Source: Lazzaretto and Tsatsaronis, 2006. **Image reproduced with permission of the rights holder, Elsevier.**

3.3.2.1 Exergoeconomic optimisation

Energy systems' design often requires the definition of a properly defined optimisation problem. At first, thermoeconomic evaluation requires to evaluate all thermodynamic and cost data known to the system. For this, a well-defined thermodynamic and cost model is necessary in order to evaluate the energy system interactions when parameters are changed (Tsatsaronis, 1993).

An essential step when formulating exergoeconomic optimisation studies is the selection of design variables that properly define the possible design options and affect system efficiency and cost effectiveness (Valero and Torres, 2009). As shown in Figure 3-17, the aim of exergoeconomic optimisation is to find the best solutions between two competing objectives: the minimisation of a cost equation dependant on capital, maintenance, and running cost, and maximisation of exergy efficiency (Tozer et al., 1996). Therefore, exergoeconomics becomes a powerful tool to optimise single components as well as the entire system.

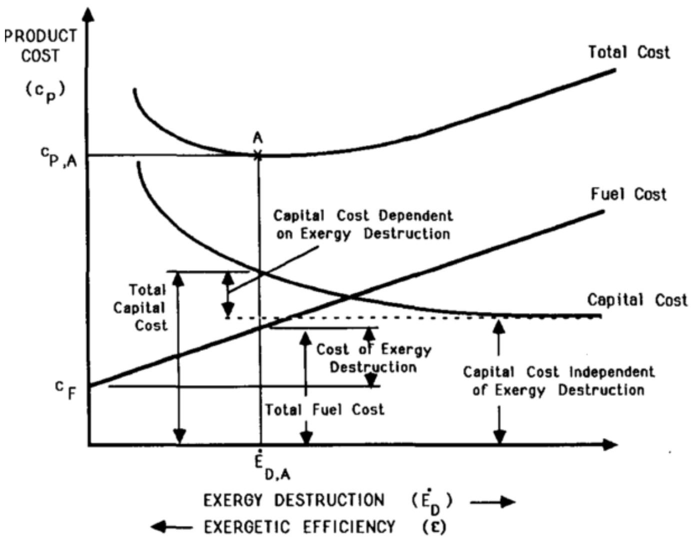


Figure 3-17 Optimisation of product cost as a function of exergy efficiency. Source: Tsatsaronis, 1993. Image reproduced with permission of the rights holder, Elsevier.

Another approach of exergoeconomic optimisation can be delivered when exergoeconomics is joined with the economic concept of ‘cost-benefit’. Exergoeconomics has been effectively combined with the cost-benefit analysis to improve operation and design. By minimising the Life Cycle Cost (LCC), the best system considering the prevailing economic conditions could be found, and by minimising the exergy loss, environmental impact could also be minimised (Wall, 1977). Valero et al. (2005a) mentioned that the concepts of price and cost are usually confused but in reality have different nature. The price of a product usually depends on the market or political decisions, where the cost depends on the physical process and the thermodynamic efficiency of its formation process. Therefore, for an accurate investment benefit maximisation it is important to have real operation costs available, particularly when prices of electricity vary day to day.

3.3.2.2 Exergoeconomic optimisation with genetic algorithms

Exergoeconomics, using several mathematical optimisation methods and algorithms such as Gradient, Iterative, Lagrange Multipliers, Simulated Annealing, and Genetic Algorithms, has been applied in the literature. The first thermoeconomic optimisation method was presented by El-Sayed and Aplenc (1970) by optimising a vapour-compression desalinating system both, thermodynamically and economically. Tsatsaronis and Moran (1997) established the foundations of using exergy-related variables to minimise the cost of a thermal system by using an iterative method.

Section 2.2.2 showed the importance of genetic algorithms in typical building design practice. However, the approach has been extensively used in thermodynamic-based research long time before. Valdés et al. (2003) used thermoeconomics optimisation to minimise production cost and maximise annual cash flow of a combined cycle gas turbine using genetic algorithms. Khoshgoftar Manesh and Amidpour (2009) developed a MatLab-based NSGA-II algorithm to optimise a system combined of a desalination plant and nuclear power plant. An exergy-cost method is used to calculate and optimise the cost of produced electricity and desalt water. Baghernejad and Yaghoubi (2011) applied an exergoeconomic analysis and genetic optimisation to an integrated solar combined cycle system. The objective functions were minimisation of the investment and exergy destructions costs. Mofid and Hamed (2011) used the same approach to optimise a 140 MW gas turbine power plant, capable of increasing the exergetic efficiency by 0.176 with the capital investment increase of 8.8%. In this particular research the following were taken as decision variables: compressor pressure ratio and isentropic efficiency, turbine isentropic efficiency, combustion product temperature, air mass flow rate, and fuel mass flow rate. Finally, Arora et al. (2016) used NSGA-II combined with a decision making methodology to optimise a solar parabolic dish Stirling heat engine. A MatLab optimisation code was developed to obtain Pareto solutions. Four different decision making methods were investigated (Shannon’s entropy, Fuzzy Bellman, LINMAP and TOPSIS). The author's objective functions were power output, thermal efficiency, and thermoeconomic function which were able to improve between 10-30% in comparison with baseline values.

3.3.3 Exergoeconomics and exergoeconomic optimisation applied to buildings

Despite the exergy-based building research developed in the last decade (Section 3.2), the application of exergoeconomics and exergoeconomic optimisation research oriented to buildings is limited. Exergoeconomic studies related to buildings can be categorised in two groups:

a) Building and building energy systems studies: building envelope, fossil-based and renewable-based HVAC systems
b) Community systems studies: District networks

The research from Robert Tozer can be regarded as the first buildings-oriented thermoeconomic research (Tozer et al., 1996, Tozer and James, 1997), showing its practical application to buildings' services. The author presented an exergoeconomic analysis of different type of HVAC systems (fan coil system, constant air volume, displacement ventilation, and an absorption-cogeneration VAV). First, baseline conditions were analysed, providing exergetic cost to investment and operation. Later, an improvement was made by locating components with high exergetic cost and largest exergy destructions. The thermoeconomic optimisation procedure produced an increase in the cooling capacity and minimisation of life cycle energy cost by 20-30%. Later, Ozgener et al. (2005) used exergoeconomics to model and determine optimal design of a ground-source heat pump with vertical U-bend heat exchangers. The exergetic efficiency was found at 0.677 with a loss-to-capital-cost ratio based at about 0.30 (kWh/US$). The highest irreversibilities were found in the compressor due to electrical and mechanical inefficiencies. Demirel and Öztürk (2006) performed a thermoeconomic analysis in a seasonal latent heat storage system, used for heating a greenhouse building. The author incorporated a discounted cash-flow diagram and exergy cost rate to enhance the analysis and determine feasible designs.

Ucar (2010) used exergoeconomic analysis to find the optimal insulation thickness in four different cities/climates in Turkey, using reference temperatures for the analysis ranging from -21 °C to 3 °C. The objective functions were cost of fuel and cost of insulation materials. It was found that exergy destructions are minimised with increasing insulation and ambient temperatures, but maximised with the increase of relative indoor humidity. A comparison between cities shows that warmer locations need less insulation thickness, having a difference of 50% in thickness between the coldest and the hottest cities. As Caliskan et al. (2013) states, the variation of reference temperatures highly affects the thermoeconomic outputs as these are strongly linked to exergy parameters, demonstrating the necessity to be very careful if the analysis is performed using static or dynamic reference temperature. The author evaluated a design composed of three types of energy storage systems (which is part of an underfloor heating system): sensible, latent and thermochemical storage under varying reference (dead state) temperatures of 8, 9 and 10 °C. The analysis suggests that at the lowest reference temperatures (8 °C), the system has the lowest energetic cost, while temperatures closer to internal environment have higher energetic cost when considering actual state of technology. For the specific case study, the research shows that energy storage technologies have paybacks of around 15-25 years.

The research from Vittorio Verda (Verda et al., 2001, Verda and Kona, 2012) has mostly been dedicated to the study and optimisation of district networks based on thermoeconomic analysis. The studies aim to discover possible supply options using low temperature networks. The author was interested in temperature supplies of 55-40 °C with returns of 25-20 °C, which will allow the direct use of energy sources such as solar, geothermal, waste heat, and connection to heat storage. Thermoeconomics was used to assess the exergy content of the energy carrier together with investment, supplied heat, and pumping costs. The lowest exergetic cost was obtained in the case of the lowest supply and return temperatures (40/20 °C), however resulting in the highest economic costs due to higher investments in larger area emission systems and increased pipe diameters in the distribution network. On the other hand, increasing supply temperatures also increases the number of potential users that can be connected. Pirkandi et al. (2016) also used thermoeconomics on a CHP-based district network system aimed to supply heat to low energy houses. The advantage of distributed systems is that the electricity and heat can be generated close to the site, minimising distribution losses and increasing overall system's efficiency. The author developed a steady-state MatLab model capable of performing energy and entropy balances in a CHP as well as performing parameter optimisation based on genetic algorithms. The design variables were compression ratio, mass flow rate, turbine inlet temperature, exergy efficiency, and irreversibilities. The optimisation process results in an increase in efficiency from 0.677 to 0.715 with an increasing total cost rate from 2.20 to 2.57 ($/h).

3.3.3.1 SPECO method applied to buildings

Campos-Celador et al. (2012) used the SPECO method to evaluate the performance of a micro-CHP generator (5.5 kW SenerTecs Dach) installed in a residential building consisting of 40 apartments. The CHP was sized to cover the base load DHW and heating demand throughout the year. A condensing gas boiler is used to cover the remaining heating demand. The CHP also covers part of the electrical demand. A dynamic exergy analysis in TRNSYS was done combined with a LCCA to analyse the accumulative exergy consumption of the power plant. The thermoeconomic analysis showed that the produced electricity from the mCHP is 17.3 cents/kWh, a value higher than the grid electricity price (12.24 cents/kWh). However, the heat produced by the CHP presented a similar price of 17.3 cents/kWh which is much lower than the heat price of 33.18 cents/kWh produced by the conventional boiler. Therefore, the combined product price for the CHP is equivalent to 34.6 cents/kWh, while the traditional way (heating by gas boiler and grid electricity) is 45.42 cents/kWh. The outputs justify the operation of the CHP plant to cover at least the base demand.

Baldvinsson and Nakata (2014) applied the SPECO method for the analysis of heating systems in a Japanese dwelling. The aim was to compare a typical heating system (kerosene-based boiler) with a district heating system based on large-scale boilers and geothermal energy. The method found that although the conventional system (boiler) presented a higher exergetic efficiency compare to the district heating system (0.054 and 0.042 respectively), the final fuel product price for both heating and DHW from the district system was lower due to less exergy destruction costs. In addition, more improvement flexibility exists in the district system due to the potential to use other low-grade energy sources and/or more efficient heat generation technologies.

Yücer and Hepbasli (2014) performed an exergoeconomic analysis based on the SPECO method on a 'LowEx' building heating system connected to a 49-room residence accommodation. Steady-state exergy analysis was performed considering 21 °C as an internal temperature and 0 °C as a reference temperature. The exergoeconomic results showed that the emission system (radiator) has the highest exergetic cost increase as the stream already comes with high irreversibility rates from previous components. The author acknowledges the limitation of using a static approach, recommending the utilisation of dynamic analysis based on TRNSYS or EnergyPlus. Later, based on the same case study, Açıkkalp et al. (2015) performed an advanced exergoeconomic analysis locating endogenous, exogenous, avoidable and unavoidable exergy destructions by component and for the whole plant. Although the generation subsystem (gas boiler) was found to have the maximum endogenous and exogenous exergy destruction cost rates, the investment cost rates can be reduced by improving other subsystems.

3.4 Summary of findings and identification of research gaps

The building sector plays a fundamental part in achieving sustainable societies. Therefore, there is a pressing need to rethink the way in which buildings are designed and refurbished. Chapter 2 showed the limitations of existing approaches and methods based on the First Law of thermodynamics and typical economic analysis used for the design of building energy retrofits, where, compared to other economic sectors, a lack of thermodynamic integration exists. In Chapter 3, state-of-the-art research suggests that energy systems are best evaluated using exergy analysis, as exergy represents the real value of an energy source. While the building sector holds potential for a significant thermodynamic improvement, exergy analysis and exergoeconomics could provide with a new insight for the building's energy system optimisation. Exergy-based analysis could be the ideal methodological complement for the assessment and comparison of retrofit projects as it focuses on improving efficiency. Lowering the exergy content of energy sources or at least trying to match supply and demand qualities eventually would lead to decrease in primary energy consumption and reduction of carbon emissions in existing buildings.

Exergy analysis, specifically applied to buildings' energy systems can be considered to be at an initial stage of development, and therefore lacks certain degree of maturity compared to other economic sectors. The main barriers for the limited application of the Second Law in building energy practice are the unfamiliarity and complexity of the concept and the results seem to be difficult to interpret. On the contrary, the energy concept (First Law) can be considered to have reached an acceptable maturity level, in which practitioners heavily rely on commercially available building performance simulation tools for design and decision making. In addition, in the last years, by taking advantage of current computational power, a wide range of energy/economics oriented optimisation tools have been developed to improve BER designs. However, as mentioned in the last chapter, the application of the First Law only can have its limitations. Exergy analysis could support a deeper sub-system analysis, with potential to provide more illuminating design comparisons.

Nevertheless, the decision making in BER design is mainly based on economic outcomes, where indicators such as NPV, LCC, and DPB are commonly used. However, these can present several limitations such as inability to calculate future techno-economic uncertainty and calculate true inefficiencies cost. Nevertheless, the latter can be tackled by combining economic and exergy analysis, which results in a field known as exergoeconomics. Although studies have shown the applicability of the exergy concept in buildings, exergoeconomics has been considered on a limited basis.

Exergoeconomics considers not only the thermodynamic inefficiencies but also the costs associated with these inefficiencies, and the investment expenditure required to reduce them. Additionally, it has the potential to allocate the budget more efficiently in order to improve the overall economics of the building and its energy systems. Widely used in process optimisation, exergoeconomic optimisation aims to find a trade-off between the energy streams/product cost and capital investment cost of energy systems within the technically possible limits. The major strengths of combining exergy and exergoeconomics is the ability to thermodynamically and economically pinpoint exact sources of inefficiencies, highlight real improvement potential, switch inefficiencies and irreversibilities to other less important subsystems, and provide a comprehensive comparison among designs. In this regard, since the decision making is mainly based on economics, exergoeconomics represents the key for the widespread practical introduction of exergy analysis in building energy design practice. Therefore, tailored methods combining these approaches should be developed.

In addition to this, exergy-based building simulation tools, despite having been created in the past decade, lack exergoeconomic evaluation and an orientation to assess retrofit measures. In order to formulate a robust framework, a thermodynamic accounting of all building processes is required. As exergoeconomics-based multi-objective optimisations have proven to be valuable for retrofit projects in power plants and chemical processes with common optimisation objectives such as cost, fuel cost, exergy destructions, exergy efficiency, and CO_2 emissions; therefore, a potential exists for its implementation in building energy design. As such, the aim of this research is to expand the current knowledge by developing a retrofit-oriented exergoeconomics-based framework with the support of a building simulation tool capable to tackle multi-objective problems and support decision making.

Chapter 4 Methodology: Enhancing BER design via integration of exergy and exergoeconomic accounting

Chapter Overview

A significant difference exists between designing new buildings and retrofitting existing buildings. In order to fill the knowledge gap presented in the Chapters 2 and 3, it was decided to limit the research to the increasingly pressing challenge of retrofitting exiting buildings. This chapter introduces a systematic methodology that considers exergy and exergoeconomic analysis starting from the auditing and baseline building modelling process to the evaluation of different energy efficiency measures. However, before presenting this BER enhanced framework, basic exergy and exergoeconomic formulae together with a thermodynamic abstraction of the building energy supply chain are presented. This will help to locate and analyse all subsystems and energy streams in a generic building energy system. Based on the fuel-product model, established for the energy structure of buildings and buildings' systems, this framework results in a quantitative exergy-economic evaluation of four different streams/products: heating, cooling, DHW, and end-use electricity. For this, several exergy methodologies have been merged, followed by a newly integrated economic-exergoeconomic evaluation assessment. As a consequence, a new economic retrofit indicator is presented (exergoeconomic cost-benefit indicator) which considers the economics of energy use, exergy destructions, and capital investments. Finally, an effort is made to include developed exergy/exergoeconomic approach into the typical BER practice context. Eventually, this novel framework will become the methodology applied to the case studies of this research.

4.1 Method for holistic building exergy analysis

Typical design guides, such as CIBSE Guide F (2012), lack awareness of exergy analysis integration in the energy-efficient buildings' design process. However, an energy/exergy balance will eventually provide more useful information than the energy balance. The exergy balance of a building as a control volume means that there is a transfer of heat and matter across the system's boundaries.

$$Ex_{in} + Ex_{out} - Ex_{sto} - Ex_{irrev} = 0 \tag{4.1}$$

For a better understanding, thermodynamic assessments typically require an input-output abstraction of all the subsystems interacting in an energy system. In order to appropriately define exergy streams of buildings and their energy systems, a thermodynamic abstraction of the system has to be made. Figure 4-1 presents decomposition of the energy system to help locate each component related to the energy conversion processes. This has been developed to cover all possible subsystems found in buildings. By performing a generic decomposition of the system it is possible to adopt the approach to any building.

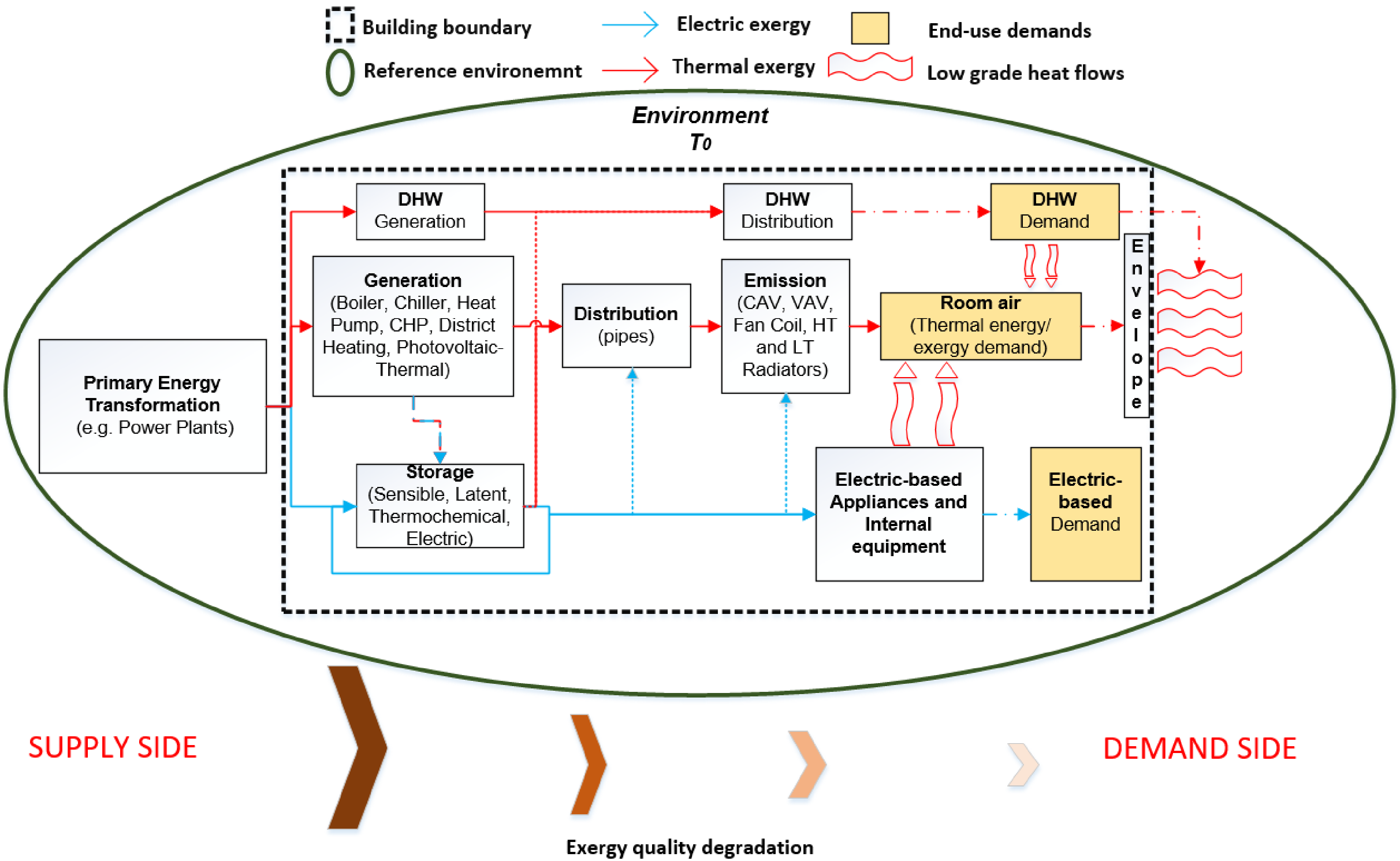


Figure 4-1 Energy supply chain and subsystems for exergy calculations. Enhanced from the IEA EBC Annex 49 method calculation

This decomposition shows eleven subsystems and thirteen energy streams. Four major energy streams can be located: heating, cooling, domestic hot water, and electric-based equipment. The subsystem analysis is more detailed for thermal based end-uses, where the energy supply chain is divided into seven components (Primary energy transformation (PET), generation, storage, distribution, emission, room, and envelope). On the other hand, for DHW, four subsystems are considered (PET, generation, distribution, demand); while for electric based equipment only three subsystems are considered (PET, distribution, demand). Abstracting the building at a sub-system level gives the advantage of providing individual component analysis capable of locating and improving single components. The challenge is developing equations capable of providing a robust understanding of components and their interactions at the whole system level. In this section, different methods (for different energy streams types) are merged and equations for each subsystem are presented. The strength of a simplified decomposition is the ability to analyse different types of technologies, especially energy generation technologies, which in exergy analysis could have some minor differences. However, in this framework a single homogenised method is employed, considering the uncertainties that this could bring to the final results.

With the intention to introduce exergy analysis in typical BER design, additions to the exergy method presented in the IEA-EBC Annex 49 (2011) were done by implementing an expanded exergy analysis on end-uses such as lighting, electric appliances, refrigeration, and catering; thus, considering all the possible exergy streams. Although the thermal exergy analysis is well documented in the literature review, this section presents a simplification of the method by showing the most important equations and some particularities of the proposed framework.

4.1.1 Building exergy demand analysis

4.1.1.1 The reference environment

First, a reference environment must be defined. As already presented in the last chapter, exergy calculations highly depend on the choice of the reference environment that is determined by a preliminary analysis, locating which environment could act as entropy-disposal sink. Although widely discussed, most the research considers the outdoor air as the most appropriate reference environment for the analysis (IEA EBC-Annex49, 2011).

There is also a discussion concerning whether static or dynamic temperatures should be chosen. As explained in section 3.2.1.2, is important to consider the dynamism of the 'dead-state' where the use of dynamic temperature is more appropriate, especially if dehumidification and cooling processes exist within the building. Following the recommendation of the majority building exergy studies, the surrounding outdoor air is chosen as the reference environment.

4.1.1.2 Exergy demand analysis of thermal exergy

In order to determine the thermodynamic parameters at different points of the building's thermal energy supply chain, the thermodynamic properties of the system should be specified. The selected thermal exergy method, is based on the model first developed by Schmidt (2004) and Torio (2012) that was further improved in the IEA EBC-Annex49 (2011) (Figure 4-2). All equations presented in this section are derived from the aforementioned studies.

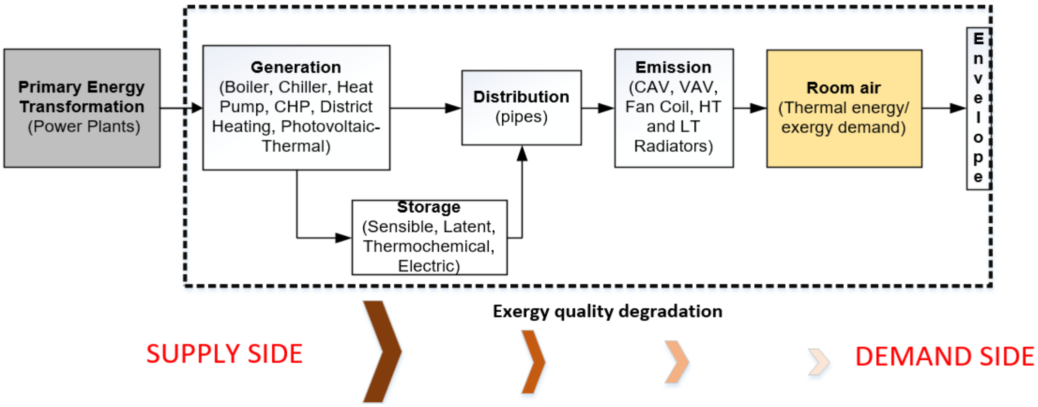


Figure 4-2 Energy supply chain for thermal-based processes

For thermal systems (HVAC only), this method follows an input-output approach based on seven different subsystems that are very strongly related to each other, and thus the performance of one subsystem is highly dependent on the other subsystems. Using the reference temperature as a reservoir, the exergy of a thermal stream is determined by the maximum work that could be obtained from that specific stream. As stated before, the system is regarded as a control volume. The calculation is performed in the opposite direction to the demand, starting from the envelope and concluding in the conversion of primary energy.

As explained, unlike energy analysis, the exergy demand is not calculated using 'exergy balance equations; but is instead calculated by using the energy balance outputs multiplied by the quality factor, given by the Carnot engine‡ equation for thermal exergy, which means that the exergy analysis has to be deduced from the first and Second Law of thermodynamics. This relies on the correct decomposition of energy streams. It is one of the reasons why exergy analysis cannot be regarded as a substitute of typical energy analysis.

I. Thermal exergy demand or 'building envelope subsystem'

Commonly, due to temperature differences between the outside and the inside, energy flows leave the building via its envelope through transmission and ventilation losses. In exergy analysis, first, building thermal exergy demand has to be calculated. For this, a detailed exergy demand approach differentiating the demand related to heat $Ex_{dem,therm}$ (Eq. 4.2) and the

‡ The Carnot formula sets the limiting value on the fraction of the heat or matter which can be used.

demand related to matter $Ex_{dem,vent}$ (Eq. 4.3) is followed. In both, the use of the Carnot factor is needed:

$$Ex_{dem,therm,zone\ ith}(t_k) = \sum_{i=1}^{n}\left(En_{dem,therm\ ith}(t_k) * \left(1 - \frac{T_0\ (t_k)}{T_{ith}\ (t_k)}\right)\right) \tag{4.2}$$

$$Ex_{dem,vent,zone\ ith}(t_k) = \sum_{i=1}^{n}\left(En_{dem,vent\ ith}(t_k) * \left(1 - \frac{T_0\ (t_k)}{T_{ith}\ (t_k) - T_0\ (t_k)} ln \frac{T_{ith}\ (t_k)}{T_0\ (t_k)}\right)\right) \tag{4.3}$$

where, T_0 is the outdoor temperature and T_{ith} is the average inside temperature of the zones, $En_{dem,therm}$ is the energy demand for thermal-based end uses, $En_{dem,vent}$ is the energy demand due to ventilation, t_k is the time-step, and *n* is the number of thermal zones analysed. These outputs are related to the 'envelope subsystem' in Figure 4.2 and represents the final exergy leaving the building to the environment.

II. 'Room air subsystem'

As the room is heated by a warm or cool 'surface' (e.g. radiators, convectors, fans, etc.), temperature differences exist between the internal environment and the energy emission system 'surface'; therefore, the air in a thermal zone has to be regarded as a hypothetical subsystem, where exergy destruction also occurs due to the temperature differences. The temperature difference between the emission surface and the room temperature defines the exergy content. This is done to not assign these losses to the emission subsystem.

In order to calculate the exergy load of the room-air temperature it is necessary to calculate the surface temperature of the emission system. This can be done by using the logarithmic mean temperature difference (LMDT) between the thermodynamic mean temperature of the carrier and the room air. By calculating this temperature, allows the designer to obtain a ΔT between the emission subsystem and the room air. Therefore, the temperature of the emission system surface is calculated as follows:

$$T_{emission}(t_k) = \left(\left(\frac{T_{in}(t_k) - T_{ret}(t_k)}{\ln((T_{in}(t_k) - T_i(t_k)) - (T_{ret}(t_k) - T_i(t_k)))}\right) * \frac{1}{2} + T_i(t_k)\right) + 273.15\ (K) \tag{4.4}$$

To calculate the room air subsystem quality factor the following formula is used:

$$F_{q,room}(t_k) = 1 - \frac{T_0\ (t_k)}{T_{emission}\ (t_k)} \tag{4.5}$$

Therefore, the exergy load of the room is:

$$Ex_{room}(t_k) = F_{q,emission}(t_k) * Q_{emm}(t_k) \tag{4.6}$$

III. ‘Emission subsystem’

Emission systems transfer the energy carried to the room, either to heat it or to cool it. Different emission systems have particular losses and efficiencies. For exergy analysis, heat losses have to be calculated first for the emission system, taking into account the emission system efficiency.

$$Q_{loss,emmision}(t_k) = \left(En_{dem,therm\ ith}(t_k) * \left(\frac{1}{\eta_{emission}} - 1\right)\right) \tag{4.7}$$

$\eta_{emission}$ is the efficiency of the emission system. The exergy is estimated in relation to inlet, return and outside temperature. The exergy demand after the emission system is a sum between the ‘room air’ exergy and the ‘emission’ exergy. Referencing to the inlet and return temperature of the system, the exergy losses of the emission system are calculated as follows:

$$\Delta Ex_{emission}(t_k) = \frac{Q_{tot}(t_k) + Q_{loss,HS}(t_k)}{T_{in}(t_k) - T_{ret}(t_k)} * \left\{ (T_{in}(t_k) - T_{ret}(t_k)) - T_0(t_k) * \ln\left(\frac{T_{in}(t_k)}{T_{ret}(t_k)}\right)\right\} \tag{4.8}$$

And the exergy load rate of the heating system is:

$$Ex_{emission}(t_k) = Ex_{room}(t_k) + \Delta Ex_{emission}(t_k) \tag{4.9}$$

IV. ‘Distribution subsystem’

Distribution system is usually comprised of pipes or ducts that distribute air or water-based energy carriers. The transportation of energy carriers produces heat losses, highly dependent on the system type and insulation values. Exergy loads and exergy losses are calculated similarly to the emission subsystem. First, heat losses are calculated and the exergy is summed from the previous subsystems. The heat loss of the distribution system is calculated as follows:

$$Q_{loss,dist} = (En_{dem,therm\ ith}(t_k) + Q_{loss,emission}(t_k)) * \left(\frac{1}{\eta_{hs}} - 1\right) \tag{4.10}$$

Losses can be calculated similarly in the inlet and the return distribution lines, as in both temperature differences exist. As a result of the heat losses in the supply pipe, a temperature drop occurs (ΔT_{dis}). The exergy demand of the distribution system is:

$$\Delta Ex_{dist}(t_k) = \frac{Q_{loss,dist}(t_k)}{\Delta T_{dis}(t_k)} * \left\{(\Delta T_{dist}(t_k) - T_0(t_k)) * \ln\left(\frac{T_{dis}(t_k)}{T_{dis}(t_k) - \Delta T_{dist}(t_k)}\right)\right\} \quad (4.11)$$

where T_{dis} is the inlet temperature of the distribution system. Hence, the exergy load of the distribution system is:

$$Ex_{dist}(t_k) = Ex_{emission}(t_k) + \Delta Ex_{dist}(t_k) \quad (4.12)$$

V. 'Storage subsystem'

If the system contains storage equipment, the losses and temperature changes of the medium have to be taken into account. The calculation of the exergy storage follows a steady-state calculation. A seasonal storage can be integrated into the system. The heat loss for the storage system is:

$$Q_{loss,strg} = (En_{dem,therm\ ith}(t_k) + Q_{loss,emission}(t_k) + Q_{loss,dist}(t_k) * (\frac{1}{\eta_{strg}} - 1)) \quad (4.13)$$

The exergy demand of the storage can be calculated as follows:

$$\Delta Ex_{strg} = \frac{Q_{loss,strg}(t_k)}{\Delta T_{strg}(t_k)} * \left\{(\Delta T_{strg}(t_k) - T_0(t_k)) * \ln\left(\frac{T_{dis}(t_k) + \Delta T_{strg}(t_k)}{T_{dis}(t_k)}\right)\right\} \quad (4.14)$$

And the exergy load is calculated as follows:

$$Ex_{strg}(t_k) = Ex_{dist}(t_k) + \Delta Ex_{strg}(t_k) \quad (4.15)$$

4.1.1.3 Exergy demand analysis for DHW, refrigeration, and cooking.

In a similar manner to heating and cooling processes, exergy demand for domestic hot water $Ex_{dem,DHW}$, refrigeration $Ex_{dem,ref}$, and cooking $Ex_{dem,cooking}$ can also be calculated using the Carnot factor.

Domestic Hot Water: The DHW process can be separated into three clear subsystems: a) generation equipment (e.g. boiler, solar collector), b) hot water distribution medium (e.g. pipes), and c) hot water demand. If a dedicated storage process is presented, a fourth subsystem can be added to the DHW energy supply chain (Figure 4-3).

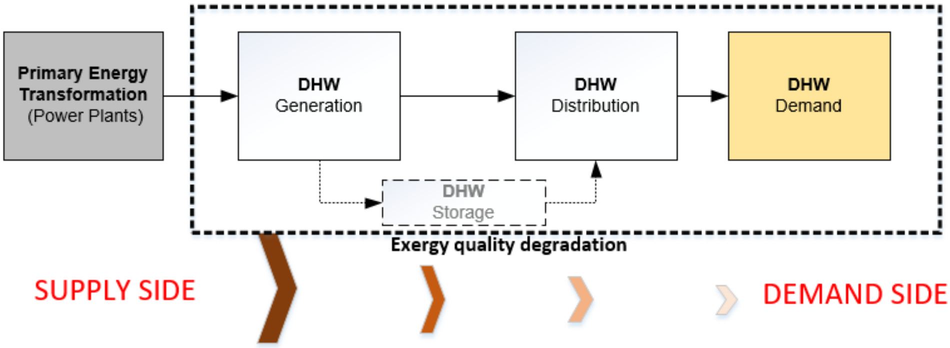


Figure 4-3 Energy supply chain for DHW processes

Generation, distribution and storage is calculated similarly to the HVAC processes presented in the previous section; however, DHW exergy demand is calculated differently.

$$Ex_{dem,DHW}(t_k) = Q_{DHW}(t_k) * \frac{\eta_{WH}(t_k)}{q_{fuel}} * \left(1 - \left(\frac{T_0(t_k)}{T_{pWH}(t_k) - T_0(t_k)}\right) * \ln\left(\frac{T_{pWH}(t_k)}{T_0(t_k)}\right)\right) \tag{4.16}$$

where Q_{DHW} is the domestic hot water energy demand, η_{WH} is the DHW generation system efficiency, q_{fuel} is the quality factor of the energy source used, and $T_{p_{WH}}$ is the hot water temperature.

Refrigeration: For refrigeration it is necessary to account for the coefficient of performance of the refrigerator. Another characteristic is the reference environment, instead of the outdoor temperature, it is the room conditions where the refrigeration is taking place. Therefore, the Carnot coefficient considers this as $T_0(t_k)$.

$$Ex_{dem,ref}(t_k) = Q_{ref}(t_k) * COP_{ref}(t_k)\left(\frac{T_0(t_k)}{T_{p_{refr}}(t_k)} - 1\right) \tag{4.17}$$

where Q_{ref} is the energy demand for refrigeration, COP_{ref} is the refrigerator's coefficient of performance, and $T_{p_{refr}}$ is the refrigerator's working temperature.

Cooking: For catering, either gas-based or electric-based, the following formula is used:

$$Ex_{dem,cooking} = Q_{cook}(t_k) * \frac{\eta_{cook}(t_k)}{q_{fuel}} * \left(1 - \frac{T_0\,(t_k)}{T_{p_{cook}}(t_k)}\right) \quad (4.18)$$

where $Q_{cook}(t_k)$ is the cooking energy demand, η_{cook} is the catering equipment efficiency, and $T_{p_{cook}}(t_k)$ is the cooking temperature. Depending on the energy source, q_{fuel} will vary.

4.1.1.4 Exergy demand analysis of electrical equipment

Electric based equipment either used to support HVAC systems or other appliances are not usually regarded in the building's exergy assessment. However, exergy demand for such equipment could have a significant impact on the outputs and its thermodynamic analysis can be assessed in the same way as any thermal system. A wide range of equipment can be found in buildings. An abstraction of electric-based streams can be seen in the next figure:

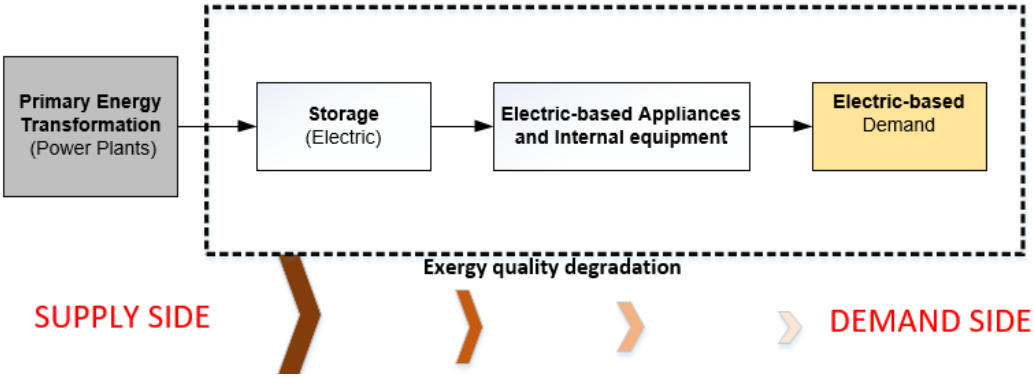


Figure 4-4 Energy supply chain for electric-based processes

As electricity has similar energy and exergy contents, most electric-based equipment such as fans, pumps, lighting, computers, and motors can be considered to have the same exergy demand and exergy efficiency as their energy counterpart and therefore similar consumption.

$$\psi_{elec} \approx \eta_{elec} \quad (4.19)$$

Hence, to calculate the electrical exergy demand $Ex_{dem,elec,ith}$ the following formula can be used:

$$Ex_{dem,elec,ith}(t_k) = En_{dem,elec,ith}(t_k) * F_{q,elec} \quad (4.20)$$

where $En_{dem,elec,ith}$ is the energy demand for the *ith* electric-based end-use equipment, and $F_{q,elec}$ is the quality factor of electricity (1.0). Table 4-1 shows energy and exergy efficiencies of typical electric devices found in buildings.

Table 4-1 Exergy efficiency values for electric-based devices (Rosen and Bulucea, 2009, Ozgener and Ozgener, 2007, Pope et al., 2010, Wei and Zmeureanu, 2009, Gasser et al., 2008)

Equipment	Energy Efficiency (-)	Exergy efficiency (-)
Motors	0.80-0.87	0.80-0.87
Electric battery (lead-acid)	0.75-0.85	0.75-0.85
Pumps	0.60-0.70	0.58-0.67
Fans	0.55-0.80	0.50-0.68
Resistance space heater	1.00	0.06
Lighting fluorescent and LED	0.20	0.20
Electric-based catering	0.85	0.50
Internal/office equipment	0.70	0.70

In some cases, exergy efficiencies are lower than the corresponding energy efficiency due to exergy destructions in conversion processes. For example, exergy efficiency for fans and pumps are much lower, because of irreversibilities due to fluid pressure and flows. Exergy efficiency of electrical equipment shows insights into inefficiencies, providing with information to improve overall system performance.

4.1.1.5 Total building exergy demand

Finally, to obtain the total exergy demand at the building level $Ex_{dem,bui}$, all the previous calculated demands are added:

$$\begin{aligned} Ex_{dem,bui} &= \sum Ex_{dem,end\ use,ith} \\ &= Ex_{dem,therm,zone\ ith}(t_k) + Ex_{dem,vent,,zone\ ith}(t_k) + Ex_{dem,DHW}(t_k) + \\ &\quad Ex_{dem,ref}(t_k) + Ex_{dem,cooking}(t_k) + Ex_{dem,elec,ith}(t_k) \end{aligned} \tag{4.21}$$

4.1.2 Exergy analysis of 'generation subsystems'

As some sort of energy has to enter the building to cover the demand of the whole energy supply chain, this usually has to be transformed or converted into heat energy or cool energy. The generation has to satisfy the demand of all the previous subsystems. The generation systems are supplied by an energy carrier (natural gas, oil, electricity, coal, etc.) with an attached quality factor $F_{q,s}$. This represents the ratio of exergy to energy in an energy carrier. The exact proportion of exergy in a substance depends on the amount of entropy relative to the surrounding. Therefore, the exergy load at the generation subsystem is calculated as a function of the whole storage energy demand and the fraction of that demand covered by each energy source:

$$Q_{gen}(t_k) = \Big\{(Q_{tot}(t_k) + Q_{loss,HS}(t_k) + Q_{loss,dist}(t_k) + Q_{loss,strg}(t_k) + Q_{DHW}(t_k) + \; Q_{ref}(t_k) + Q_{cook}(t_k)) * (1 - F_s)\frac{1}{\eta_{gen}}\Big\} + (En_{dem,elec,ith}(t_k) * F_{q,elec}) \qquad (4.22)$$

$(1 - F_s)\frac{1}{\eta_{gen}}$ is applicable if a heat pump is part of the HVAC system. However, in the next section, special equations for renewables-based equipment are presented, which have the characteristic to account for renewable exergy input into the process.

For fossil fuel-based systems, the exergy load rate of the heat production can be calculated as:

$$Ex_{gen}(t_k) = Q_{gen}(t_k) * F_{q,s}\;(t_k) \qquad (4.23)$$

$F_{q,s}$ is a predefined quality factor of the energy carrier (the values will be reviewed in Section 4.1.3).

4.1.2.1 Exergy analysis of renewable generation systems

In the last decades, energy generation technologies based on renewable sources for buildings, such as photovoltaic panels, solar collectors, hybrid PV/T, and ground/air source heat pumps, have been widely used, and require a different exergy analysis from conventional systems. The following equations were taken from Torío et al. (2009), who undertook a comprehensive review of exergy analysis for renewable-based systems.

Direct solar systems: Photovoltaic panels and solar thermal collectors are considered to be direct solar systems. To calculate the exergy of the incoming solar radiation Ex_{sun} to the equipment the following formula is used:

$$Ex_{sun}\,(t_k) = \; G(t_k) * A_{col} * \left(1 - \frac{T_0\,(t_k)}{T_{sun}}\right) \qquad (4.24)$$

where G is the incident solar radiation, A_{col} is the collector surface area, T_0 is the reference environment, and T_{sun} is the sun's temperature, which is taken as 6000 K. This is defined as the first input for the energy supply chain, regarded as the primary energy transformation subsystem. Hence, the output of the collector Ex_{col} is the generation subsystem output and is calculated as follows:

$$Ex_{col}(t_k) = \dot{m}(t_k) * c_{Pheat} \left[(T_{out}(t_k) - T_{in}(t_k) - T_0(t_k) * ln \left(\frac{T_{out}(t_k)}{T_{in}(t_k)} \right) \right] \quad (4.25)$$

where $\dot{m}$ is the mass flow rate (kg/s), c_{Pheat} is the carrier specific heat, T_{out} is the temperature provided by the collector, and T_{in} the return temperature to the collector. Finally, the exergy efficiency for solar collectors Ψ_{col} is obtained as follows:

$$\Psi_{col}(t_k) = \frac{Ex_{col}(t_k)}{Ex_{sun}(t_k)} \quad (4.26)$$

For hybrid PV/T panels, exergy efficiency Ψ_{PVT} is calculated as follows:

$$\Psi_{PVT}(t_k) = \frac{E_{PV}(t_k) + Ex_{col}(t_k)}{Ex_{sun}(t_k)} \quad (4.27)$$

where E_{PV} is the electrical energy generated by the panel (which has the same exergy value), Ex_{col} is the thermal exergy output, and Ex_{sun} is the incoming solar radiation. Saitoh et al. (2003) showed that exergy efficiencies from single PV systems can be around 0.11, while for solar thermal systems it is 0.04, and for hybrid systems reach efficiencies of close to 0.13-0.14.

Heat Pumps: Heat pumps can also be considered renewable systems, as it mainly uses renewable thermal energy found in the air, water bodies, or in the ground. For the heat pumps, the formula accounts for the exergy coming from electricity needed to operate the compressors and the evaporators, where the exergy content of the reservoir (water, air, or ground) is considered as a free exergy. Therefore, the efficiency Ψ_{HP} is calculated as follows:

$$\Psi_{HP}(t_k) = \frac{Ex_{th.dem}}{W} = \frac{\sum_{i=1}^{n} \left(En_{th,dem\, i}(t_k) * \left(1 - \frac{T_0(t_k)}{T_i(t_k)} \right) \right)}{W(t_k)} = COP_{HP}(t_k) * \left(1 - \frac{T_0(t_k)}{T_i(t_k)} \right) \quad (4.28)$$

where $Ex_{th.dem}$ is the building thermal exergy demand, W is the electrical power input, $En_{th,dem}$ is the building's thermal energy demand, T_0 is the reference temperature, T_i is the internal temperature, and COP is the heat pump coefficient of performance.

Finally, Table 4-2 shows a compassion of energy and exergy efficiency for fossil fuel and renewable-based energy generation technologies.

Table 4-2 Exergy efficiency values for electrical generation systems-power plants. Adapted from Rosen and Bulucea, 2009 and Favrat et.al 2008.

Generation system	Energy Efficiency *η (-)*	Exergy efficiency Ψ (-)
Coal-fired power plant	0.37	0.36
Nuclear power plant	0.32	0.32
Hydroelectric power plant	0.90	0.90
Fuel cell system	0.33	0.33
Wind turbine system	0.20-0.40	0.19-0.29
Solar photovoltaic system	0.06-0.25	0.06-0.25
Solar thermal power generation	0.10-0.30	0.10-0.30
Combined cycle	0.54	0.54
Cogeneration system	0.74	0.31
Trigeneration system	0.94	0.28

4.1.3 Supply-side exergy analysis: Primary Exergy Input

In terms of energy sources, different sources have associated corresponding quality factors, related to the exergy content of chemical enthalpy of a given energy flow. Energy resources in their natural form are extracted to cover human necessities. They are considered to be the primary energy sources that subsequently have to go through a transformation and conversion process. Energy sources with high exergy contents are typically more valued and useful than energy forms with low exergy (Dincer and Zamfirescu, 2012). For example, considering a T_0 of 25 ºC, an energy source such as coal has a ratio of 1.03, fuel oil of 1.01, and natural gas of 0.94 (Cooper et al., 2014). If an exergy analysis is performed only at this level, without considering the exergy demand and its losses through the energy supply chain, the results will be similar to a common energy analysis. In order to analyse exergy input at the primary generation subsystem Ex_{prim} and distinguish the impact of using different types of energy sources, the next equation has to be applied:

$$Ex_{prim}(t_k) = \sum_i \left(\frac{Q_{gen,i}(t_k)}{\eta_{gen,i}(t_k)} * F_{p,source,i} * F_{q,source,i}\right) + \left(Ex_{dem,elec,ith}(t_k) * F_{p,elec}\right) \quad (4.29)$$

where, Q_{gen} is the total energy used by the building HVAC/DHW generation systems (chiller, boiler, CHP, etc.), η_{gen} is the system efficiency, $F_{p,source}$ and $F_{q,source}$ are the UK primary energy factor (Pout, 2011) and fuel quality factor (IEA EBC-Annex49, 2011); respectively, $Ex_{dem,elec,ith}$ is the exergy demand for electric based equipment, and $F_{p,elec}$ is the primary energy factor for electricity. This result is the total amount of exergy supplied to the building. The fuels' primary energy factors and quality factors used in this study are shown in Table 4-3

Table 4-3 Primary energy factors and quality factors by energy sources

Energy source	**Primary energy factor** (F_p) **(kWh/kWh)**	**Quality factor** (F_q) **(kWh_{ex}/kWh_{en})**
Natural gas	1.11	0.94
Electricity (grid supplied)	2.58	1.00
District energy[§]	1.11	0.94
Oil	1.07	1.00
Biomass (Wood pellets)	1.20	1.05
Coal	1.01	1.04

4.1.4 Irreversibilities or exergy destructions calculation

After the demand-supply analysis of the subsystems and of the whole-system are performed, calculations of internal 'exergy destructions' Ex_{dest} at both subsystem and whole-system level are required. Also called internal 'exergy losses' or 'irreversibilities', they are strongly related to the system's entropy generation. It can also be regarded as a thermodynamic imperfection of the process and can be produced in several ways. When the energy supply passes through the energy supply chain, exergy destructions are expected throughout all of the subsystems. These are dependent on factors such as the building's envelope or the system components' characteristics. In building's systems, exergy destructions are often produced in two ways: a) by non-homogeneities, when large temperature and pressure difference exist between the components (e.g. heat exchangers or compressors), and by b) chemical reactions, when the reaction of a substance occurs losing its chemical potential (e.g. gas combustion to produce hot water).

Although the 'Primary Energy Transformation Subsystem' is located outside the building's boundary, the exergy method used in this study also considers the destructions at this stage. This makes it possible to distinguish from many different sources (e.g. electricity, natural gas, and district energy), and external supplies (gas, oil, renewables), which gives a more robust understanding of the impact of different primary energy sources used for buildings and their systems. To calculate the destructions at building level, the following formula is used:

$$Ex_{dest,bui}(t_k) = Ex_{prim}(t_k) - Ex_{dem,bui}(t_k) \quad (4.30)$$

[§] The District system was assumed to be run by a single-effect indirect-fired absorption chiller with a coefficient of performance (COP) of 0.7.

where Ex_{prim} and $Ex_{dem,bui}$ are the total primary exergy supplied and total building exergy demand respectively. However, destructions can also be calculated at a subsystem level, subtracting the exergy entering the subsystem *ith* with the exergy leaving the subsystem *ith*:

$$Ex_{dest,sys\ ith}(t_k) = Ex_{in,ith}(t_k) - Ex_{out,ith}\ (t_k) \tag{4.31}$$

This is useful in locating components with higher destruction rates, and therefore considering its replacement or improvement.

4.1.5 Exergy efficiency and other indexes

As demonstrated in the literature, no energy system can be 100% efficient. The most common assessment parameter for comparison of the system and design in exergy analysis is the 'exergy efficiency'. This similarly to the calculation of destructions can identify components with low thermodynamic performance and high improvement potential. Therefore, a building's exergy efficiency Ψ_{bui} is obtained as follows:

$$\Psi_{bui}(t_k) = \frac{Ex_{dem,bui}(t_k)}{Ex_{prim}(t_k)} = 1 - \frac{Ex_{dest,bui}(t_k)}{Ex_{prim}(t_k)} \tag{4.32}$$

Exergy efficiency of the subsystem can be formulated in two ways: simple exergy efficiency or rational exergy efficiency:

$$\Psi sim_{sys,ith}(t_k) = \frac{Ex_{out,ith}\ (t_k)}{Ex_{in,ith}(t_k)} \tag{4.33}$$

$$\Psi rat_{sys,th}(t_k) = \frac{Ex_{dest,out,ith}\ (t_k)}{Ex_{in,ith}(t_k)} \tag{4.34}$$

The main difference here is that the simple efficiency considers the total exergy output of the system, which could have an unwanted exergy part, but has no use for the system. On the other hand, the rational efficiency, by taking into account the destructions within the subsystem, considers the difference between the desired exergy output useful for the system and the useless exergy part (IEA EBC-Annex 49, 2011).

Apart from exergy efficiencies (ψ), Hepbasli (2012) proposed a series of key indices useful for comparison and ranking of different buildings, with a potential use to evaluate the success of exergy-based retrofits and optimisation. Similarly, to the energy use index (EUI), the total primary exergy input index $ExIU$ provides information on the amount of exergy supplied to the building.

$$ExIU = \frac{Ex_{total}}{Area} \tag{4.35}$$

The exergy destruction rate Ex_d provides the amount of irreversibilities, occurring due to the thermodynamic nature of the process (e.g. temperature/pressure drop or increase, friction, etc.), giving a useful indicator to help pinpoint and locate inefficient equipment or whole-systems.

$$\dot{Ex}_d = (1 - \psi)Ex_{total} \tag{4.36}$$

Several other indexes can provide with important information about the system. Indicators such as relative exergy destruction, exergy of resources, exergy products, and exergy destruction ratio could also be used. In addition, thermoeconomic indexes, which provide important economic information, will be presented in the following section.

4.2 Method for economic and exergoeconomic analysis for BER

Economics are important in evaluating and comparing designs, and become essential in the assessment of retrofit projects. The selection of BER measures is a trade-off between the total capital investment and revenue due to energy savings. Contrary to exergy analysis integration in energy studies, the addition of exergoeconomics into a broader economic analysis applied to buildings is not as simple. Nevertheless, the following sections will try to overcome this by proposing a novel exergoeconomic framework applied to BER design. Additionally, the framework's strengths and barriers for practical implementation will be discussed.

4.2.1 Life Cycle Cost (LCC), Net Present Value (NPV), and Discounted Payback Period (DPB)

As showed in section 2.2.2, in BER projects 'Life Cycle Cost' (LCC), 'Net Present Value' (NPV), and 'Discounted Payback Period' (DPB) are the most typical and widely used economic methods/indicators for cost-benefit assessment. The proposed framework recommends and considers typical economic calculations as a first assessment. Therefore, these three indexes are calculated as follows:

$$LCCA = \sum_{n=1}^{N} \frac{CF_n}{(1+r_d)^n} \tag{4.37}$$

where CF_n is the annual cash flow of year *n,* N is the total years of evaluation, and r_d is the discount rate. The annual cash flow is calculated as follows:

$$CF_{\boldsymbol{n}} = [C_n^B + O\&M_n^B] + [C_n + O\&M_n] + [C_{en}] \tag{4.38}$$

where C_n^B is the baseline capital cost, $O\&M_n^B$ is the baseline operation and maintenance cost, C_n is the incremental capital cost in year *n,* $O\&M_n$ is the incremental operation and maintenance cost in year n, and C_{en} is the annual energy cost.

To calculate the NPV, the following formula is required:

$$NPV_{Nyears} = -TCI + \left(\sum_{n=1}^{N} \frac{R}{(1+i)^n}\right) + \frac{SV_N}{(1+i)^N} \tag{4.39}$$

where *TCI* is the initial total capital investment, *R* is the annual revenue cost (composed of the annual energy cost savings minus the additional operation and maintenance cost), and *SV* is the salvage cost or residual value with measures with longer lifespan (considering a common rate of 15%). In this research, a lifespan (N) of 50 years and a discount rate (i) of 3% (HM_Treasury, 2003) are considered. Finally, DPB can be calculated by contracting the Taylor Series of the NPV formula and by accounting for the retrofit project annual revenue (Rysanek and Choudhary, 2013):

$$DPB = -\frac{\ln\left[\left(\left(1-(1+i)\right)*\left(\frac{TCI}{R}\right)\right)+1\right]}{\ln(1+i)} \tag{4.40}$$

In order to reduce uncertainties in the results, grant schemes, incentive programs, and subsidies have to be considered, as they are part of a range of measures that act as drivers for a quicker deployment and uptake of low carbon and renewable technologies, which have a big impact on the economics of projects, often increasing the cost-benefit ratio. Specifically, in the UK's case, programs such as FiT and RHI have to be accounted for when an economic analysis is performed. Other economic parameters that have to be considered are energy price escalation, inflation rate, labor and maintenance cost, taxes, etc. This will be discussed in Chapter 5, where a computation tool comprised of an economic module, considering these parameters, will be presented.

4.2.2 Exergoeconomic analysis (SPECO)

Simple economic indicators are straightforward to implement but may lead to misleading conclusions, giving a wrong impression of the process under study. The calculation of the aforementioned economic indicators does not consider the degradation and consumption of natural resources, as no link exists between the typical economic analysis and the real physical value of energy sources. When costs are not allocated appropriately, it becomes difficult to assess the cost-effectiveness of a measure, especially, when multiple products exist as is in the case of buildings.

Therefore, there is a challenge of integrating an appropriate exergoeconomic method into the economic assessment of BER. Exergoeconomic methods consider cumulative exergy cost destruction through the energy supply chain; therefore, cost always increases in any real thermodynamic process. Cost is defined as the amount of resources necessary to obtain a desired product and is strongly related to the generation of irreversibilities. The exergy cost of any energy stream is considered as the amount of exergy necessary to produce it. In buildings, the final energetic products, needed to cover any end-use (heating, cooling, DHW, electricity), has embodied in it some form of cost increase due to inefficiency conversion processes in the previous steps of the energy supply chain.

From a wide range of thermoeconomic methods, the SPECO (specific exergy cost) method was considered the most appropriate for the proposed framework. It was initially developed by Tsatsaronis (1993) and further improved by Lazzaretto and Tsatsaronis (2006) as the most adaptable framework for BER due to its robustness and widely tested methodology in other types of energy systems. SPECO method is based on the calculation of exergy efficiencies, exergy destructions, exergy losses, and exergy ratios (destructions/inputs) at a component and system level, giving the advantage of an ability to locate economically inefficient systems and processes along the whole system. Since exergoeconomics depends on the calculation of exergy and irreversibilities, the exergy cost of components or whole-system can be calculated with the help of the equations presented in the previous section. SPECO then uses these values as a basis to combine economics and exergy analysis.

The proposed economic-exergoeconomic BER framework is able to perform exergoeconomic analysis of fuel and products, as well as a thermoeconomic life cycle cost analysis of a running building within a specific retrofit project. After identifying and calculating the exergy streams, the method follows two main steps:

1. *definition of fuel and product costs considering input cost, exergy destruction cost, and increase in product costs, and,*

2. *identification of exergy cost equations.*

4.2.2.1 Fuel-Product (F-P) definition

After quantifying the energy and exergy streams through the energy supply chain, a definition of fuel(s) and product(s) for each component has to be constructed and the cost balance equations have to be applied. Exergy cost of a product (P) can be regarded as the exergy content plus the sum of irreversibilities along the process. As exergy destructions directly affect the cost of the products, whilst being consumed along the process, the product's exergy cost inevitably increases. The value depends on two factors: the amount of destructions and the current price of the entering stream (fuel). A generalised analysis at a component level can be seen in Figure 4-5.

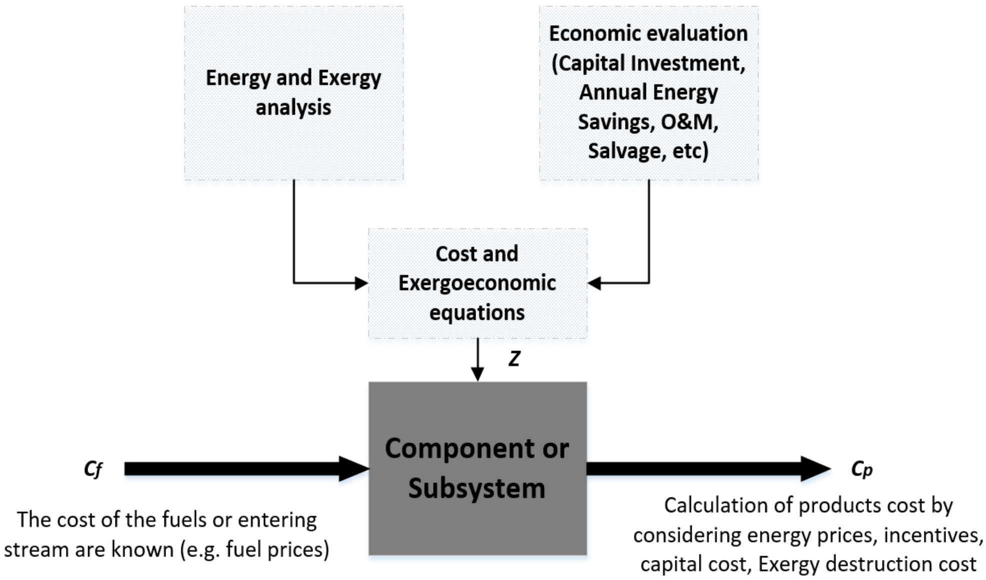


Figure 4-5 Representation of a cost-balance and exergoeconomic analysis in an energy component

Similarly, to the analysis performed in power plants, this research considers cost allocation for the different four products located in a building: a) space heating, b) space cooling, c) hot water, and d) electricity for end-use appliances. Thus, the price for each of the final products is obtainable. Lowering these final prices should be the objective of any building exergoeconomic optimisation. However, as each product was developed through different components, each subsystem of the plant has to be characterised by its fuel and its product. Figure 4-6 presents a schematic block diagram of the subsystems and streams that are proposed as an abstraction of a typical building energy system.

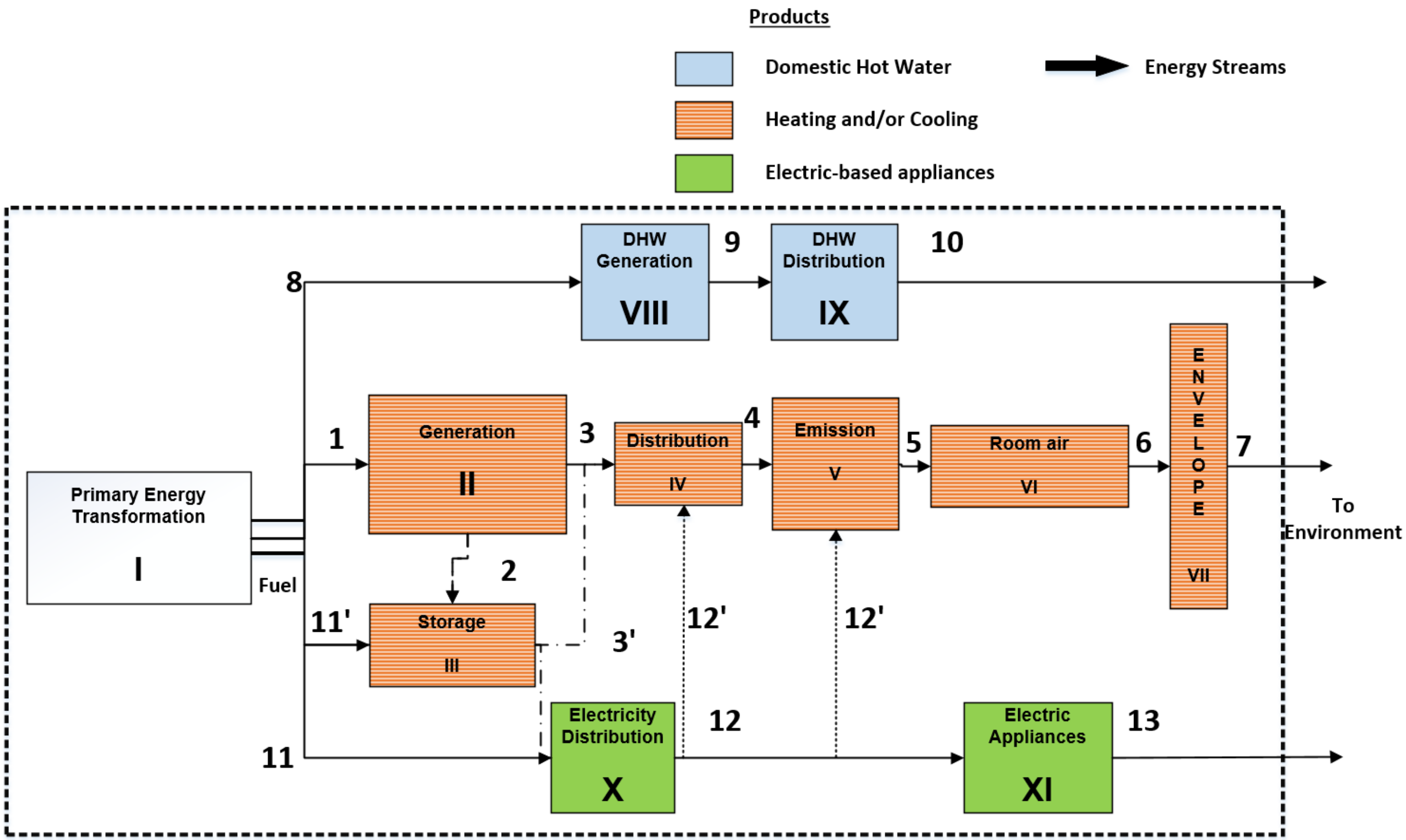


Figure 4-6 Schematic diagram of energy supply subsystems and energy streams in a building (HVAC, DHW, and electric appliances)

4.2.2.2 Exergy cost equations

After the definition of fuel and products has been established, exergoeconomic equations have to be identified. The most important cost equations from the SPECO method are summarised below. First, the general exergy balance can be written as follows:

$$\dot{Ex}_{F,k} = \dot{Ex}_{P,k} + \dot{Ex}_{D,k} \quad (4.41)$$

where $\dot{Ex}_{F,k}$, $\dot{Ex}_{P,k}$, and $\dot{Ex}_{D,k}$ are the fuel exergy, product exergy, and exergy destruction of the component k, respectively.

An exergy cost stream $\dot{C}_k$ associated with the corresponding stream *i* is calculated as follows:

$$\dot{C}_i = c_i Ex_i \quad (4.42)$$

where c_i and Ex_i are the streams' specific cost and exergy, respectively.

By combining exergy balance and thermoeconomics, a general cost balance expression is obtained. Where the exergy cost balance $\dot{C}_{p,k}$ related to a subsystem is expressed as follows:

$$\dot{C}_{p,k} = \dot{C}_{D,k} + \dot{Z}_k \quad (4.43)$$

where $\dot{C}_{D,k}$ and $\dot{Z}_k$ is the exergy destruction cost and sum of capital investment rate for the component *k*, respectively. In addition, the exergy destruction cost of a component $\dot{C}_{D,k}$ is defined as:

$$\dot{C}_{D,k} = c_{f,K} \dot{Ex}_{D,k} \quad (4.44)$$

where $c_{f,K}$ and $\dot{Ex}_{D,k}$ are the fuel cost and exergy destructions for the component *k*, respectively. To obtain building total exergy destruction cost, a sum of all subsystems' components has to be made:

$$\dot{C}_{D,sys} = \sum_{k=0}^{n} (c_{f,K} \dot{Ex}_{D,k}) \quad (4.45)$$

To account for the component capital investment Z_k, we have to convert it into an hourly rate dependant also on the project's lifetime:

$$\dot{Z}_k = \frac{PW \cdot CRF}{\tau} \tag{4.46}$$

where *PW* is the present factor of the retrofit measure, *CRF* is the capital recovery, and τ is the equipment annual working hours. *PW* and *CRF* are obtained by using Eq. 4.47 and 4.48 respectively:

$$PW = TCI - \frac{SV_N}{(1+i)^N} \tag{4.47}$$

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{4.48}$$

Following the thermodynamic subsystem's abstraction (Figure 4-6), Table 4-4 shows the exergy and exergoeconomic balance used in a generic building energy model. By solving these equations, the average cost of fuel, average cost of products, cost of exergy destructions, and other exergoeconomic indexes by subsystem are obtained. Outputs can be presented as an average cost per unit (£/kWh). For simplification and to be able to use the framework in different building energy systems designs, it was intended to produce a building-oriented exergoeconomic framework with the same number of streams and components; therefore, no auxiliary costing equations were required as no difference between the inlet and outlet in the fuel definition is considered (Lazzaretto and Tsatsaronis, 2006). Notwithstanding, in the F-P diagram (Figure 4-6), it appears that there are two extra exergy streams; however, for simlification of the diagram, the 'Primary Energy Transformation' (PET) is presented as a single subsytem, when in reallity it has to be divided into three subsystems (PET for air-conditioning, DHW, and end-use electricity), where each subsystem has attached an independent product (P) stream.

Table 4-4 Exergoeconomic balance for subsystems and streams

No.	Subsystem	Exergy Fuel	Exergy Product	Exergoeconomic balance
I	Primary Energy Transformation	F_I = *(Raw energy sources)*	$P_I = \dot{Ex}_1\ (\dot{Ex}_8\ or\ \dot{Ex}_{11})$	$\dot{C}_0 + \dot{Z}_I = \dot{C}_1\ (\dot{C}_8\ or\ \dot{C}_{11})$
II	Generation HVAC	$F_{II} = \dot{Ex}_1$	$P_{II} = \dot{Ex}_2 + \dot{Ex}_3$	$\dot{C}_1 + \dot{Z}_{II} = \dot{C}_2$
III	Storage HVAC	$F_{III} = \dot{Ex}_2 + \dot{Ex}_{11'}$	$P_{III} = \dot{Ex}_{3'}$	$\dot{C}_2 + \dot{C}_{11} + \dot{Z}_{III} = \dot{C}_3$
IV	Distribution HVAC	$F_{IV} = \dot{Ex}_3 + \dot{Ex}_{3'} + \dot{Ex}_{12'}$	$P_{IV} = \dot{Ex}_4$	$\dot{C}_3 + \dot{C}_{12'} + \dot{Z}_{IV} = \dot{C}_4$
V	Emission HVAC	$F_V = \dot{Ex}_4 + \dot{Ex}_{12'}$	$P_V = \dot{Ex}_5$	$\dot{C}_4 + \dot{C}_{12'} + \dot{Z}_V = \dot{C}_5$
VI	Room Air HVAC	$F_{VI} = \dot{Ex}_5$	$P_{VI} = \dot{Ex}_6$	$\dot{C}_5 + \dot{Z}_{VI} = \dot{C}_6$
VII	Envelope HVAC	$F_{VII} = \dot{Ex}_6$	$P_{VII} = \dot{Ex}_7$	$\dot{C}_6 + \dot{Z}_{VII} = \dot{C}_7$
VIII	DHW Generation	$F_{VIII} = \dot{Ex}_8$	$P_{VIII} = \dot{Ex}_9$	$\dot{C}_8 + \dot{Z}_{VIII} = \dot{C}_9$
IX	DHW Distribution	$F_{IX} = \dot{Ex}_9$	$P_{IX} = \dot{Ex}_{10}$	$\dot{C}_9 + \dot{Z}_{IX} = \dot{C}_{10}$
X	Electricity Distribution	$F_X = \dot{Ex}_{11} + Ex_{3'}$	$P_x = \dot{Ex}_{12}$	$\dot{C}_{11} + \dot{C}_{3'} + \dot{Z}_X = \dot{C}_{12}$
XI	Electric Appliances	$F_{XI} = \dot{Ex}_{12}$	$P_{XI} = \dot{Ex}_{13}$	$\dot{C}_{12} + \dot{Z}_{XI} = \dot{C}_{13}$

4.2.3 Main exergoeconomic indexes and the ‘exergoeconomic cost-benefit indicator’ for BER

Apart from the basic exergoeconomic evaluation, within the SPECO method, two additional performance indicators can be calculated:

- *Relative cost difference*
- *Exergoeconomic factor*

These indicators could be especially useful for comparison of different BER design options. The *relative cost difference* r_k is calculated as follows:

$$r_k = \frac{c_{P.k} - c_{F,k}}{c_{F,k}} \quad (4.49)$$

Where $c_{P.k}$ is the average cost of the product and $c_{F,k}$ is the average cost of fuel at the component *k*. The indicator shows the increase in the product price compared to the price of the entering stream (fuel). For example, the price that occupants pay for heating as a final product is not solely composed of the fuel price on entering the building (e.g. net price per kWh for gas or electricity), but also an embedded additional cost such capital cost, operation cost, and exergy destruction cost. This indicator can show the cost differences of the four main products in the building (heating, cooling, hot water, and electricity for appliances).

On the other hand, the *exergoeconomic factor* f_k shows the ratio of the component’s capital cost to the component’s ‘total cost’. The ‘total cost’ consists of capital cost, O&M cost, and exergy destructions cost. This is obtained as follows:

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + c_{F,k}(\dot{Ex}_{D,k})} \quad (4.50)$$

These outputs show the principal source of a component’s expenditure. If the value is close to the unity it means that the component’s capital cost is the main origin of expenditure, while if the value is close to zero it means that the exergy destruction cost is the main origin of expenditure. This is useful, as it allows the practitioner to choose between reducing the necessary capital investment for the component/system and focusing on increasing the component exergy efficiency.

4.2.3.1 Exergoeconomic cost-benefit indicator

The formulation of an expanded exergoeconomic indicator tries to solve the gap of integrating exergoeconomic evaluation in typical economic analysis for BER design, by expressing exergy losses and its relative cost into an indicator that is straightforward to understand. As typical economic cost-benefit assessment does not consider exergy destructions, SPECO method was extended by including a novel levelised exergoeconomic indicator, the *exergoeconomic cost-benefit indicator* $Exec_{CB}$. This indicator was developed for the purpose of this particular research and is calculated as follows:

$$Exec_{CB} = \dot{C}_{D,sys} + \dot{Z}_{sys} - \dot{R} \quad (4.51)$$

where $\dot{C}_{D,sys}$ is the building's total exergy destruction cost (eq. 4.44), $\dot{Z}_{sys}$ is the annual capital cost rate for the retrofit measure (eq. 4.45), and $\dot{R}$ is the annual revenue rate. All three parameters are levelised considering the project's lifetime (50 years) and the present value of money. The outputs are given in £/h.

For retrofit analysis, first, a benchmark value has to be calculated for the baseline building. This indicator will only be composed of exergy destruction costs $\dot{C}_{D,sys,baseline}$ (as no retrofit measure ($\dot{Z}_{sys}$) has been applied and consequently no revenue ($\dot{R}$) has been generated). Therefore, after the retrofit analysis is performed, if the retrofitted building presents a $Exec_{CB}$ lower than the baseline $\dot{C}_{D,sys,baseline}$, the design represents both a cost-effective solution and an improvement in exergy performance.

Exergy-efficient and cost-effective → $Exec_{CB} < \dot{C}_{D,sys,baseline}$

Exergy-inefficient and cost-ineffective → $Exec_{CB} > \dot{C}_{D,sys,baseline}$

This indicator appears promising as it considers the economics of energy use, exergy destructions, and capital investments.

4.3 Overall approach of the proposed enhanced BER framework

After integrating a comprehensive exergy analysis and an exergoeconomic method into a typical energy balance and life cycle cost analysis respectively, the proposed holistic framework (Figure 4-7) aims to allow the practitioner to quantify the First and Second Law parameters, in order to locate more opportunities for improvement. This systematic methodology covers an existing gap that limits the introduction of exergy into practice.

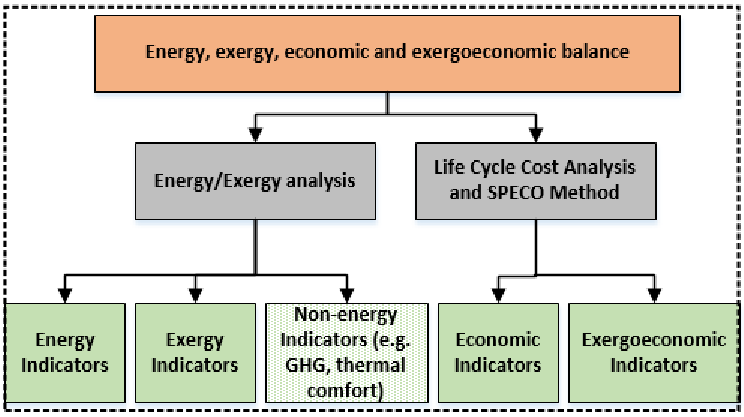


Figure 4-7 Energy, exergy and exergoeconomic calcuation diagram

Several steps with different activities exist in common BER practice. Ma et al. (2012) identified five key phases/activities in any generic building retrofit problem. These are: 1) project setup and building survey, 2) auditing and performance assessment, 3) identification of retrofit options, 4) implementation and commissioning, and 5) measurement and verification of installed project. The phases, with potential of including the exergoeconomic-based framework, are identified by the red square in Figure 4-8 (phases 2 and 3).

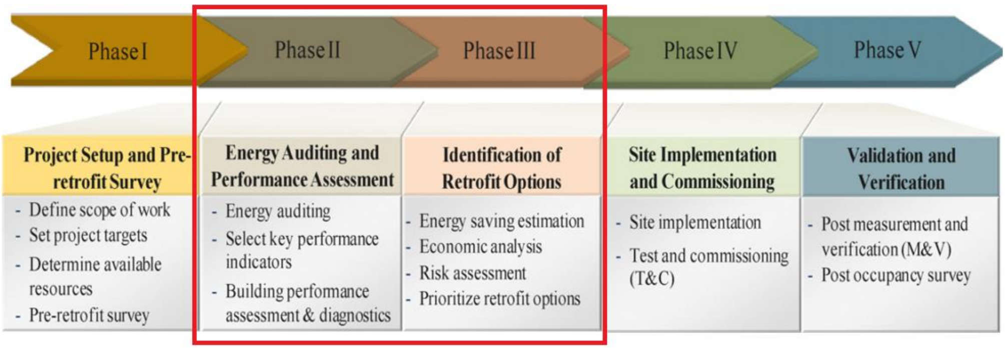


Figure 4-8 Major activities in a sustainable building retrofit programme and potential locations for thermodynamic analysis. Modified from Ma et al. (2012)

The proposed global framework, which enhances these two phases, consists of three levels and takes into account exergy and exergoeconomic criteria in order to find the most thermodynamically efficient and cost-effective BER solution:

I. *Building energy/exergy auditing and baseline modelling*

II. *Retrofit evaluation*

III. *Analysis and ranking of possible solutions*

The complete methodological framework illustrating the integration of exergy/exergoeconomic analysis and optimisation is presented in Figure 4-9 and explained in the following sections.

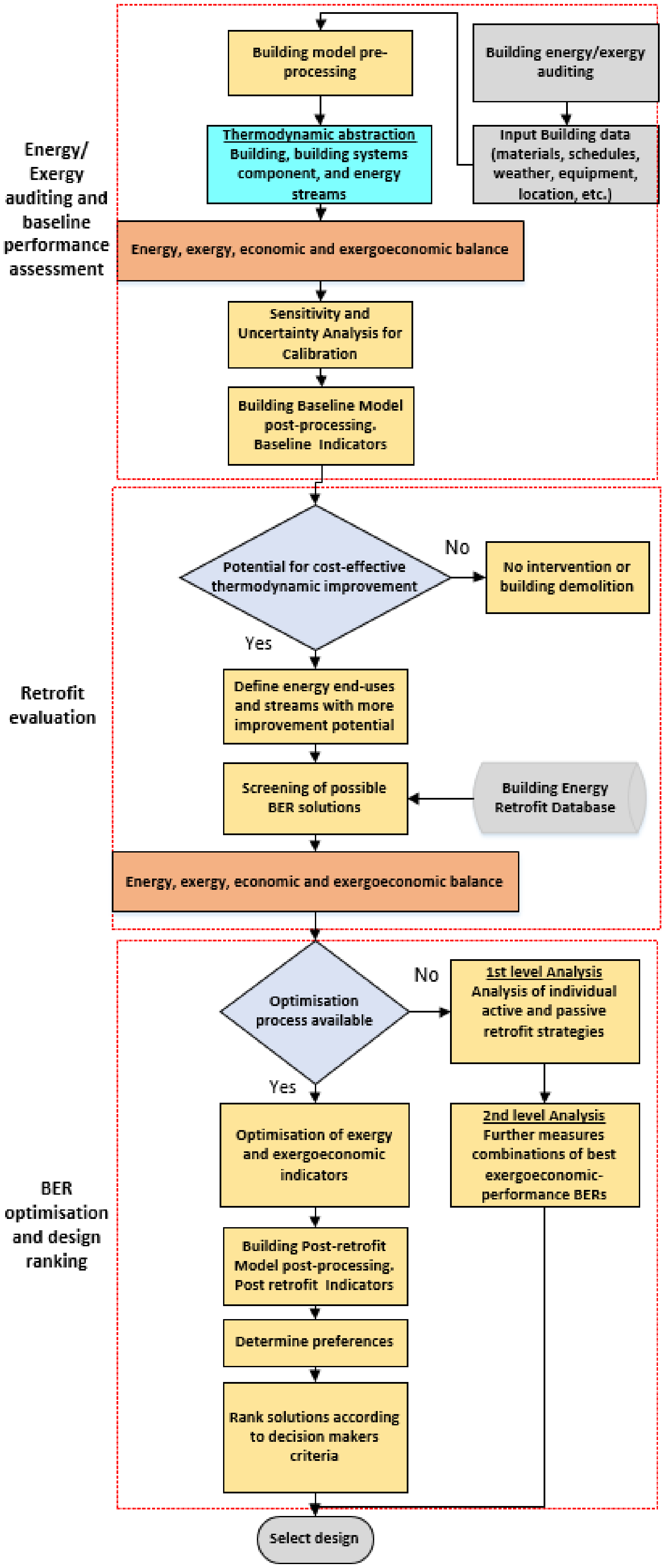


Figure 4-9 Flowchart of the proposed BER process integrating exergy/exergoeconomic analysis and multi-objective optimisation

4.3.1 Building energy/exergy auditing and baseline modelling

First level intends to prepare the data of the building and its system aiming to obtain Second Law-based benchmark values. This level should be considered as the most important, as the results highly depend on the accuracy of the baseline model, which requires comprehensive data extraction, energy/exergy performance assessment, and selection of adequate performance indicators. However, a limitation to the data extraction in buildings lies in energy records, control systems, and building automation and management systems that provide data based on the First Law indicators only. If this is the case, exergy indicators have to be calculated, thus potentially making this phase more tedious for the practitioner. However, in recent years, novel studies (Razmara et al., 2015, Yang et al., 2015) have developed building controls based on exergy optimisation, thus embedding exergy data inside BMS systems. Both studies, apart from more precise control capabilities, are fundamental as it creates building energy/exergy systems capable of providing data based on exergy indicators.

Regardless of the auditing process, the extracted information can be then applied to a modelling process, which can range from a simple spreadsheet (e.g. Annex 49 pre-design tool) to more complicated dynamic simulation tools (in the next chapter, a novel dynamic simulation tool, based on EnergyPlus® will be introduced). This first modelling process, which covers all the formulae presented in this chapter, aims to provide benchmark data, where the selection of key performance indicators is essential for further improvement. At this stage of the process, subsystems that achieved better exegetic efficiency and better exergoeconomic performance are located. Depending on the audit data, it is recommended that any modelling exercise to be subject to a calibration process.

4.3.2 Retrofit evaluation

As shown in the literature, most exergy-based studies limit the study to the first level of the analysis, and exergoeconomic analyses are rarely performed. By considering benchmark values, a decision of whether to perform a retrofit project or not has to be made. Depending on the project’s scope this can be done at a subsystem level or at a whole-system level. Regardless of the scope, a comprehensive retrofit database considering technologies at each stage of the energy supply chain with its corresponding capital investments is necessary.

If conditions exist to perform a comprehensive retrofit evaluation, at this stage, the energy/exergy saving estimation as well as economic/exergoeconomic analysis is performed in an iterative way, screening as many as BER solutions as possible. A first comparison of exergy and exergoeconomic indicators against the baseline might give some insightful information; however, extra analysis is recommended to explore all possible technical and non-technical solutions. At this stage of the process the novel exergoeconomic cost-benefit indicator is useful to locate cost-effective solutions with better thermodynamic performance. With the support of this index, measures with the best performance can be combined in a deep BER design for further exploration.

4.3.3 Optimisation and ranking of possible solutions

However, as a manual exploration can be tedious, the possibility to explore a wider range of design combinations in a time-effective manner can be achieved with the aid of computational tools. Considering that energy-efficient building performance needs to be environmentally-friendly, cost-effective, and more importantly provide occupants with thermal comfort, an optimisation practice based on several objective functions is recommended. These objectives can be related to thermodynamics, user behaviour, economics, or the environment. Optimal solutions will provide optimised parameters based on a trade-off between objectives chosen by the users.

After applying the optimisation process and depending on the algorithm and number of objective functions, there can be more than one optimal solution. To aid the decision making process, a decision support tool is necessary. To cover this, the implementation of 'Multi-criteria decision making' methods to rank Pareto design alternatives based on the practitioner criteria is recommended.

4.4 Summary

With the intention to make the Second Law methodologies more familiar and practical for BER practice, it is important for the proposed decision-making framework to be able to deliver solutions based on cost-effective low-carbon designs, while also maximising occupant thermal comfort and minimising building carbon emissions. However, introducing exergy and exergoeconomic theory into common practice could bring many challenges, as traditional approaches and tools, focusing on primary energy reductions using simple economic evaluations, are well established.

Highly exergy-efficient and cost-effective building designs rely on the practitioner to locate opportunities for improvement and propose measures to reduce exergy destructions footprint. In addition to the literature and theory presented in the Chapters 2 and 3, a more comprehensive calculation framework covering a wider range of building energy subsystems and energy/exergy streams was developed that serves as a basis for a generic exergy and exergoeconomic assessment in buildings. This methodology then was adapted for BER designs.

The proposed enhanced BER framework suggests the integration of exergy analysis at three levels, starting from the diagnosis and auditing of the current building, secondly, the evaluation of several retrofit solutions, and finally, the optimisation and ranking of the best solutions. In addition, exergoeconomic analysis and Life Cycle Cost analysis (LCCA) were combined, allowing the use of exergy and cost accounting in the evaluation of retrofit designs. This combination was achieved by relating energy and cost information in the SPECO method, enabling to deliver a novel return of investment indicator based on exergy (*exergoeconomic cost-benefit index*). Nevertheless, the proposed BER exergoeconomic evaluation method had to be simplified to make it possible to cover different building energy systems designs. Assessing the actual cost of energy streams and the way building systems impact the cost formation process, allows users locate inefficient products and discover opportunities for techno-economic improvement. Integrating the equations in a robust methodology that starts with the data collection and modelling, followed by the retrofit assessment, and finalising in the optimisation and ranking of measures, provides an improvement in the traditional process by providing decision makers with a tool to deliver more thermodynamically-efficient solutions under real economic constraints.

When integrated in a systemic approach, exergy/exergoeconomic analysis is a powerful tool for the optimisation of buildings' energy systems. However, before applying the developed methodology in a case study, the intention is to complement the framework with a building performance computational tool. The tool's objective will be to include several methods such as parametric analysis, optimisation, and decision support methods in order to automate the enhanced BER framework capable to provide final optimal solutions under a time-effective manner.

Chapter 5 ExRET-Opt: A building simulation tool for exergy/exergoeconomic analysis and BER design optimisation

"*Software is like entropy. It is difficult to grasp, weighs nothing, and obeys the Second Law of thermodynamics; i.e. it always increases*"

Normal Ralph Augustine

The concept of exergy and exergoeconomics has been presented as a potential method for BER analysis, but current building modelling tools do not have the capabilities to perform Second Law calculations. ExRET-Opt, a retrofit-oriented modular-based dynamic exergy and exergoeconomic analysis tool has been developed by embedding the calculation method into a typical open-source building simulation tool – EnergyPlus. The aim of this chapter is to show the decomposition of ExRET-Opt, presenting modules, submodules and subroutines used for the tool's development. As the tool relies on a decomposition of several modules, coupling of different software environments was necessary. In addition, the possibility to perform multi-objective analysis for design optimisation and multi-criteria decision for final design selection was included in ExRET-Opt. Optimal designs based on objectives such as, capital cost, life cycle cost, exergoeconomic indicators, carbon emissions, thermal comfort, among others, can be obtained by utilising a Non-Sorted Genetic Algorithm (NSGA-II) combined with Compromise Programming (CP). Therefore, the ExRET-Opt is capable to perform the whole methodological framework presented in the last chapter. Finally, the tool has been validated through an existing steady-state modelling tool and other academic research.

5.1 General overview of ExRET-Opt

ExRET-Opt is a simulation tool that enhances typical building retrofit-oriented tools with the addition of exergy and exergoeconomic analysis and multi-objective optimisation. The tool was developed exclusively for the purpose of this research and is comprised of different methods:

1. Sensitivity and uncertainty analysis for calibration (Latin Hypercube Sampling and Monte-Carlo Analysis)
2. Dynamic energy and exergy analysis (EnergyPlus and the IEA-EBC Annex 49 exergy method)
3. Economic analysis (LCCA, NPV and DPB) coupled with exergoeconomic analysis (Specific exergy cost - SPECO)
4. Multi-objective optimisation based on genetic algorithms (Non-dominated sorting genetic algorithm - NSGA-II)

5. Retrofit solutions ranking by means of Multi-Criteria Decision Making (Compromise Programming based on Chebyshev distance)

Typically, multidisciplinary software environments are needed for the development of retrofit-oriented building simulation tools. Although the development of exergy and exergoeconomic software tools is scarce in the building practice, other sectors, especially industrial processes, have shown the strengths of implementing the Second Law concepts into tools oriented to aid retrofit design of energy systems (Gourmelon et al., 2015). In this research, in addition to exergy and exergoeconomics, multi-objective optimisation coupled with a multi-criteria decision making process has been considered. Therefore, a selection of appropriate modelling environments is essential. ExRET-Opt, consisting of several software subroutines (Figure 5-1), was developed combining different modelling environments such as EnergyPlus, SimLab (SimLab_2.2, 2011), Python (Python_Software_Foundation), and the Java-based jEPlus (jEPlus_1.6, 2016) and jEPlus + EA (jEPlus+EA_1.7, 2016). These software were chosen for four main reasons:

a. Open source software that can be modified and adapted according to the research necessities.
b. EnergyPlus is the most widely used building performance simulation programme in research and industry
c. Python programming language is ideal as a scripting tool for object-oriented system languages, which also supports post-processing analysis by including data analysis packages.
d. All chosen software has the ability to work with text based inputs/outputs which facilitates the communication between the environments.

ExRET-Opt was designed to be modular and extensible (Figure 5-1). This framework gives the possibility to study a wide range of BER measures and optimise designs under different objective functions. The modelling engine is based on different existing modelling environments and five modules specifically developed for this research. These modules are:

Module 1. Input data and baseline building modelling

Module 2. Building model calibration

Module 3. Exergy and exergoeconomic analysis (and parametric study)

Module 4. Retrofit scenarios

Module 5. GA optimisation and MCDM

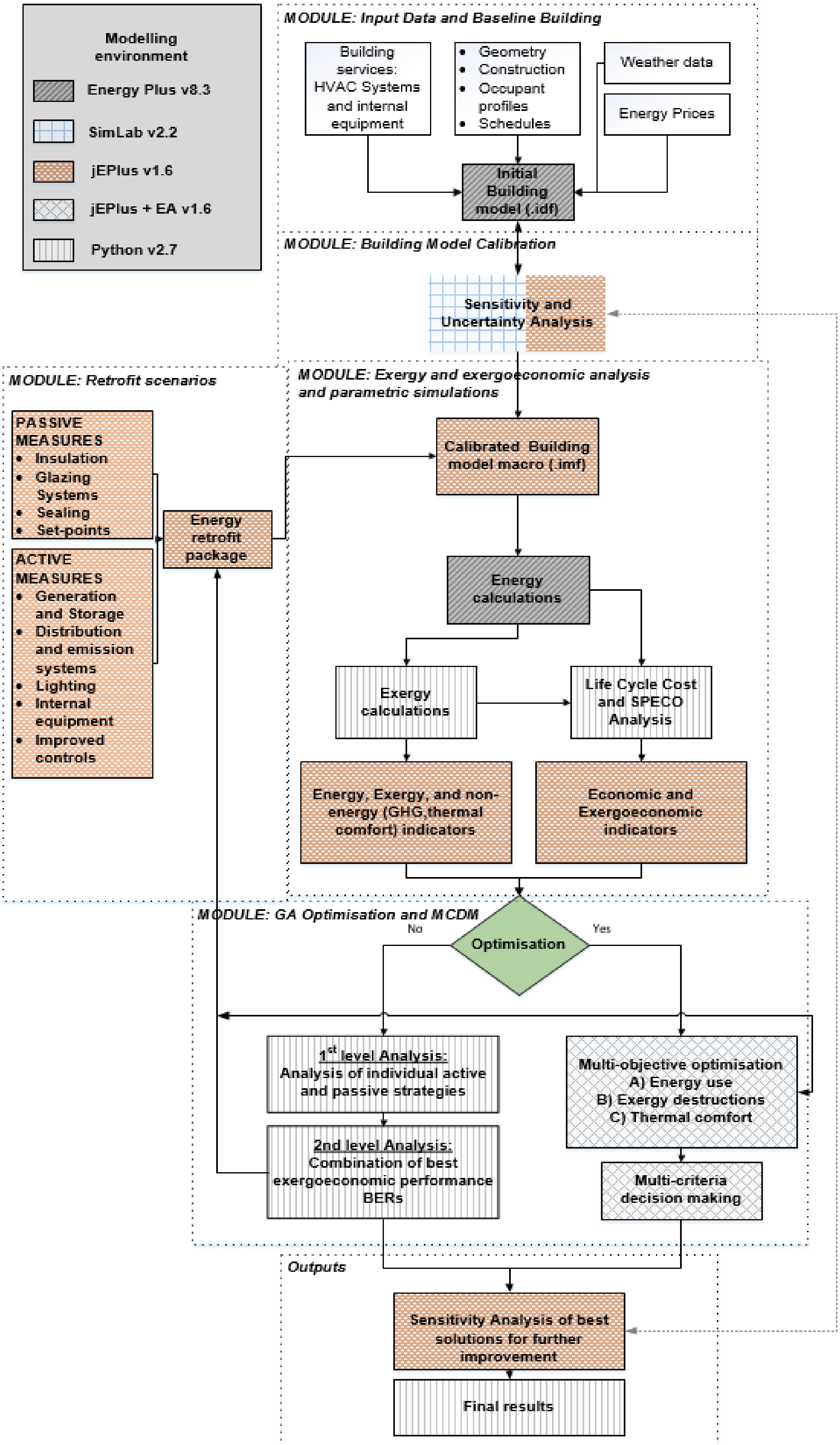


Figure 5-1 Workflow overview: Exergy-based Model for Retrofit Optimisation (ExRET-Opt)

In addition, ExRET-Opt has three operation modes:

Mode I. **Baseline evaluation:** A dynamic energy/exergy analysis and economic/thermoeconomic evaluation is performed to obtain baseline values and benchmarking data.

Mode II. **Parametric retrofit evaluation:** Using a retrofit database, a parametric analysis can be performed for comparison and exploration of a wide range of active and passive retrofit measures.

Mode III. **Optimisation:** Considering a wide range of measures and all possible combinations within the developed retrofit database, based on constraints and objectives given by the user, ExRET-Opt can use a genetic algorithm-based optimisation procedure to search for close-to-optimal solutions in a time-effective manner.

Depending of the operation mode, the tool modules that are active are the following:

Table 5-1 Active modules depending on ExRET-Opt operating mode

ExRET-Opt	Mode I	Mode II	Mode III
Module 1: Input data and baseline building modelling	x	x	x
Module 2: Building model calibration	x	x	x
Module 3: Exergy and exergoeconomic analysis	x	x	x
Module 4: Retrofit scenarios		x	x
Module 5: MOGA optimisation and MCDM			x

Following sections will focus on describing these modules in detail by explaining the simulation process involved and the coupling of different software environments and routines.

5.2 Modules and process description

5.2.1 Module 1: Input data and baseline building modelling

First, a pre-processing phase is involved were data collection, with regards to the building physical characteristics, occupancy profiles, energy systems, weather data, and energy prices, should be carried out in order to construct a pre-calibrated baseline building model. For the buildings' energy modelling, ExRET-Opt has its foundation on EnergyPlus 8.3. EnergyPlus is an interface-less energy analysis and thermal load simulation program, which was developed based on two typical 1990s building simulation tools: BLAST and DOE–2. However, neither BLAST nor DOE–2 were able to realistically model HVAC systems, and thus they were not capable of handling feedback information from the system to the thermal zone(s) conditions. With the development of EnergyPlus, heating and cooling loads, and energy requirements of HVAC systems can be calculated. In addition, its biggest strength for this research is the fact that it works with .txt files, which makes it possible to receive and produce data in a generic text files form, making it easy to create third party add-ins. As shown in Figure 5-2, at this stage of the process only the EnergyPlus environment is required, where the single task is to construct the baseline building model with the gathered information.

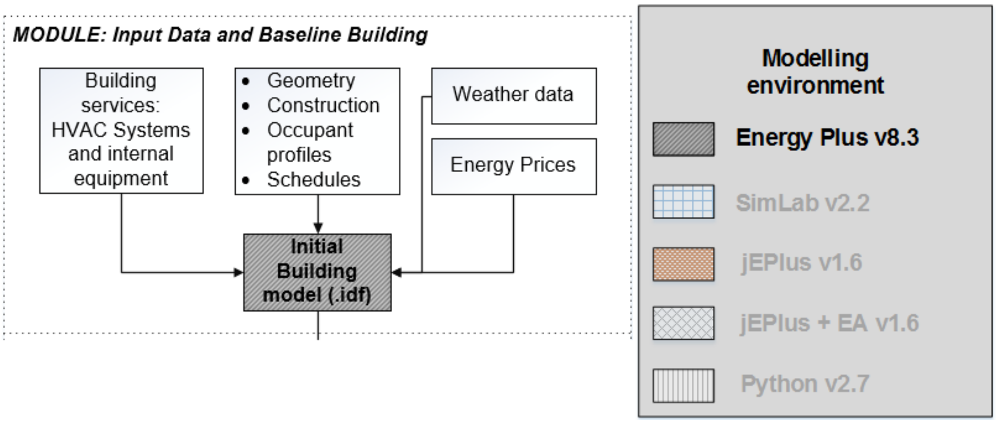
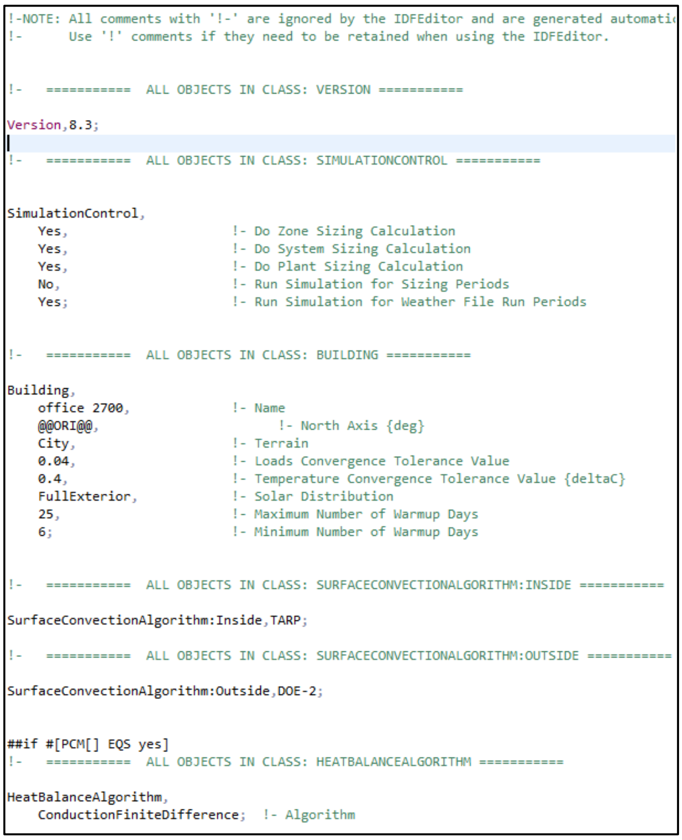


Figure 5-2 ExRET-Opt Module 1 simulation process

Figure 5-3 shows how the building EnergyPlus model (.idf) is represented in the ExRET-Opt interface. At this stage, a first simulation to check errors or misconnections in the model is recommended as ExRET-Opt is only able to work with error-free EnergyPlus files.



```
!-NOTE: All comments with '!-' are ignored by the IDFEditor and are generated automati
!-      Use '!' comments if they need to be retained when using the IDFEditor.


!-   ===========  ALL OBJECTS IN CLASS: VERSION ===========

Version,8.3;

!-   ===========  ALL OBJECTS IN CLASS: SIMULATIONCONTROL ===========


SimulationControl,
    Yes,                     !- Do Zone Sizing Calculation
    Yes,                     !- Do System Sizing Calculation
    Yes,                     !- Do Plant Sizing Calculation
    No,                      !- Run Simulation for Sizing Periods
    Yes;                     !- Run Simulation for Weather File Run Periods


!-   ===========  ALL OBJECTS IN CLASS: BUILDING ===========

Building,
    office 2700,             !- Name
    @@ORI@@,                       !- North Axis {deg}
    City,                    !- Terrain
    0.04,                    !- Loads Convergence Tolerance Value
    0.4,                     !- Temperature Convergence Tolerance Value {deltaC}
    FullExterior,            !- Solar Distribution
    25,                      !- Maximum Number of Warmup Days
    6;                       !- Minimum Number of Warmup Days


!-   ===========  ALL OBJECTS IN CLASS: SURFACECONVECTIONALGORITHM:INSIDE ===========

SurfaceConvectionAlgorithm:Inside,TARP;

!-   ===========  ALL OBJECTS IN CLASS: SURFACECONVECTIONALGORITHM:OUTSIDE ===========

SurfaceConvectionAlgorithm:Outside,DOE-2;


##if #[PCM[] EQS yes]
!-   ===========  ALL OBJECTS IN CLASS: HEATBALANCEALGORITHM ===========

HeatBalanceAlgorithm,
    ConductionFiniteDifference;  !- Algorithm
```

Figure 5-3 Building energy model in an .idf file (text based)

5.2.2 Module 2: Baseline building model calibration

Considering the effects of uncertainties in building energy modelling, as a second step in the modelling process, ExRET-Opt has included a 'calibration module'. As simulation tools are highly dependent on user data entry, SA&UA can be used throughout many stages of the modelling, being 'model calibration' one of them. After defining the model in EnergyPlus (Module 1), both with reference to the thermal envelope and the HVAC system, the parameters that most affect the energy performance should be identified. This selection can be performed after a sensitivity analysis or can be derived from a detailed study of the system; however, the latter requires a satisfactory expertise in the matter of building physics and energy efficiency in buildings.

For the calibration process, a three software process is required (Figure 5-4). Apart from EnergyPlus, both SimLab 2.2 and jEPlus 1.6.0 (jEPlus 1.6, 2016) are necessary. SimLab is a software designed for Monte Carlo (MC) based uncertainty and sensitivity analysis, able to perform global sensitivity analysis, where multiple parameters can be varied simultaneously and sensitivity is measured over the entire range of each input factor. MC methods are widely used for pseudorandom number generation, sampling a set of inputs based on probability distributions. On the other hand, JEPlus is a Java-based open source tool, created to manage complex parametric studies in EnergyPlus.

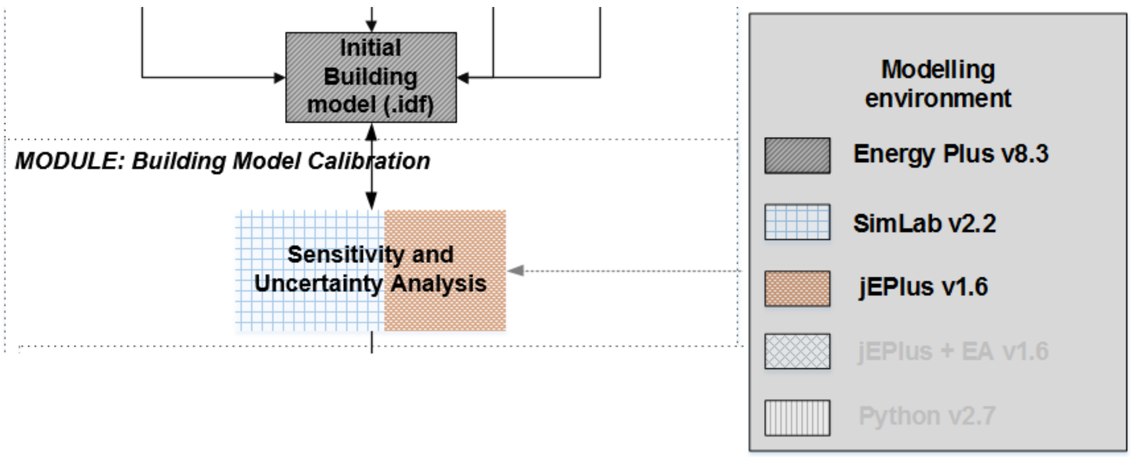


Figure 5-4 ExRET-Opt Module 2 simulation process

Therefore, by coupling these three software, the calibration modelling process is comprised of four main steps (Figure 5-5):

A. definition of inputs and its probability distribution,

B. sample generation using Latin Hypercube Sampling method,

C. simulations run and model output evaluation (estimation of the effect of each input), and

D. model selection

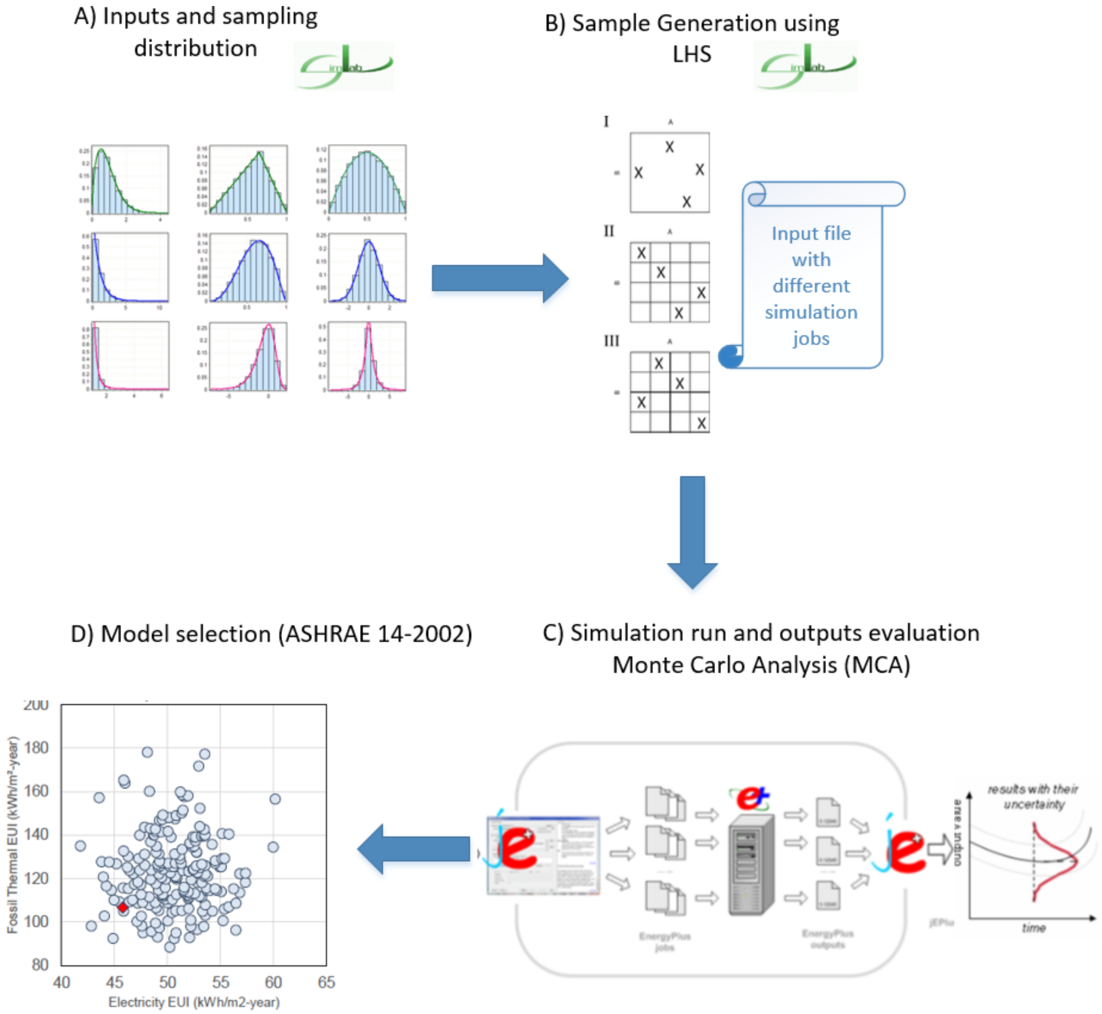


Figure 5-5 Calibration process within ExRET-Opt using SimLab, jEPlus, and EnergyPlus

The sampling method is based on Latin Hypercube Sampling (LHS) in order to keep the number of required simulations at an acceptable level. SimLab creates a spreadsheet with the new sample to be introduced to EnergyPlus. Then, with the aid of jEPlus, ExRET-Opt handles the spreadsheet where the new EnergyPlus building models (idf files) are created. Following, jEPlus passes the jobs to EnergyPlus for thermal simulation, where parallel simulation is available to make full use of all available computer processors.

The most common calibration processes use monthly electricity and gas consumption from the utility bills due to their ubiquitous availability. However, if sub-metered data is available (15-min, 30-min, 60-min), a more accurate calibration model can be obtained. In either case, the final calibrated baseline energy model should meet the requirements of the ASHRAE

Guideline 14-2002: *Measurement of Energy Demand and Savings* (ASHRAE, 2002). According to the guideline, the main indicators used to evaluate models are the Mean Bias Error (MBE) and the Coefficient of Variation of the Root Mean Squared Error (CVRMSE).

MBE is a non-dimensional bias measure between the simulated and the measured data. It calculates the mean difference between empirical and predicted data points:

$$MBE\ (\%) = \frac{\sum_{i=1}^{Np}(m_i - s_i)}{\sum_{i=1}^{Np}(m_i)} \tag{5.1}$$

where m_i is the measured point, s_i is the simulated point, and N_p is the sample size.

CVRMSE is a measure of the variability of the data. The sum of squares is added for each month and divided by the sample mean of measured data. The index allows to determine how the model fits the data:

$$CVMRSE(\%) = \frac{\sqrt{\sum_{i=1}^{Np}(m_i - s_i)^2 / N_p}}{\bar{m}} \tag{5.2}$$

Where $\bar{m}$ is the average of the measured data points. If monthly data is used, an MBE≤5% and a CVRMSE≤15% are sufficient to consider a model calibrated. On the other hand, if hourly data is employed, the requirements are more flexible, with MBE≤10% and CVRMSE≤30%.

5.2.3 Module 3: Energy/Exergy and Exergoeconomic analysis

Undoubtedly, Module 3 can be considered as the most important main routine within ExRET-Opt. This module represents a novel approach as there is a lack of joint dynamic exergy analysis and exergoeconomic evaluations in the current building energy performance simulation tools. The entire modelling process of Module 3 is based on two subroutines: 'subroutine: *dynamicexergy*' and 'subroutine: *exergoeconomics*'. The code of these subroutines is based on the mathematical functions described in the Chapter 4 and were further developed in Python scripts. Python is an interpreted, object-oriented, high-level programming language with dynamic semantics. One of the strengths of Python programming language and the main reason of its integration in this research is its strength to program modularity and code reuse. Miller et al. (2013) outlined the capabilities of using Python for building energy performance simulation and analysis, where adaptability, reliability, and calculation speed were the main advantages. As mentioned before, EnergyPlus is used to perform the First Law or energy analysis. While EnergyPlus in its original format is not capable of performing the Second Law or exergy analysis, its characteristics allow users to easily develop external add-ons. As EnergyPlus has the capability to calculate transient heat conduction through building envelope, using conduction transfer functions, it made it possible to construct a transient energy/exergy analysis subroutine. EnergyPlus is able to deliver detailed transient inputs needed for the dynamic exergy analysis such as building energy demand, primary energy use, indoor and outdoor temperatures, and HVAC/DHW working fluids temperatures, mass, and enthalpies at any location of the system (inputs/outputs required by Module 3 can be seen in Appendix B.1).

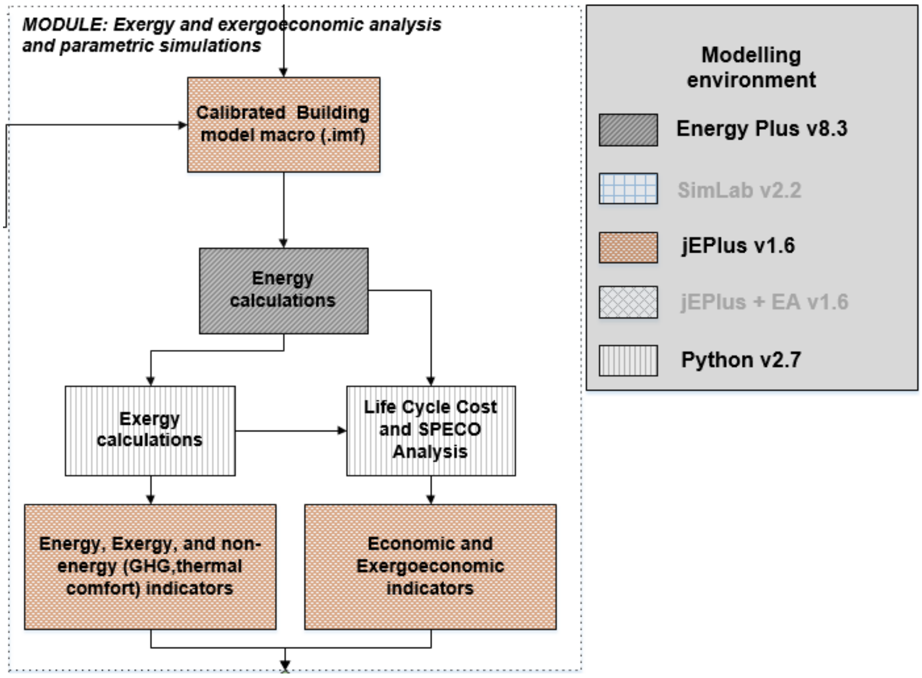


Figure 5-6 ExRET-Opt Module 3 simulation process

Before ExRET-Opt calls the first subroutine, the reference environment has to be specified. As the exergy method only considers thermal exergy, the .epw weather file with hourly data on temperature and atmospheric pressure has to be used. As mentioned in Chapter 4, exergy analysis calculated by the 'subroutine: *dynamicexergy',* performs the analysis in the four different products of the building (heating, cooling, DHW, and electric appliances). This procedure is used to split the typical approach of a single stream analysis into multiple streams' analysis, able to calculate exergy indicators of each product in more detail. Following the end of the first subroutine, the 'subroutine: *exergoeconomics'* is called by ExRET-Opt and finally produces all the needed thermodynamic and thermoeconomic outputs.

5.2.3.1 Integration of exergy-based subroutines into EnergyPlus

For the integration of the subroutines into EnergyPlus, jEPlus is required. JEPlus latest versions provide users with the ability to use Python scripting for running own-made processing scripts, where communication between EnergyPlus and the Python-based exergy model is mainly supported through the use of .rvx files (extraction files data structure represented in JSON format). These files also allow the manipulation and handling of data back and forth among EnergyPlus, Python, and jEPlus. Main parts of the .rvx extraction file that allows communication in ExRET-Opt Module 3 can be seen in Appendix B.2. The developed Python scripts manipulate a series of outputs obtained from EnergyPlus, and then a new set of thermodynamic equations are applied to provide a new set of outputs for jEPlus to handle in the form of spreadsheets. After both, 'subroutine: *dynamicexergy*' and 'subroutine: *exergoeconomics*' are called and calculations are finalised, a new spreadsheet version is obtained with all the required outputs. However, if required, an extra level of calculation can be performed, as JSON programming is available for further integration of mathematical equations. Notwithstanding, the total computational time can become expensive due to the inefficient processing time of JSON code. Nevertheless, the current version of the model is capable of providing 250+ outputs between energy, exergy, economic, exergoeconomic, environmental, and other non-energy indicators. The list of outputs delivered by ExRET-Opt Module 3 can be seen in Appendix B.3. The entire Module 3 process is shown in Figure 5-7.

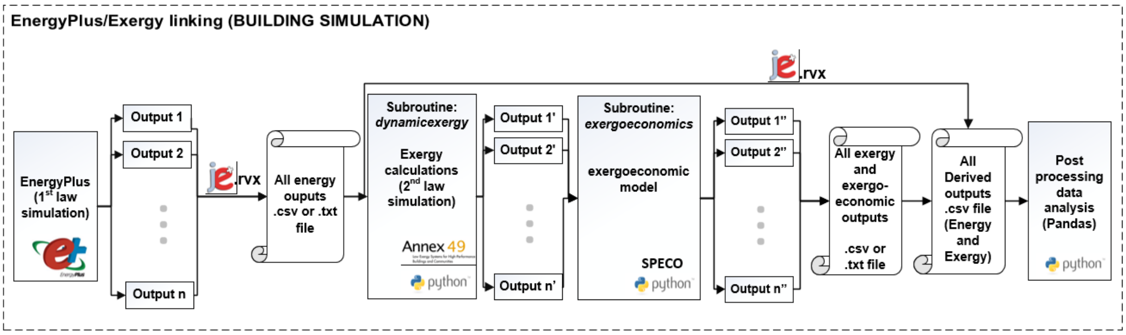


Figure 5-7 Flow of Energy/Exergy co-simulation using EnergyPlus, Python scripting and jEPlus

5.2.4 Module 4: Retrofit scenarios and economic evaluation

The selection of BER measures is complex as it depends on the factors such as location, building age and size, occupants' and client requirements and most importantly, budget allocations and constraints. Over the last decades several measures and technologies have been implemented in buildings to reduce its environmental impact. As building's energy efficiency can usually be improved by both passive and active technologies, a comprehensive BER database including both technology types was compiled as part of the tool (Figure 5-8). Different retrofit measures were designed at each level of the building's energy supply system and building's envelope. This module encompasses a variety of retrofit measures (parameters) typically applied to non-domestic buildings in the UK (CIBSE, 2012, ARUP, 2013).

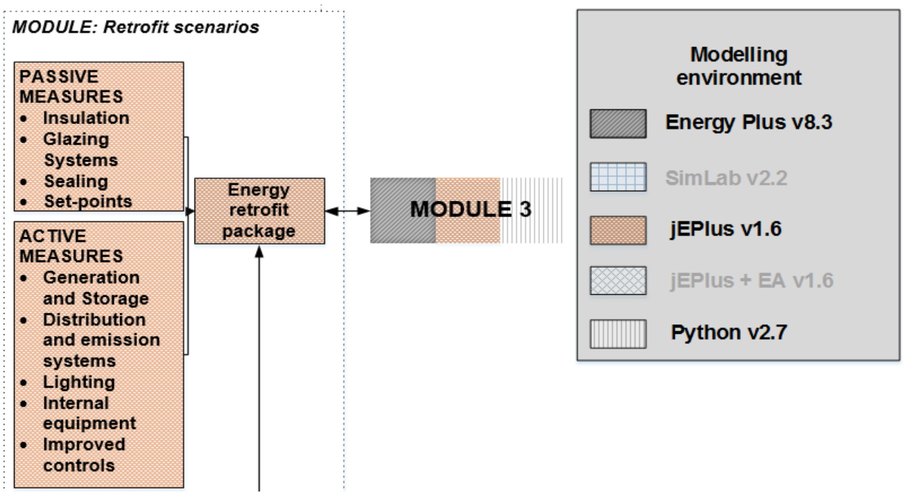


Figure 5-8 ExRET-Opt Module 4 simulation process

The solutions were implemented by developing an individual stand-alone code recognisable ('.idf files') by EnergyPlus. Since the manual evaluation of retrofit measures is not feasible, ExRET-Opt uses parametric simulation to manipulate models, modify building model code, and simulate them. By using the EP-Macro function within EnergyPlus and coupling the process with jEPlus, it is possible to handle these 'pieces of code' and introduce them into the main building model. The internal process of retrofit model construction in Module 4 process can be seen in Figure 5-9.

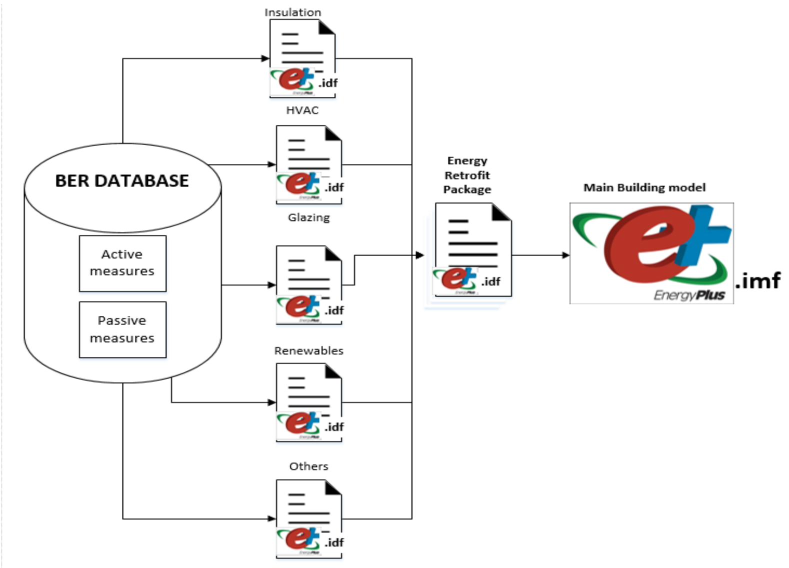


Figure 5-9 Building model construction using ExRET-Opt BER database

This module has the largest embedded database within ExRET-Opt. Each retrofit strategy code has also embedded emission and financial data which allows the environmental and economic evaluation of each measure. The tool includes more than 100 individual energy saving measures for low energy/low exergy retrofitting. ExRET-Opt current version consists of seven retrofit types that can be applied to a building model: a) envelope insulation (roof, wall, ground), b) HVAC systems, c) glazing systems, d) building infiltration measures, e) lighting systems, f) renewable generation systems (solar and wind), and g) set-point controls. To illustrate the database techno-economic variables, Table 5-2 shows the modelled HVAC characteristics. Description of additional active and passive technologies included in ExRET-Opt are presented in Appendix B.4.

Table 5-2 Characteristics and investment cost of HVAC systems

HVAC ID	System Description	Emission system	Cost
H1	*Condensing Gas Boiler + Chiller*	CAV	*Generation systems* • £160/kW Water-based Chiller (COP=3.2) • £99/kW Condensing gas boiler (η=0.95) • £70/kW Oil Boiler (η=0.90) • £150/kW Electric Boiler (η=1.0) • £208/kW Biomass Boiler (η=0.90) • £1300/kW ASHP-VRF System (COP=3.2) • £1200/kW GSHP (Water-Water) System (COP=4.2) • £452/kW ASHP (Air-Air) (COP=3.2) • £2000/kW PV-T system • £27080 micro-CHP (5.5 kW) + fuel cell system Emission systems • £700 per CAV • £1200 per VAV • £35/m² wall heating • £35/m² underfloor heating • £6117 per Heat Recovery system Other subsystems: • £56/kW District heat exchanger + £6122 connection charge • £50/m for building's insulated distribution pipes
H2	*Condensing Gas Boiler + Chiller*	VAV	
H3	*Condensing Gas Boiler + ASHP-VRF System*	FC	
H4	*Oil Boiler + Chiller*	CAV	
H5	*Oil Boiler + Chiller*	VAV	
H6	*Oil Boiler + Chiller*	FC	
H7	*Electric Boiler + Chiller*	CAV	
H8	*Electric Boiler + Chiller*	VAV	
H9	*Electric Boiler + ASHP-VRF System*	FC	
H10	*Biomass Boiler + Chiller*	CAV	
H11	*Biomass Boiler + Chiller*	VAV	
H12	*Biomass Boiler + ASHP-VRF System*	FC	
H13	*District system*	CAV	
H14	*District system*	VAV	
H15	*District system*	Wall	
H16	*District system*	Underfloor	
H17	*District system*	Wall+Underfloor	
H18	*Ground Source Heat Pump*	CAV	
H19	*Ground Source Heat Pump*	VAV	
H20	*Ground Source Heat Pump*	Wall	
H21	*Ground Source Heat Pump*	Underfloor	
H22	*Ground Source Heat Pump*	Wall+Underfloor	
H23	*Air Source Heat Pump*	CAV	
H24	*PVT-based system (50% roof) with supplemental Electric boiler and Old Chiller*	CAV	
H25	*Condensing Boiler + Chiller*	Wall	
H26	*Condensing Boiler + Chiller*	Underfloor	
H27	*Condensing Boiler + Chiller*	Wall+Underfloor	
H28	*Biomass Boiler + Chiller*	Wall	
H29	*Biomass Boiler + Chiller*	Underfloor	
H30	*Biomass Boiler + Chiller*	Wall+Underfloor	
H31	*Micro-CHP with Fuel Cell and Electric boiler and old Chiller*	CAV	
H32	*Condensing Gas Boiler and old Chiller. Heat Recovery System included.*	CAV	
H33*	*Ground Source Heat Pump + Heat Recovery System*	MT Radiators	

5.2.4.1 BER measures capital costs

Cost estimation is one of the major challenges in BER design. To support the economic analysis, prices must be properly defined. Every single retrofit option file has an embedded capital cost and cost of the operation, owning and maintenance, depending on different parameters. Consequently, prices are provided per unit (either kW or by m^2) since the model automatically calculates the total capital price for either individual or combined measures. The cost data were obtained from a wide range of databases such as *Spons* manuals (AECOM, 2015a, AECOM, 2015b), DECC (2015c) and NREL (2015) reports, RSmeans (2015), webstores (Just_Insulation, 2015), and academic publications (Asadi et al., 2014, Shao et al., 2014). The list of technologies, variables, and prices[**] for all retrofit measures are detailed in Appendix B.5. These are the measures that will be implemented in the case studies presented in the following chapters. However, the technology adoption decision should be made under some degree of uncertainty due to some simplification in the data structure and model's limitations. For example, at the moment, the model cannot differentiate between different fixed costs (labour and maintenance costs) across the country or a technological capital cost decrease due to higher adaptation rates.

5.2.4.2 Future energy prices and government incentive programs

Cost accounting for energy projects is a complicated task because of the several methods and assumptions that can be applied. All costs due to the operation depend on the type of financing. As the typical economic analysis is based in NPV and LCC, a future evaluation has to be performed. This involves the specification of important economic parameters such as expected life of the system, initial investment, interest rates, inflation etc. As default values, the ExRET-Opt considers a lifespan of 50 years and a residual value (RV) of 15% for equipment with longer lifespan. An interest rate of 3% is selected based on the UK Green Book: Appraisal and Evaluation in Central Government (HM Treasury, 2003). No inflation rate was assumed. However, all these variables can be modified to investigate different scenarios.

To reduce economic uncertainties even more, several other considerations were included in the model such as future energy prices and government incentives. For specific energy prices, the module considers a present average fuel prices for the corresponding size band, given by the amount of annual energy use. These baseline values can be obtained from the government's bulletin quarterly energy prices (DECC, 2015b). For this particular research, the prices were taken as of September 2015 and consider the Climate Change Levy (CCL)[††].

[**] If prices for some measures were not in local currency (GBP), conversion rates from 25th-October-2015 were considered.
[††] CCL is a tax for some energy sources delivered to non-domestic users where the aim is to incentivise users to install energy efficient technologies.

Table 5-3 shows energy tariffs including CCL for 'small' non-domestic consumers (annual electricity use between 20 - 499 MWh; annual gas use between 278 – 2,777 MWh).

Table 5-3 Energy tariffs for small non-domestic buildings in the UK in 2015 (considering CCL)

Energy source	Prices (£/kWh)
Natural gas	0.030
Electricity (Grid supplied)	0.121
District Heating and Cooling	0.066[‡‡]
Oil	0.054
Biomass (Wood pellets)	0.044

In addition, as the LCCA is based on 50 years, an annual energy price escalation has to be considered. Future energy price is one of the biggest uncertainties in the model and economic outputs have to be treated with caution. Since electrification of the commercial sector is envisioned with the addition of new technologies (e.g. heat pumps) at large scale, it is expected that electricity prices will rise strongly over the coming years; however, the cost of wholesale gas price is more difficult to predict. In any case, the forecast of the future energy prices is a challenge and factors, such as social, political, and economic could have unexpected consequences. However, the effects of policy are more certain and the UK Government estimates that the price per unit of electricity in the non-domestic sector will increase by 43% between 2009 and 2020 (DECC, 2014b). The price escalation for gas and electricity, with the price forecast until 2035, was estimated from the analysis of the past 15 years of energy prices combined with the support of DECC medium forecast scenario and the UK National Grid Future Energy Scenarios Report (National Grid, 2015) (Figure 5-10). However, due to lack of data, a limitation of the current model is that prices from 2035 onwards maintain the same value. Additionally, energy price forecasts for other energy sources are not considered.

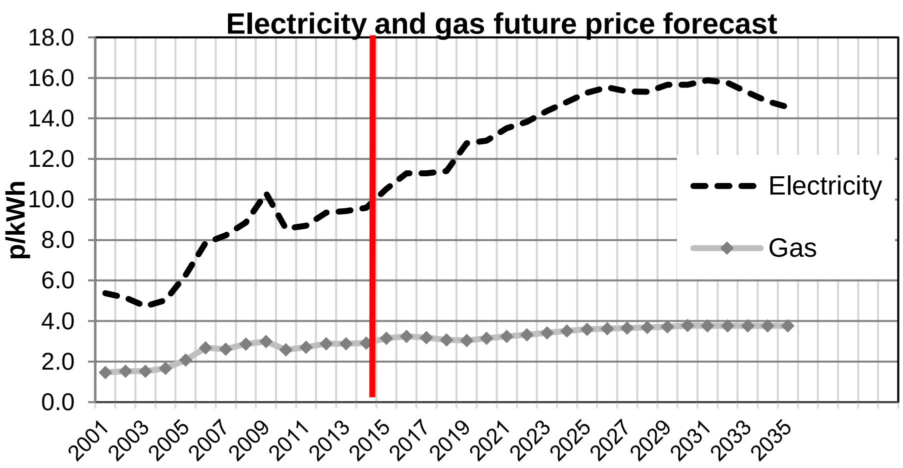


Figure 5-10 Electricity and gas future price estimation in the UK

[‡‡] Prices taken from Shetland Heat Energy & Power Ltd - Lerwick's District Heating Scheme (Commercial tariffs http://www.sheap-ltd.co.uk/commercial-tariffs) Accessed: 15-October-2015

Moreover, government incentives that provide financial help to certain renewable and low-carbon technologies were also included. Depending on the retrofit technology, this could play a major role in the financial viability of some BER designs. The two main government incentives are the Feed-in Tariff (FiT) and the Renewable Heat Incentive (RHI).

FiT, a UK policy mechanism, was introduced in April 2010 with the aim to accelerate the investment and deployment of renewable energy generation technologies. Under FiT, the owner could be paid for the generation and export of renewable electricity. The incentive works in three ways:

1) A generation tariff is provided by the energy supplier on renewable electricity the user generates;
2) An export tariff is provided by the energy supplier for each unit the user exports back to the electricity grid;
3) The user benefits from energy bill savings due to consumption of the on-site generated electricity instead of importing electricity from the grid.

FiT focuses on technologies such as mCHP, hydroelectric plants, wind turbines, and photovoltaic panels. These technologies, except hydroelectric plants, are considered in the BER database. Payments are made over the lifetime of the system and are generally thought to give more confidence and security to consumers and installer businesses.

RHI, introduced in November 2011, is a grant scheme based on a payment system for the generation of heat from renewable energy sources. Unlike FiT that has been implemented on several countries, RHI is the first of its kind. The scheme prioritises technologies such as biomass/biogas heating, ground/water/air-source heat pumps, and solar collectors. Through the non-domestic RHI, for every unit of heat generated, buildings can be paid up to 10p/kWh for hot water and up to 8.7p/kWh for heat. The type of tariff will depend on the selected technology. Whilst these incentives are constantly changing, for the model, tariffs and payments from October 2015 were considered[§§]. However, no fluctuations for future years were considered (Table 5-4).

Table 5-4 FiT and RHI tariffs included in ExRET-Opt. Prices are from September, 2015

Incentive Schemes Tariff	Prices (£/kWh)
FiT Electricity Exported	0.048
FiT PV Electricity Generation	0.059
FiT Wind Electricity Generation	0.138
RHI Solar Heat Generation	0.103
RHI GSHP Heat Generation	0.090
RHI ASHP Heat Generation	0.026
RHI Biomass Heating Generation	0.045

[§§] OFGEM, https://www.ofgem.gov.uk/environmental-programmes/

5.2.4.3 'dynamicexergy' and 'exergoeconomic' subroutine call

After the building model is finally constructed with its corresponding retrofit measures, including its physical, technical, and economic characteristics, a post-retrofit performance and prediction has to be performed. For this, ExRET-Opt Module 3 'subroutine: *dynamicexergy'*, which includes an EnergyPlus simulation plus an energy/exergy analysis, has to be called again. One of the main features of this subroutine is the capability to auto-size equipment. The HVAC system's capacity and costs greatly depend on the building's energy demand, which is in turn influenced by the envelope characteristics, internal equipment, activity type, and set-points. Therefore, the capability to auto-size any primary and secondary HVAC equipment, as well as insulation volumes, glazing surface, and electric/lighting power demand provides precise capital cost for each BER design. Once exergy of inputs and outputs are defined for each subsystem, the annual inefficiency of the building and the building system components can be defined.

After Module 3 'subroutine: *dynamicexergy'* calculates the energy/exergy performance and in order to establish a cost-optimality of the project, the 'subroutine: *exergoeconomics'* is called for post-retrofit economic/exergoeconomic evaluation. Having the whole economic picture, the exergoeconomic and expanded exergoeconomic indicators (Section 4.2.2 and 4.2.3) can finally be explored.

5.2.5 Module 5: Multi objective optimisation with NSGA-II and MCDM

As expected, an analysis of single buildings can be time consuming, and with the integration of Module 3 into a typical building simulation, the model simulation time was increased to double. Modules 3 and 4 have the capability to perform parametric or full-factorial simulations where an automation process of creating and simulating a large number of building models can be done. However, this process has its limitations, mainly depending on time constrains and computing power, making the parametric process impractical to find an optimal solution. In the case of ExRET-Opt, as the retrofit database is composed of more than 100 different measures divided into different technologies, all the possible design combinations that represent the whole design search space is composed of millions of designs. For this reason, the tool has the option of being used with an optimisation module, able to tackle multi-objective problems, reducing computing time, and achieving sub-optimal results in a time-effective manner.

To couple the tool with the optimisation module, a call function is required to automatically call the different generated building models, process the simulation, and return outputs for the subsequent energy/economic and exergy/exergoeconomic analysis. As seen in Figure 5-11, this process is integrated within ExRET-Opt with the help of the Java platform JEPlus+EA. jEPlus+EA provides an interface with little configuration where the necessary controls (population size, crossover rate and mutation rate) are provided in the GUI or can be coded using Java commands. Meanwhile, the communication between platforms was done with the help of the .rvx file (jEPlus extraction file), where, in addition, objective functions and constraints have to be defined.

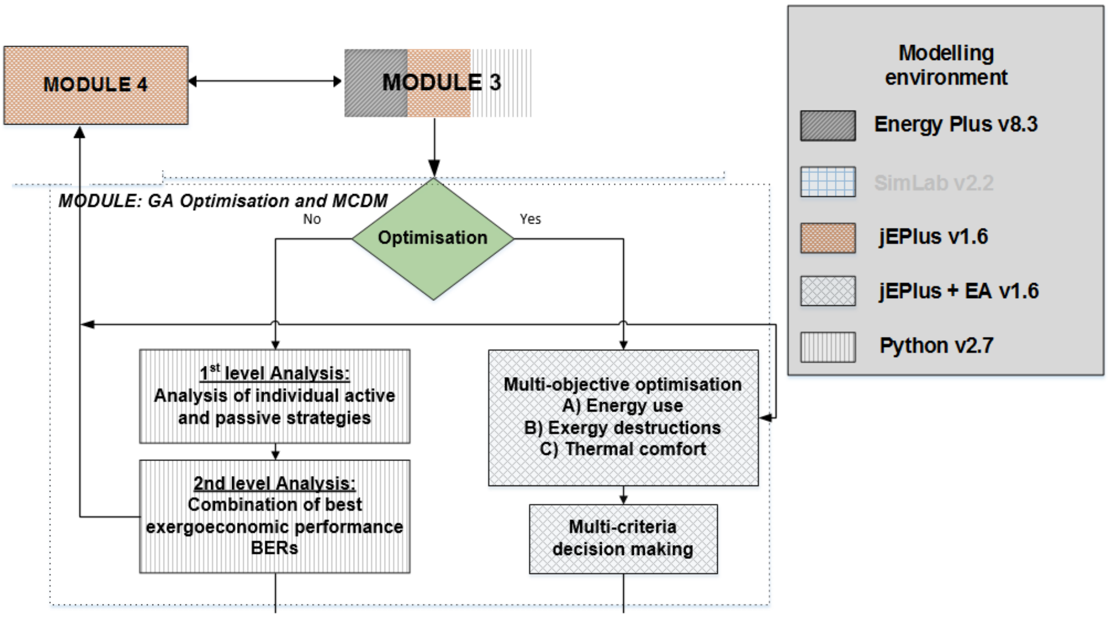


Figure 5-11 ExRET-Opt Module 5 simulation process

The linking makes ExRET-Opt able to tackle multi-objective optimisation by using a Non-Dominated Sorting Genetic Algorithm (NSGA-II). This stochastic method imitates the evolution of species described by Charles Darwin. The algorithm works with a set of individuals, which can represent possible solutions to the problem. In this case, the individuals are the different building models created previously. Each of these individuals (or chromosomes) are composed of a set of genes, which in this case are the different building parameters or retrofit measures $\{X^1, X^2, ..., X^n\}$. The selection of individuals is undertaken through the application of the 'survival of the fittest' principle (Spencer, 1898), which selects the building models that are the closest to the objective functions. More specifically within the tool, the function call converts the vector of X variables into a EnergyPlus (.idf) file. Then, after simulation is performed inside Module 3, jEPlus+EA gathers the outputs of the current population, ranks 'chromosomes' and calculates a uniqueness value related to the distance between each solution and its two closest neighbours. The 'genes' or variables (retrofit options) located in the best chromosomes often go through to the next generation, so building models with similar characteristics have a better chance to be evaluated. For more variability among models, other recombination processes such as crossover and mutation take place to drive better solutions to the next generation, by avoiding the algorithm's focus on only a limited number of parameters. This algorithm process allows a more reliable evaluation of the Pareto frontier. As explained in section 2.2.3.1, Pareto Front is a set of nondominated solutions, being chosen as optimal, if no objective can be improved without sacrificing at least one other objective; additionally, it is a useful technique for reducing a set of candidates prior to further analysis. Finally, the genetic algorithm stops when one of the following criteria is met: (i) the maximum number of generation specified by the user was reached; (ii) the value for the fitness function for the best Pareto point is less than or equal to the fitness limit; or, (iii) the user manually stops the optimisation process. The detailed optimisation algorithm process as well as the modelling environments is shown in more detail in Figure 5-12.

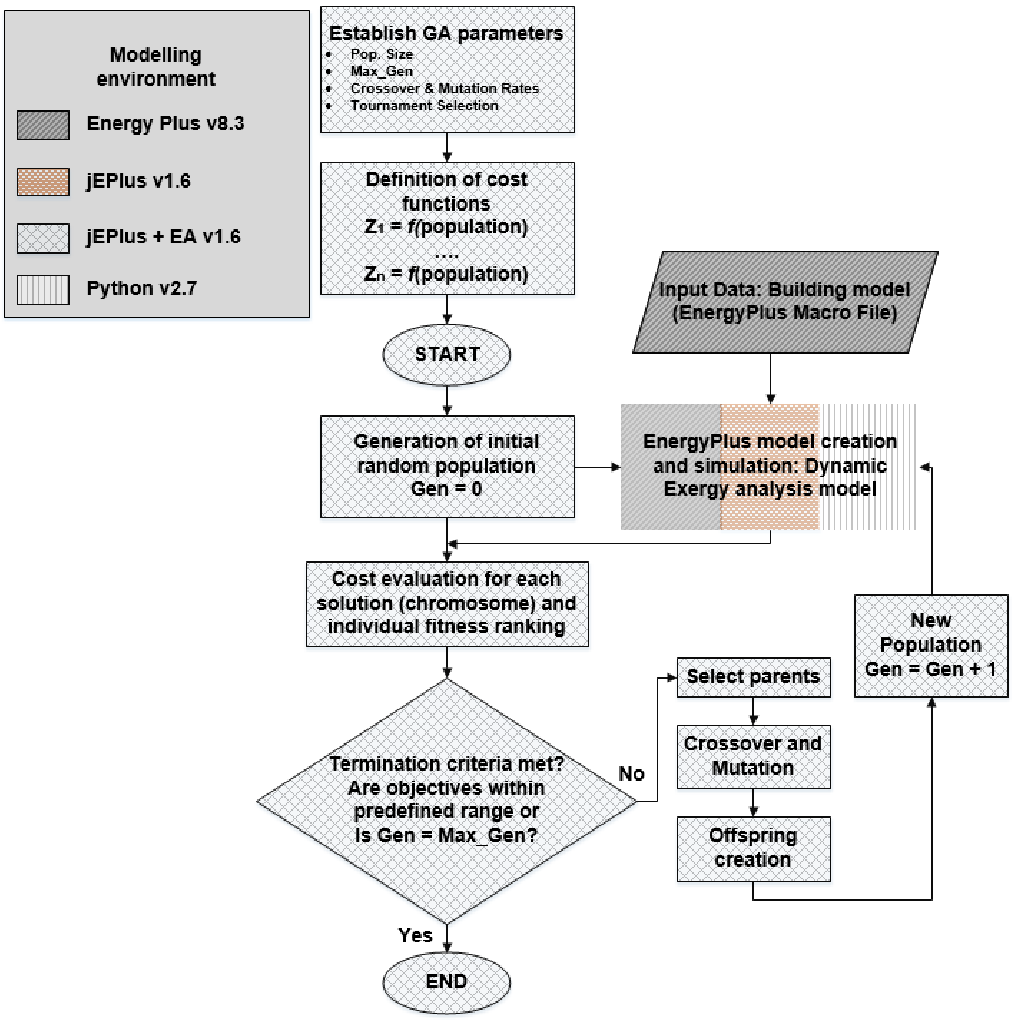


Figure 5-12 Genetic algorithm optimisation process applied to the ExRET-Opt tool.

The advantages of using NSGA-II as the optimisation algorithm, is the ability to deal with large number of variables, ability for continuous or discrete variables' optimisation, simultaneous search from a large sample, and ability for parallel computing (Haupt and Haupt, 2004).

5.2.5.1 Variables

As mentioned, the design variables are represented by single BER options built as macro parameters (Appendix B.5). Each design's variables have a feasible region that represents a feasible design search space.

5.2.5.2 Objective functions

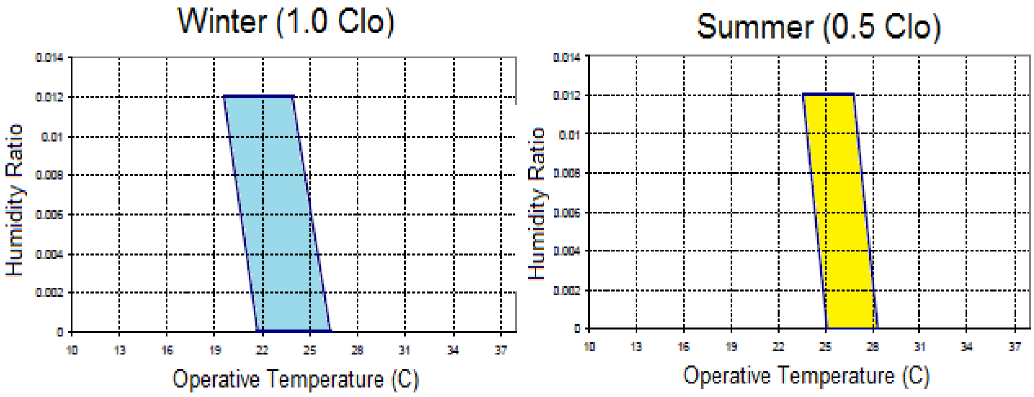
In general, an energy optimisation problem requires at least two conflicting problems. The most common objective function studies are either energy or economic related. By default, the tool handles three objectives specified by the user that have to be satisfied simultaneously. Among primary objectives that this tool sought to handle are the energy use, primary energy consumption, exergy destructions, exergy efficiency, life cycle cost, net present value, and exergoeconomic cost-benefit.

However, as building practice represents a multi-disciplinary problem (CIBSE, 2012), non-thermodynamic objectives were also included within ExRET-Opt. Among a large range of non-thermodynamic indicators that the model could provide, special attention is put on two main indicators for its integration, which the modeller could use as the main constraints or objective functions for optimisation purposes. These are occupants' thermal comfort and carbon emissions. The inclusion of these objectives required extra coding within the scripting files located in Module 3.

a) Occupants thermal comfort

CIBSE Guide F (2012) states the following: *"An energy efficient building provides the required internal environment and services with minimum energy use in a cost-effective and environmentally-sensitive manner. There is, therefore, no conflict between energy efficiency and comfort"*. To account for thermal comfort, two main calculation methods can be used: the heat balance model and the adaptive model. Hence, ExRET-Opt is based on the heat balance model, as the adaptive model is focused on natural ventilated buildings.

Therefore, the model can calculate a value representing the '*Total not comfortable hours during occupied time*' which is extracted from EnergyPlus. This value, based on the ASHRAE 55-2004 method (ASHRAE, 2004), provides the number of hours per year that internal conditions are not in the summer or winter clothes' region. The calculation simplifies the operative temperature to be the average of the air temperature and the mean radiant temperature. It considers the combination of humidity ratio and operative temperature with personal factors (physical, adaptive, and organismic) that will produce acceptable conditions to 80% or more occupants within the entire building. Depending on the humidity ratio, comfortable temperatures in winter are confined between 19.6 °C and 23.9 °C for humid conditions and between 21.7 °C and 26.3 °C for dry conditions. On the other hand, comfortable temperatures in summer oscillate between 23.6 °C and 26.8 °C for humid conditions and 25.1 °C and 28.3 °C for dry conditions. These ranges can be seen in Figure 5-13.



Operative Temp(degC)	Humidity Ratio
19.6	0.012
23.9	0.012
26.3	0.000
21.7	0.000

Operative Temp(degC)	Humidity Ratio
23.6	0.012
26.8	0.012
28.3	0.000
25.1	0.000

Figure 5-13 Winter (Left) and Summer (right) comfort range as established in ASHRAE 55-2004

b) Carbon emissions

For the analysis of CO_2 emissions, the model considers emissions related to the energy use during the building's lifetime operation, thus emissions embodied in technology and materials were neglected in this research. The emission factors for different fuels provided in $kgCO_2e/kWh$ are shown in Table 5-5.

Table 5-5 Emission factors for different energy sources (Pout, 2011)

Energy source	$kgCO_2e/kWh$
Natural gas (Boiler, CHP, District)	0.212
Electricity (grid)	0.522
Fuel oil	0.313
Biomass (Wood pellets)	0.039
PV/T electricity and solar thermal	0.075
Wind electricity	0.038

For future years, based on the UK Future Energy Scenarios document (National Grid, 2011) a future electricity linear decarbonisation was also considered, starting from the current value of 0.522 to a value of 0.222 $kgCO_2e$ /kWh by 2030 and 0.048 $kgCO_2e$ /kWh by the end of the analysis (50 years). The factors for the other fuel types were assumed to remain constant.

5.2.5.3 Problem definition and constraints

Once design variables, objective functions and constraints are set, the multi-objective optimisation problem is defined. Hence, the tool formulates the optimisation problem as follows: *given a N-dimensional decision variable vector x={X^1, X^2,……X^N } in the solution space X, find the vector(s) x* that minimises a given set of three (or more) objective functions:*

$$Z(x^*) = \{Z_1(x^*), Z_2(x^*), Z_3(x^*)\} \tag{5.3}$$

In addition, constraints as objective functions, can be defined from physical values, building characteristics, or other building-related phenomena. The utilisation of constraints is fundamental as it may increase or decrease Pareto optimal solutions.

Box 2 Example of an exergy-based optimisation problem

For example, a typical exergy-based multi-objective optimisation problem can be defined as follows:

Given the three objective functions:

Obj. 1) Building annual exergy destructions (kWh/m²-year)

$$Z_1(x)min = \left\{\sum_i \left[\frac{En_{gen,i}(t_k)}{\eta_{gen,i}(t_k)} * F_{p,source,i} * F_{q,source,i}\right] - \left[F_{q,building} * \sum_i Q_i(t_k)\right]\right\}$$

Obj. 2) Occupant thermal discomfort (Nº. Hours)

$$Z_2(x)min = \left(\left|PMV\right| > 0.5\right),$$

Obj. 3) Discounted payback (years)

$$Z_3(x)min == -\frac{\ln\left[\left((1-(1+i))*\left(\frac{TCI}{R}\right)\right)+1\right]}{\ln(1+i)}$$

Moreover, the two constraints given below could be used to carry out multi-objective optimisation:

Cons. 1) Initial investment cost, as capital costs of BER can be limited by available budget

0.0 ≤ TCI ≤ max. budget

Cons. 2) Maximum of 70% of carbon emission compared to the baseline

*0.0 ≤ CO_2 emissions ≤ ($CO_{2,baseline}$ *0.7)*

Constrains, beside quantifiable criteria, can also be categorised as implicit. For example, given by the natural dimensions of the building, the envelope physical characteristics, or national regulations (e.g. Part L – minimum envelope thermal properties).

5.2.5.4 *Pareto optimal results*

As there is usually no single solution that can satisfy all the objectives in MOO, a Pareto front is always obtained. All of these solutions can be equally satisfactory, unless the decision maker puts more importance on one objective than others. Regardless, the main goal of the tool is to find as many optimal solutions as possible. If the research is based on three objectives, this will create a Pareto surface in a 3D space; therefore, finding solutions becomes more complicated. As ExRET-Opt in optimisation mode lacks a defined GUI the presentation of results is delivered in spreadsheets. In the future, it is intended to implement 3D graphs to explore surfaces and non-convex solutions.

5.2.5.5 *Decision Support Tool: Solution ranking using Multi-Criteria Decision Making*

The Pareto front(s) generated by Module 5 provides the decision maker with valuable information about the trade-offs for the objectives involved. As shown, when the number of objectives is limited to two, the display of the Pareto front can be shown graphically. However, when the number of objectives increases to 3 or more, this task becomes challenging. A method that can be used at this stage is Multi Criteria Decision Making (MCDM). MCDM is used in order to access the qualities of the optimal solutions (in the Pareto Front) and identify and rank an optimal solution from a large space of solutions The typical MCDM process can be seen in Figure 5-14.

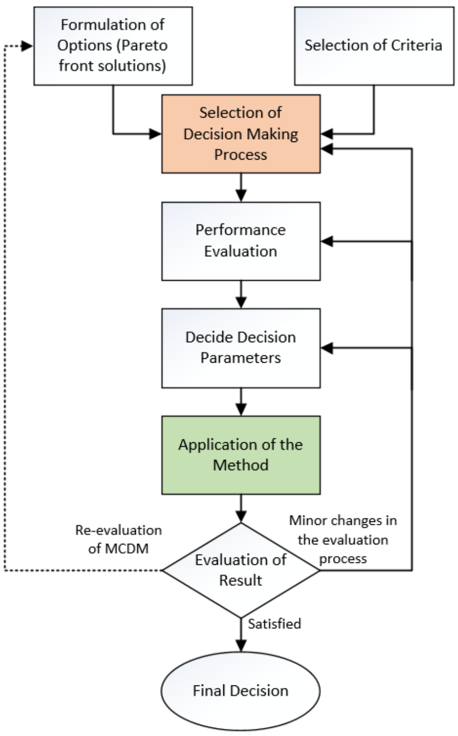


Figure 5-14 Multi-criteria decision process. Modified from Pohekar and Ramachandran, 2004

In ExRET-Opt, MCMD was included as a post-processing external module, where the Pareto solutions have to be exported to an Excel-based spreadsheet. For the MCDM method, Compromise Programming (CP) was selected. CP allows reducing the set of Pareto solutions to a more reasonable size, identifying an ideal or utopian point which serves as a reference point for the decision maker. Thus, the decision model has to be modified by including only one criterion. For this, a distance function has to be analysed to find a set of solutions closest to the ideal point. This distance function is also called Chebyshev distance.

For example, in a two objective problem where it is tried to maximise $\boldsymbol{Z_j(x)}$, let's also define the utopian point as $\boldsymbol{Z_j^*}$ which represents the ideal minimum solution. The degree of closeness between the objective $\boldsymbol{Z_j(x)}$ and its ideal is given by the distance d_j which is calculated as follows:

$$\boldsymbol{d_j = Z_j^* - Z_j(x)} \tag{5.4}$$

On the other hand, if we try to minimise $\boldsymbol{Z_j(x)}$, the calculation is:

$$\boldsymbol{d_j = Z_j(x) - Z_j^*} \tag{5.5}$$

Deviations could be normalised to avoid biases towards objectives. The normalised degrees of closeness measure the percentage of achievement of one objective with respect to its ideal value. Thus, the Chebyshev distance can be defined as:

$$\boldsymbol{d_j} = \frac{\left|Z_j^* - Z_j(x)\right|}{\left|Z_j^* - Z_{*j}\right|} \tag{5.6}$$

Where $\boldsymbol{Z_{*j}}$ is the anti-ideal (nadir) point of the jth objective**.** The normalised degrees $\boldsymbol{d_j}$ are expected to be between 0 and 1. If $\boldsymbol{d_j}$ is 0 it means that it has achieved its ideal solution. On the other hand, if $\boldsymbol{d_j}$ achieves 1, the objective function is showing the anti-ideal or nadir solution. In practical terms, for compromise programming there is a need to know only the relative preferences of the decision maker for each objective. This process can be done by the weighted sum method. The method can transform multiple objectives into an aggregated objective function. The corresponding weight factors (p_{ith}) reflect the relative importance of each objective. This allows the decision maker to express the preferences by assigning a number between 0 and 1 to each objective. However, the sum of weight coefficient has to satisfy the following constraint:

$$\sum_{j=1}^{n} p_j = 1 \qquad (5.10)$$

Therefore, the problem definition for compromise programming results in the following:

$$\alpha_j \geq \left(\frac{\left|z_j^{*}- z_j(x)\right|}{\left|z_j^{*}- z_{*j}\right|}\right) * \left(p_j\right) \qquad (5.11)$$

where a minimisation of the Chebyshev distance α_j is sought. In this definition, weights can be changed to obtain a series of compromised solutions. This can be sought to sample the entire Pareto front and provide the decision maker with different trade-off results. ExRET-Opt MCDM submodule has the capability to scan different weights in 0.1 intervals. Therefore, several solutions can be obtained by varying the weight of the objectives, giving the possibility to the DM to scan through a large number of possible solutions. Finally, is at this stage where ExRET-Opt ends the processing. Further post-processing data analysis is not automated in the simulation framework. However, modules created for this purpose can be developed based on Python or R code for statistical analysis and visualisation. To test a preliminary module, a t-test statistical analysis based on R will be showed in Chapter 8.

5.3 Tool Validation and Verification

To ensure that a modelling tool is reliable, a validation and/or verification process is necessary. Model validation is considered to be a method where a model produces results that represent the real world behaviour; whereas model verification describes the extent to which a model produces results that compare with some alternative method or standard. The former provides a truth connotation, while the latter a reference connotation. There is a big difference between choosing the right equations and solving the equations right. According to Underwood and Yik (2004) there a three general validation and verification methods established to test building energy performance tools. A typical method for model validation is '*Empirical Validation*', where results predicted from the modelling tool are compared to experimental or field monitored data. However, a limitation exists for ExRET-Opt, since an empirical validation cannot be performed due to the lack of experimental/monitored robust and comprehensive building exergy data, because current BMS systems fail to deliver thermodynamic parameters. Nevertheless, other alternatives exist. One of them is '*Inter-model Comparison'*, where results are compared with an alternative modelling tool. This method is useful for bug-fixing but it does not guarantee model consistent calibration. Finally, there is the '*Analytical Verification*', where modelling outputs are compared to mathematically derived solutions, typically found in similar research reports.

As ExRET-Opt outputs come from modelling, both, the '*Inter-model Comparison*' using the Annex 49 pre-design LowEx tool and the '*Analytical Verification*' using various case studies found in the literature, were chosen to perform. However, this can be considered as non-comprehensive as it has the disadvantage of being restricted to a small sample of results. However, while numerical examples of exergy flow calculations are not numerous, three numerical examples, provided by the literature will be shown in the following sections.

5.3.1 Inter-model verification

5.3.1.1 Steady-state exergy calculation tool (LowEx)

First, an Inter-model verification, using the Annex 49 LowEx pre-design tool, was chosen to perform. The last version of this tool, developed to promote exergy analysis among practitioners and researchers, dates back in 2012. It is based on MS Excel calculation spreadsheet, which includes similar equations to those presented in Chapter 3; where the majority were implemented in ExRET-Opt. However, compared to ExRET-Opt, the LowEx tool lacks transient/dynamic calculation as it only relies on a steady state energy balance analysis included in the spreadsheet. Secondly, it only considers heating and DHW as energy end-uses, lacking equations to calculate cooling and electric processes. Nevertheless, with the aim to test Module 3 within ExRET-Opt, steady-state calculations were performed.

For the selection of the case study the LowEx tool is used, which contains numerical examples of real pre-configured building cases. For this task 'The IEA SHC Task25 Office Building' was selected. The steady-state analysis considers a reference temperature of 0 °C and an internal temperature of 21 °C. In order to test different HVAC equipment, the same building with two different HVAC systems was chosen to test: a GSHP and a condensing gas boiler. The case studies input data for both verification tests can be seen in Table 5-6.

Table 5-6 Input data for simulation (Annex 49 pre-design tool pre example building)

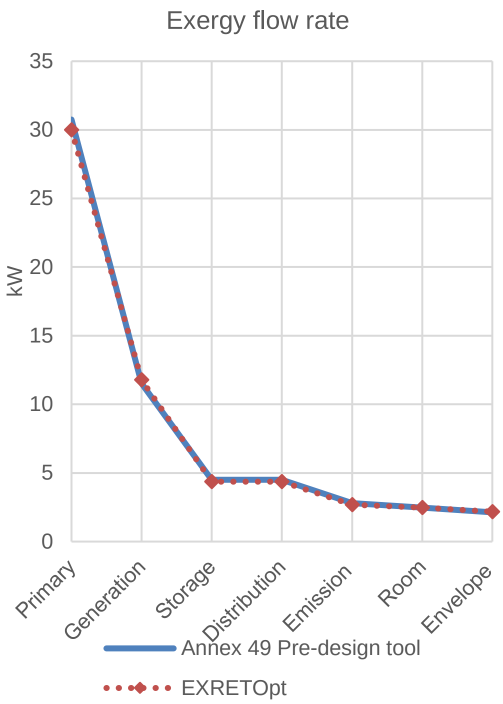
Baseline characteristics A/C Office	**Verification 1**	**Verification 2**
Case study	The IEA SHC Task25 Office Building	The IEA SHC Task25 Office Building
Number of floors	1	1
Floor space (m^2)	929.27	929.27
Orientation (°)	0	0
Air tightness (ach)	0.6	0.6
Exterior Walls	U-value=0.35 (W/m^2K)	U-value=0.35 (W/m^2K)
Roof	U-value=0.17 (W/m^2K)	U-value=0.17 (W/m^2K)
Ground floor	U-value=0.35 (W/m^2K)	U-value=0.35 (W/m^2K)
Windows	U-value=1.10 (W/m^2K)	U-value=1.10 (W/m^2K)
Glazing ratio	32%	32%
HVAC System	GSHP COP=3.5	Condensing Boiler η=0.95
Emission system	Underfloor Heating: 40/30°C	CAV: 35/25°C
Heating Set Point (°C)	20.5	20.5
Cooling Set Point (°C)	--	--
Occupancy (people)	12.5	12.5
Equipment (W/m^2)	1.36	1.36
Lighting level (W/m^2)	2	2

<u>Verification 1 - GSHP:</u> For the case study considering the heat pump, the comparison between the results, provided by the Annex tool and the ExRET-Opt model under steady-state conditions, is given in Table 5-7 . Deviations between outputs were no larger than 5% with similar results in assessing energy supply chain exergy efficiency.

Table 5-7 Comparison of exergy rates results for verification #1

Subsystems	**Annex 49 Pre-design tool**	**ExRET-Opt**	**Difference kW- (Deviation %)**
Envelope (kW)	2.13	2.18	0.05 (+2.3%)
Room (kW)	2.47	2.47	0.00 (0.0%)
Emission (kW)	2.79	2.69	0.10 (-3.6%)
Distribution (kW)	4.51	4.37	0.14 (-3.1%)
Storage (kW)	4.51	4.37	0.14 (-3.1%)
Generation (kW)	11.51	11.77	0.26 (+2.3%)
Primary (kW)	30.75	30.00	0.75 (-2.4%)
Exergy efficiency ψ	0.069	0.072	--

Figure 5-15 shows the exergy flow rate and the exergy loss rate by subsystems. As can be noted, no larger differences exist, and the model under steady-state conditions performs well.



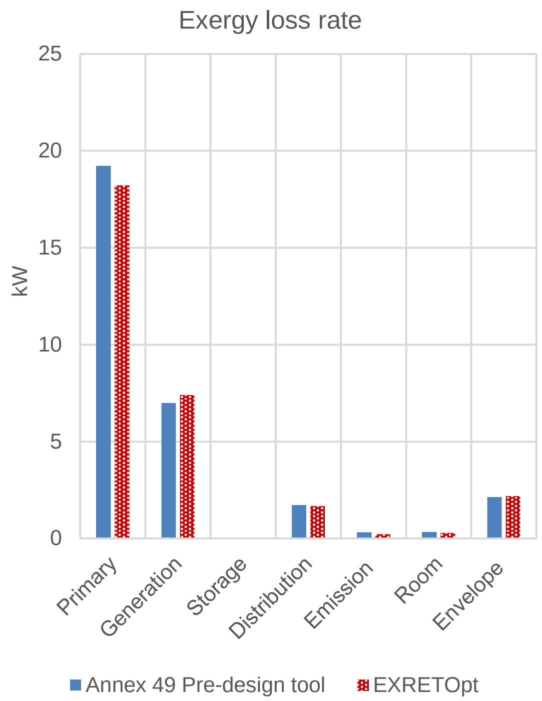


Figure 5-15 Comparison of exergy flow rates and exergy loss rates by subsystems for Verification #1.

Verification 2 - Condensing boiler: The second steady-state evaluation was performed using a different HVAC system (condensing boiler). Table 5-8 reports the comparison between the tools' outputs. However, the results show larger discrepancies compared to the first verification process.

Table 5-8 Comparison of exergy rates results for verification #2

Subsystems	Annex 49 Pre-design tool	ExRET-Opt	Difference kW- (Deviation %)
Envelope (kW)	2.14	2.91	0.77 (+35.9%)
Room (kW)	2.12	2.82	0.70 (+33.0%)
Emission (kW)	2.31	2.88	0.57 (+24.6%)
Distribution (kW)	3.05	2.88	0.17 (-5.6%)
Storage (kW)	3.05	2.88	0.17 (-5.6%)
Generation (kW)	30.24	32.71	2.47 (+8.2%)
Primary (kW)	33.26	33.82	0.56 (+1.7%)
Exergy efficiency Ψ	0.064	0.086	--

Nevertheless, when looking at Figure 5-16, the models present similar behaviours, where some parameters, especially regarding the quality factors, are different. This is because the LowEx tool is based on German standards, where the natural gas quality factor is taken as 0.92, while the ExRET-Opt is based on British guidelines, where the quality is 0.94, affecting directly the exergy analysis of the generation subsystem. If the same factor is utilised, the exergy rate at the generation subsystem is found at 30.78 kW, presenting a deviation of just

1.7%. Although the largest deviation percentage is in the last part of the supply chain (emission, room, and envelope), the absolute values are minimal.

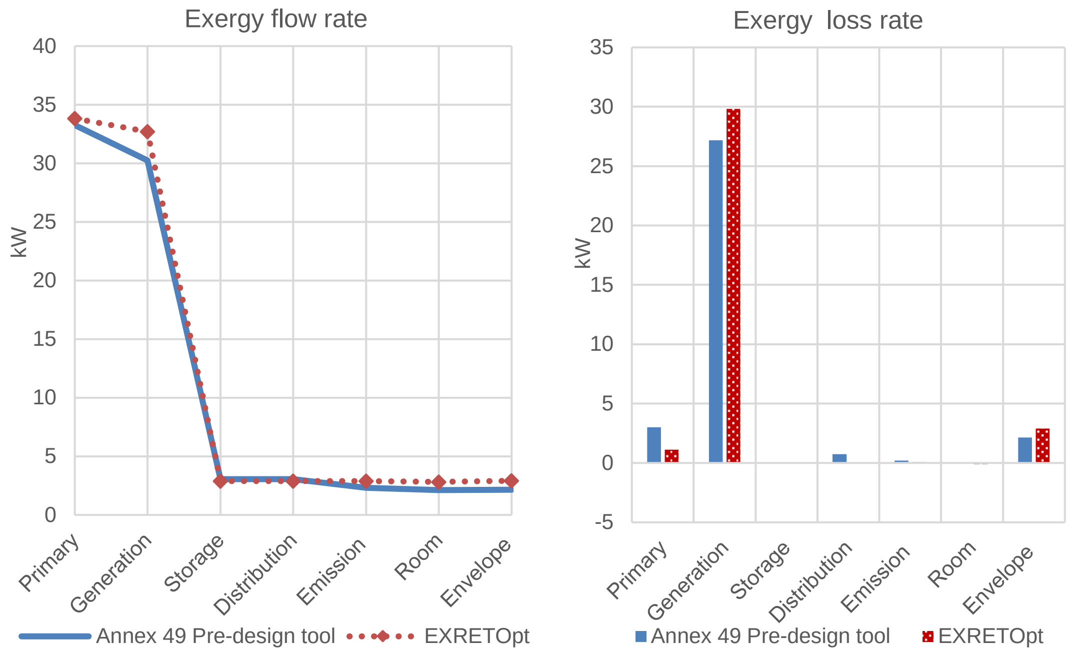


Figure 5-16 Comparison of exergy flow rates and exergy loss rates by subsystems for Verification #2

By looking at both inter-models' verification, it can be concluded that ExRET-Opt under steady-state calculation presents comprehensive results for different HVAC system configurations.

5.3.2 Analytical verification of subroutines

For the analytical verification of the tool, ExRET-Opt is compared against two numerical examples from the literature. The intention of this analysis is to verify the two Module 3 subroutines separately ('subroutine: *dynamicexergy'* and 'subroutine: *exergoeconomics')*. Although the research in dynamic exergy and exergoeconomic analyses is limited, two highly cited articles can be relied on. Sakulpipatsin et al. (2010) work can be used to verify the dynamic exergy analysis outputs and Yücer and Hepbasli (2014) work to verify exergoeconomic outputs.

5.3.2.1 Dynamic exergy analysis verification

Sakulpipatsin et al. (2010) presented an exploratory work showing the application of dynamic exergy analysis in a single-zone model. These dynamic calculations were implemented in TRNSYS dynamic simulation tool. The strength of this particular research is the calculation of both heating and cooling outputs, which are going to be used for verification. The case study building is a cubic-box with a net floor area of 300m^2 spread along 3 stories. The heating system is based on district heating supplying hot water at 90 °C. The cooling system is based on a small-scale chiller with a COP of 1.5. Both systems supply the thermal energy to a low-temperature heating/high-temperature cooling panels. For the reference temperature, the De Bilt, Netherlands weather file is used. The full input data of the building can be seen in Table 5-9.

Table 5-9 Input data for analytical verification of 'subroutine: *dynamicexergy* within ExRET-Opt

Baseline characteristics A/C Office	Verification
Case study	Office building
Location	De Bilt, Netherlands
Number of floors	3
Floor space (m²)	300
Orientation (°)	0
Air tightness (ach)	0.6
Natural ventilation rate (m3/h)/m3	4
Exterior Walls	U-value=0.511 (W/m²K)
Roof	U-value=0.316 (W/m²K)
Ground floor	U-value=0.040 (W/m²K)
Windows	U-value=1.300 (W/m²K)
Glazing ratio	42.5% (south façade only)
HVAC System	Heating: District Heating, T: 90 Cooling: Small Chiller COP: 1.5 (In both cases, distribution pipes have a temperature drop of 10 °C)
Emission system	Low temperature Heating: 35/28°C High Temperature Cooling: 10/23 °C
Heating Set Point (°C)	20
Cooling Set Point (°C)	24
Occupancy (people)	30 (75 W per person)
Equipment (W/m²)	23
Lighting level (W/m²)	1.33

Table 5-10 compares two groups of data (heating and cooling) between the research data and the ExRET-Opt outputs. The results show the exergy demand at each part of the supply chain, considering auxiliary energy for the HVAC system components. The corresponding differences in absolute value and in percentage are also shown. Results show that ExRET-Opt was capable of accurately predicting the heating exergy performance of the system. In the cooling case, larger deviations' percentage can be noted, mainly due to lower values, where small absolute value discrepancies can represent larger deviations. If compared to the heating case, the absolute values for cooling are much lower. However, considering the fact that different weather files were used, the outputs seem reasonable. Nevertheless, exergy efficiency values were rather similar. As can be noted, the lower efficiency of the cooling case is due to the utilisation of electricity for the chiller to produce cold water.

Table 5-10 Comparison of annual exergy use results for analytical verification of ExRET-Opt

	Sakulpipatsin et al. (2010)	**ExRET-Opt**	**Difference - (Deviation %)**
Heating case Subsystems			
Building (kWh/m^2-y)	5.66	4.51	1.15 (-20.31%)
Emission (kWh/m^2-y)	16.17	13.93	2.24 (-16.6%)
Distribution (kWh/m^2-y)	19.57	16.46	3.11 (-15.9%)
Primary Generation (kWh/m^2-y)	33.03	33.78	0.75 (+1.14%)
Exergy efficiency Ψ	0.171	0.133	--
Cooling case Subsystems			
Building (kWh/m^2-y)	0.17	0.37	0.20 (+117.6%)
Emission (kWh/m^2-y)	0.25	0.80	0.55 (+220.0%)
Distribution (kWh/m^2-y)	0.33	0.88	0.55 (+166.6%)
Primary Generation (kWh/m^2-y)	2.63	4.39	1.76 (+66.9%)
Exergy efficiency Ψ	0.065	0.060	--

5.3.2.2 Exergoeconomics verification

In the literature, no comprehensive example of a dynamic exergy analysis, combined with an exergoeconomic analysis, applied to a building, exists. However, Yücer and Hepbasli (2014) performed a steady-state exergy and a SPECO exergoeconomic analysis of a building's heating system. The limitation of this research is that the exergy outputs are presented for just one temperature, neglecting the dynamism of an actual ambient reference. For this reason, a steady-state exergy calculation was also performed. For the case study, a house accommodation of 650 m^2 was considered. The reference environment is taken as 0 °C, with an internal temperature of 21 °C. The HVAC system is composed of an oil boiler that provides hot water to panel radiators to finally heat the room. Solar and internal heat gains have been neglected. The characteristics of the case study can be seen in Table 5-11.

Table 5-11 Input data for analytical verification of subroutine: exergoeconomics within ExRET-Opt

Baseline characteristics A/C Office	Verification
Case study	House accommodation building
Location	Izmir, Turkey
Number of floors	3
Floor space (m²)	650
Orientation (°)	0
Air tightness (ach)	1.0
Natural ventilation rate (m3/h)/m3	--
Exterior Walls	U-value=0.96 (W/m²K)
Roof	U-value=0.43 (W/m²K)
Ground floor	U-value=0.80 (W/m²K)
Windows	--
Glazing ratio	--
HVAC System	Heating: Oil Boiler, T: 110 °C (Distribution pipes have a temperature drop < 10 °C)
Emission system	Radiator panels Heating: 35/28°C
Heating Set Point (°C)	21
Cooling Set Point (°C)	--
Occupancy (people)	--
Equipment (W/m²)	--
Lighting level (W/m²)	--

However, another limitation exists for the exergoeconomic analysis, as the authors have reduced the subsystems' analysis from seven to just three: generation, distribution, and emission subsystems. Since the capital cost of the subsystem is essential for this analysis, it is provided in Table 5-12.

Table 5-12 Components capital cost of the building HVAC system

Subsystems	Capital cost ($)***
Distribution pipes	3,278
Radiator panels	5,728
Steam boiler	13,810
Envelope	3,959

The exergy price of the fuel is fundamental for exergoeconomic analysis as is it the product price entering the analysed stream. While only the heating mode is analysed, oil used for heating is the only energy source utilised. As the energy quality for oil is set at 1.0 (Table 4-3),

*** Monetary values (USD) given as per original source both the energy price and exergy price are similar (0.096 $/kWh). Table 5-13 summarises the results for this verification.

Table 5-13 Comparison of exergy rates results for subroutine: exergoeconomics verification

Subsystems	Yücer and Hepbasli (2014)	ExRET-Opt Exergy analysis	Difference (Deviation %)
Envelope (kW)	3.78	3.11	0.67 (-17.7%)
Room (kW)	11.93	8.13	3.80 (-31.9%)
Emission (kW)	12.61	13.20	0.61 (-4.6%)
Distribution (kW)	17.15	18.09	0.94 (+5.5%)
Generation (kW)	82.38	94.98	-12.60 (+15.3%)
Primary (kW)	107.09	101.44	-5.65 (-5.3%)
Exergy efficiency (Ψ)	**0.035**	**0.031**	--

First, a comparison of the steady-state exergy analysis was done to ensure that exergy values are within acceptable range. Some deviations were found, with the greatest at the room air subsystem (31.9%). However, as the deviations for the other subsystems are lower and the overall exergy efficiency of the whole system is similar, the obtained results seem acceptable.

Table 5-14 shows the verification of the exergoeconomic outputs for the reduced system analysis.

Table 5-14 Exergoeconomic comparison between Yücer and Hepbasli (2014) and ExRET-Opt

Subsystems	Yücer and Hepbasli (2014) Exergoeconomic analysis			ExRET-Opt Exergoeconomic analysis			Difference (Deviation %)		
	C, product $/kWh	Z $/h	C, fuel $/kWh	C, product $/kWh	Z $/h	C, fuel $/kWh	C, product $/kWh	Z $/h	C, fuel $/kWh
Generation	0.096	0.46	0.628	0.096	0.44	0.327	0.00 (0.0%)	0.02 (-4.3%)	0.301 (-48.1%)
Distribution	0.628	0.07	0.861	0.327	0.07	0.726	0.301 (-48.1%)	0.00 (0.0%)	0.135 (-15.7%)
Emission	0.861	0.17	0.925	0.726	0.18	0.812	0.135 (-15.7%)	.01 (+5.9%)	.0113 (-12.2%)

Cost of fuels and products at each stage of the energy supply chain presented a similar increase trend. However due the simplicity of the approach by Yücer and Hepbasli (2014), a great part of exergy destruction cost is not accounted correctly. On the other hand, ExRET-Opt calculates the exergy cost formation throughout the whole thermal energy supply chain.

Figure 5-17 shows the stream cost increase comparison. The exergy cost formation increase is due to the system inefficiencies in the energy supply system with high volumes of exergy destructions. At each stage, an amount of economic value is added to the energy stream when it passes the energy supply chain. Yücer and Hepbasli (2014) found that the final product cost had a value of 0.925 $/kWh, while ExRET-Opt calculated a final product value of 0.812 $/kWh.

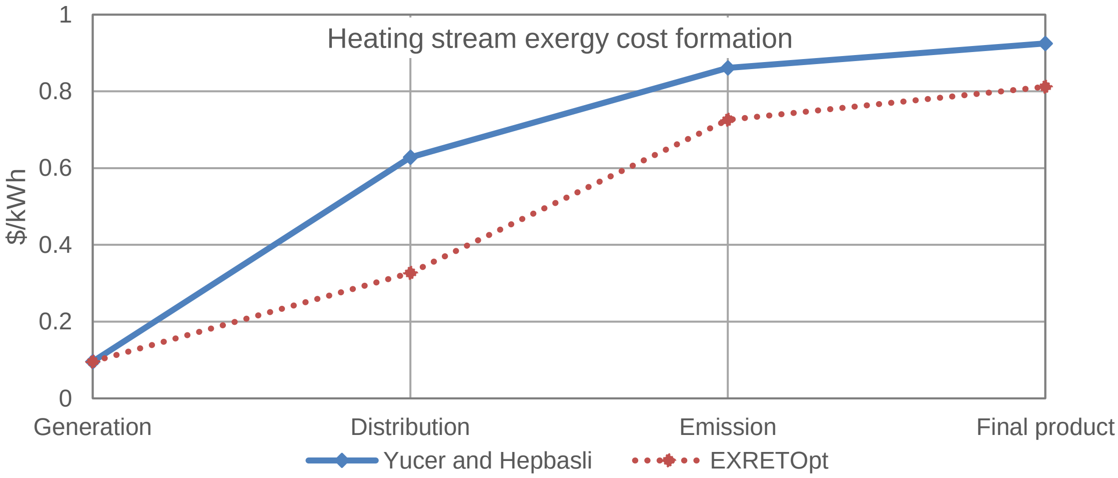


Figure 5-17 Exergoeconomic cost increase of the stream

Although the graph shows a similar behaviour, the deviations can be related to several factors. One is that ExRET-Opt performs the calculation for a supply chain composed of 7 subsystems, so exergy formation is more detailed and considers inefficiencies of different type of equipment. Another factor, is that the author does not mention the number of hours that the equipment is working, which affects the capital cost rate ($\dot{Z}$) and thus affects the exergy cost formation of the stream. However, final cost deviation was only found at 12.2%.

5.4 Summary

This chapter presented ExRET-Opt, a retrofit-oriented simulation tool, which has become a part of EnergyPlus in performing exergy and exergoeconomic balances. The addition was done thanks to the development of external Python-based subroutines, interacting with the typical simulation tool, with the support of the Java-based software jEPlus. The tool was developed with the intention to support the enhanced BER methodological framework presented in the last chapter.

ExRET-Opt, apart from providing the user with exergy data and pinpointing sources of inefficiencies along the energy supply chain, gives the possibility to perform a comprehensive exploration of a wide range state-of-the-art building energy technologies, with the intention to minimise energy use and improve thermodynamic efficiency of existing buildings. The retrofit technologies include high and low temperature HVAC systems, envelope insulation technologies, insulated glazing systems, efficient lighting, energy renewable generation technologies, and set-points control measures. Moreover, integration of exergoeconomic analysis and multi-objective optimisation into EnergyPlus allows users to perform a comprehensive exergoeconomic optimisation similar to those found in the optimisation of chemical or power generation processes. It means that the indicators, such as energy, exergy, economic (capital cost, NPV), exergoeconomic, and carbon emissions combined with occupants' thermal comfort, can be used as constraints or objective functions in the optimisation process. With the development of ExRET-Opt, several new additions to the knowledge were provided.

I. A dynamic building exergy simulation modelling supported by EnergyPlus.

II. An exergoeconomic analysis module linked to building energy performance simulation.

III. Exergoeconomic-based multi-objective optimisation and multi-criteria decision making methods applied to buildings.

The limited availability of robust and comprehensive test data has restricted the application of full validation tests to the results of energy simulation programs. However, an inter-model and an analytical verification was performed. By reviewing different existing exergy tools and exergy-based research, the calculation process of the two main subroutines, developed for this tool, was verified with acceptable results.

Finally, from a research point of view, using the tool for real case studies will provide with new insights into the thermodynamic behaviour of different buildings and the impact of different design combinations, including active and passive energy systems. Although the presented framework has been restricted to BER design, it can be easily transferrable to the early design stage of new buildings with some minor modifications in the overall process. The applicability of the methodological framework and ExRET-Opt (with its different modes) will be illustrated in the next three chapters through different case studies.

Chapter 6 Exergy and exergoeconomic analysis of non-domestic building archetypes and a BER parametric study

In this chapter, the proposed retrofit framework and simulation tool is applied to demonstrate its usefulness and robustness in retrofit-oriented research and practice. The case studies concern two UK non-domestic archetypes: primary school and air conditioned office. In addition to performing an exergy/exergoeconomic evaluation on the baseline case studies, a retrofit parametric study is performed, exploring a wide range of active and passive solutions. The application of the newly developed cost-benefit exergoeconomic factor combined with exergy, energy use, occupant thermal comfort, and life cycle cost indexes, serve as basis to account for the best performance technologies, and to further develop deep retrofit packages. This study differs from currently existing ones in the following ways:

I. dynamic exergy analysis is applied to non-domestic buildings by using a newly developed physics-based simulation tool,

II. a robust exergoeconomic analysis is conducted, examining the whole building energy supply chain (including the building's envelope), to obtain a series of benchmark values,

III. and, an impact assessment of the different retrofit strategies and the development of new building energy systems designs, based on the proposed exergoeconomic indicator, is provided.

6.1 Description of the case studies: UK non-domestic archetypes

The concept of an archetype is an abstract model that generalises the characteristics of a particular building type, and represents variability in a building's stock, by parameterising construction elements, components, design features, and occupancy/usage. Two building research areas need to be investigated in order to build comprehensive archetypes for energy modelling: a) building physics (geometry, form, thermal properties), and b) building energy systems (building services, HVAC systems). There is plenty of evidence to believe that building's energy systems, envelope characteristics, activity, and building's service efficiency have an effect on energy use (Korolija et al., 2013a). According to Dineen and Gallachoir (2011), the basis of the archetype approach is to calculate baseline data using the engineering method based on technical factors, such as floor area, glazing area, envelope thermal properties, HVAC system characteristics, and occupant behaviour. The selection of an optimal retrofit measure depends on several of these factors. Archetype models have been used in numerous research to quantify their current level of energy use and potential for retrofit application, with the possibility for screening a wide range of technologies individually or combined (Hernandez et al., 2008, Chidiac et al., 2011a).

For the development of the archetypes used in this study, research in the UK's context is taken into consideration. The case studies selected for this chapter are two representative UK's non-domestic building archetype models: a primary school and an air-conditioned office. The buildings belong to two-subsectors in the UK, which have an annual energy demand larger than 200 PJ (Pout et al., 2002). The types of analysed buildings were chosen for comparative purposes and to perform an analysis for both heating and cooling processes (A/C Office). Also, due to more complex energy systems found in non-domestic buildings, exergy and exergoeconomic analysis could present more meaningful results than those applied to the building-scale domestic energy systems.

6.1.1 Case study #1: Primary school archetype

The form and geometry of the selected archetype is based on the baseline designs for primary schools developed by the UK Education Funding Agency (EFA, 2014). These designs demonstrate good practice and are based on the departmental guidelines for area planning (Figure 6-1). According to Steadman's classification (Steadman et al., 2000a, Steadman et al., 2000b), a primary school of these characetristics can be regarded as a 'daylit cellular' building.

Figure 6-1 Primary school archetype layout (left) and 3-D rendering (right). Source: EFA, 2014

The simulation model consists of a fourteen-thermal zone building, distributed over two storeys. The largest proportion of the floor area is occupied by classrooms, staff offices, laboratories, and the main hall. Other minor zones include corridors, bathrooms, and other common rooms. Heating is provided by means of conventional gas boiler and high temperature radiators (80°C/60°C) with no heat recovery. As no artificial cooling system is regarded for this archetype, natural ventilation is considered during summer months. Appendix C.1 contains detailed technical information of the building model. A schematic layout of the building system and subsystems is illustrated in Figure 6-2.

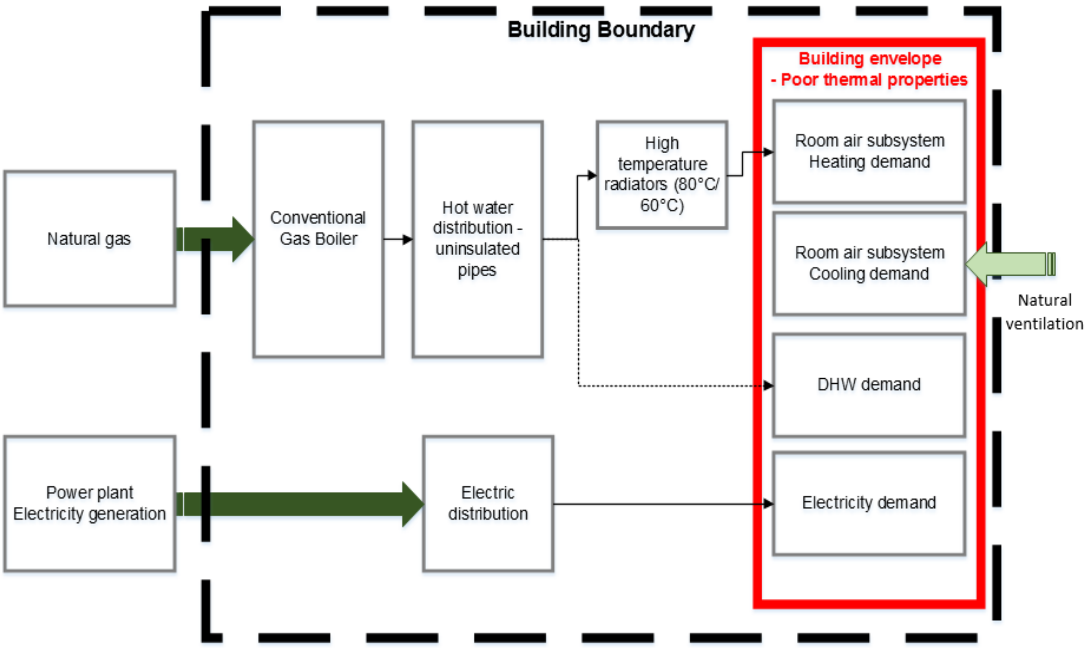


Figure 6-2 Schematic layout of the energy system for the Primary School base case

6.1.2 Case study #2: Air-conditioned office archetype

For the office case, an archetype developed by Korolija et al. (2013a) is used. The model consists of an open-plan office based on two thermal zones per floor, spread over three storeys (Figure 6-3). As the previous analysis of this model showed high homogeneity between the areas, fewer thermal zones were analysed compared to the primary school archetype. This archetype consists of only office areas and common areas (including bathrooms and kitchen) on each of the three floors.

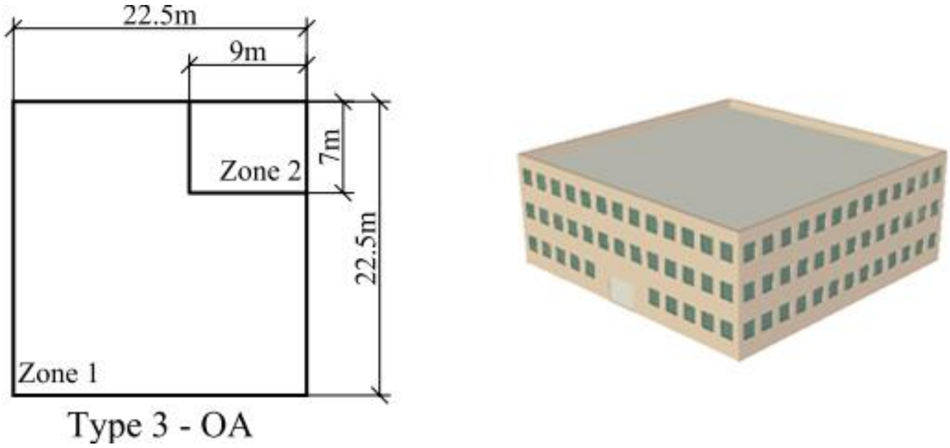


Figure 6-3 A/C office archetype layout (left) and 3-D rendering (right). Source: Korolija et al. 2013

The HVAC system includes a conventional gas boiler for heating, and hot water and an air-based chiller (COP: 2.0) to meet the cooling requirements. The air distribution system is composed of Constant Air Volume (CAV) fan-coil units. Appendix C.2 contains detailed technical information on the building model. A schematic layout of the building system and subsystems is illustrated in Figure 6-4

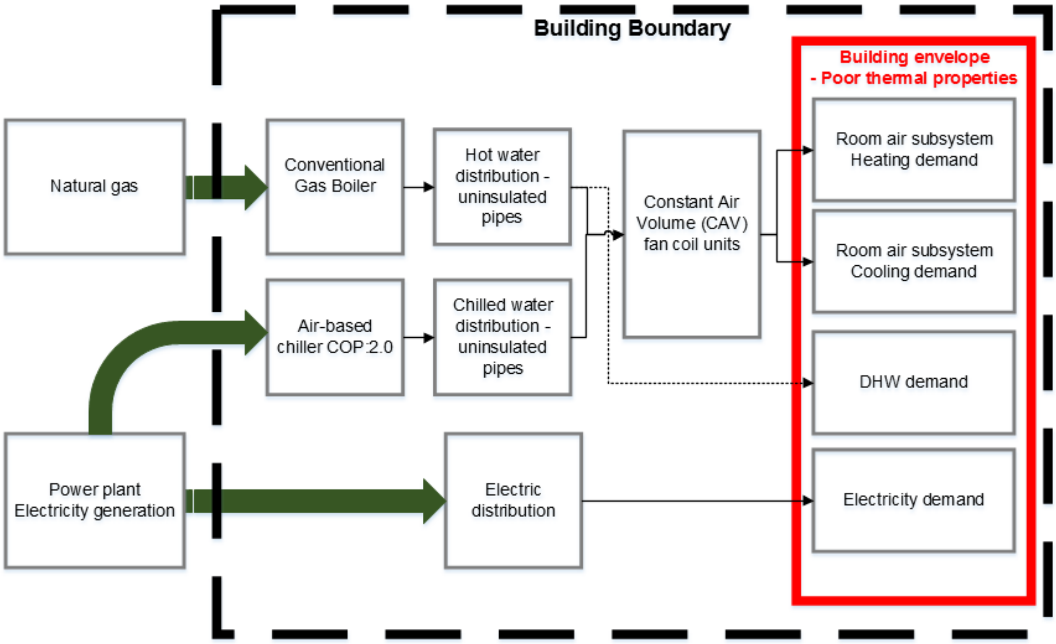


Figure 6-4 Schematic layout of the energy system for the A/C/ Office base case

6.1.3 Other building properties

For both archetypes, minimum fabric thermal values from the 1985 UK Building Regulations (DEWO, 1985) were considered for the envelope thermal characteristics. As a result, it is assumed that all model's façade characteristics have the same levels of U_{values}, infiltration, type of glazing and G_{values}.

Other model variables, such as thermostat temperatures, infiltration, and interior equipment, were based on ASHARE and CIBSE Guides. As schedules, occupancy patterns, and internal gains from people have a large impact on the modelling outputs, in this regard the document ASHRAE 90.1-2010 (ASHRAE, 2010) reference guide was used to build the models. This includes standardised occupancy diversity factors for different building types. Furthermore, additional information was derived from the U.S. Department of Energy (DOE) commercial reference buildings (Deru et al., 2011). As an example of the diversity of the models, typical weekday occupancy from the studied buildings is illustrated in Figure 6-5.

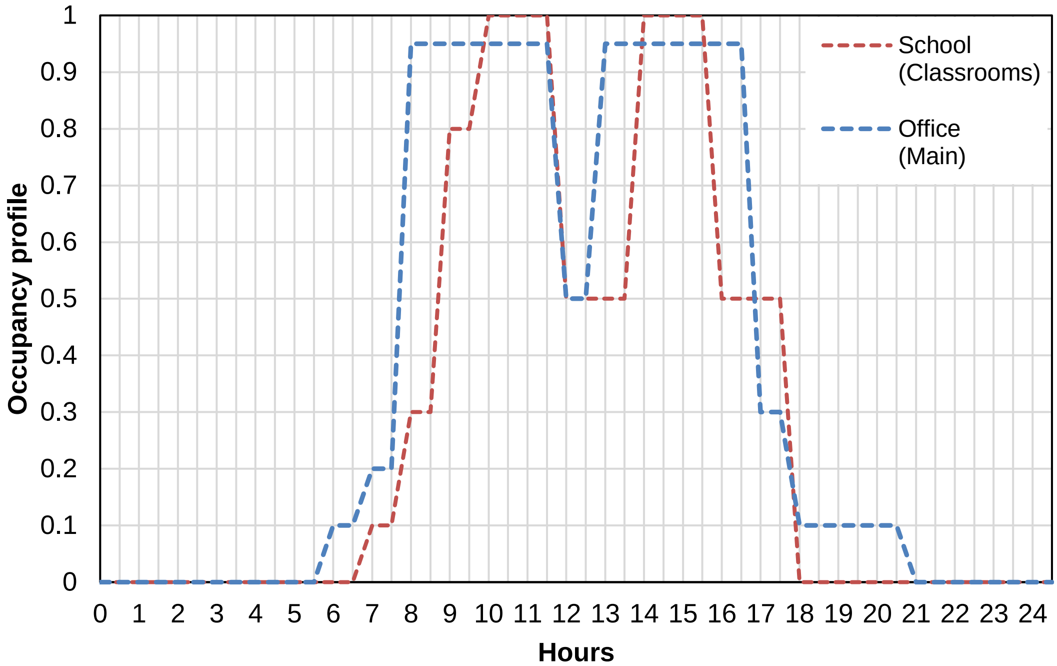


Figure 6-5 Main areas weekday typical occupancy profile for both case studies

However, both Appendix C.1 and C.2 show a detailed load assumption and weekly occupancy profiles for each zone. Relevant weather data for London was taken from the TMY2 format weather files (the London-Gatwick) used in the energy simulation process and thus employed as the reference temperature for exergy analysis.

6.2 Model simulation, calibration, and baseline values

After the development of the initial building model, which is related to Module 1 within ExRET-Opt, the next step is to calibrate the model in order to obtain thorough baseline values. However, the challenge in a calibration process is the complexity and the number and type of parameters that have to be analysed, which typically requires to have significant domain expertise (O'Neill and Eisenhower, 2013).

As the modeller has to make many assumptions for inputs that are unknown or hard to measure, and can have a significant impact on outputs, a comprehensive calibration procedure is performed. For the parameter variation and simulation, some numerical parameters are chosen to remain constant, while others are selected as uncertain. Based on the research from Daly et al. (2014), which examines the sensitivity of hard-to-measure simulation inputs on total predicted building energy use, eight parameters that have a significant impact on energy consumption were sampled: 1) lighting power density, 2) equipment power density, 3) building orientation, 4) envelope thermal conductivity, 5) air tightness, 6) occupant density, 7) set-point controls, and 8) HVAC system efficiency. To create an exhaustive sample of buildings, with the help of ExRET-Opt Module 2 in which SimLab 2.2

is embedded, the Latin-hypercube sampling method (McKay et al., 1979) is used to create two hundred building cases.

From the numerous outputs that can be available to calibrate the models, the calibration analysis is limited to two outputs; electricity and gas use. These two outputs characterise all the energy consumed by the building. To ensure that both models' predicted energy use is realistic, these are calibrated to the national mean values for electricity and gas use, presented in different research, which used thousands of Display Energy Certificates (DEC) of non-domestic buildings located in England and Wales (Godoy-Shimizu et al., 2011, Hong and Steadman, 2013, Armitage et al., 2015a).

Godoy-Shimizu et al. (2011) performed a bottom-up analysis of 7,155 primary school buildings' DECs. After analysing the results, the author found that the provided national CIBSE benchmarks underestimated the mean for the electricity use and overestimated the mean gas use. The report found that the national mean values stand at 44 kWh/m² for electricity and 140 kWh/m² for fossil thermal fuel. On the other hand, Armitage et al. (2015b) analysed 2,600 offices' DECs. In this case, also CIBSE benchmarks underestimated the mean values for both energy sources. Results show that air-conditioned offices have a mean value of 155 kWh/m² for electricity and 132 kWh/m² for fossil thermal fuel.

6.2.1 Calibration results

Figure 6-6 and

Figure 6-7 illustrates all the two-hundred simulated buildings (in blue) and the selected baseline model (in red) for both the primary school and office archetype respectively. The selected model is chosen due to its relative proximity to the national mean values. However, for comparative purposes, values for the 75th percentile are also shown. The final baseline building's main characteristics for both models are presented in

For the office case, the mismatch between the simulation models and the national mean value is lower than in the school case. In this case, models tend to have a better performance suggesting that assumed physical properties and systems' performance are slightly better than in the average A/C office, suggesting a poor sub-sector performance.

Table 6-1. A more detailed explanation of the physical and technical characteristics can be found in Appendixes C.1 and C.2.

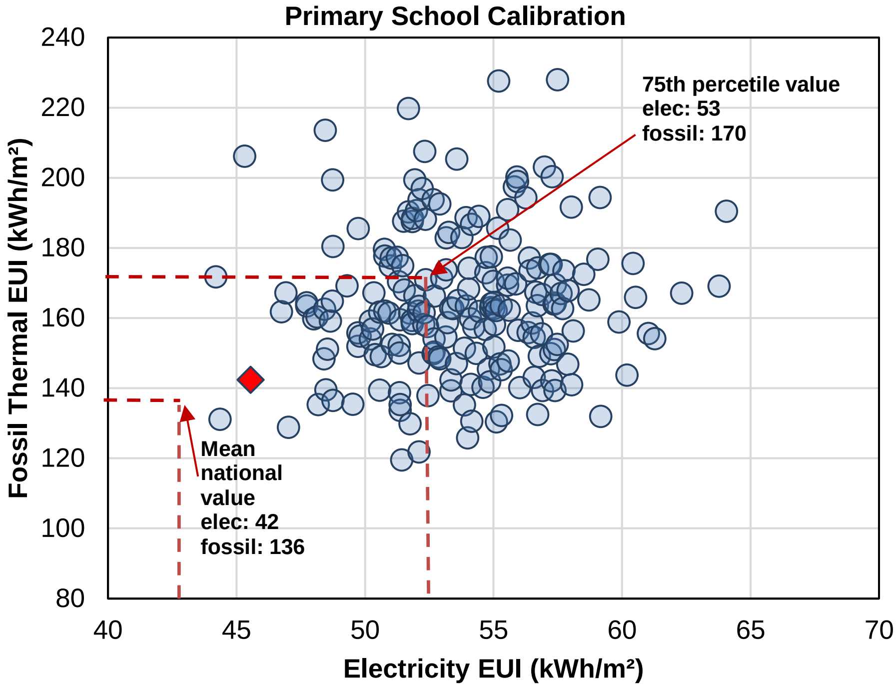


Figure 6-6 **Simulation from LHS cases and final model selection (in red). Primary School**

For the school case, there is a mismatch between majority of the simulation models compared to the national mean value. In this case, it can be concluded that assumed building physical properties (1985 building regulations) and systems' performance are worse than real values found in the average UK primary school. As shown in the graph, majority of models are closer to the 75th percentile value. Nevertheless, the model has been calibrated using national mean values.

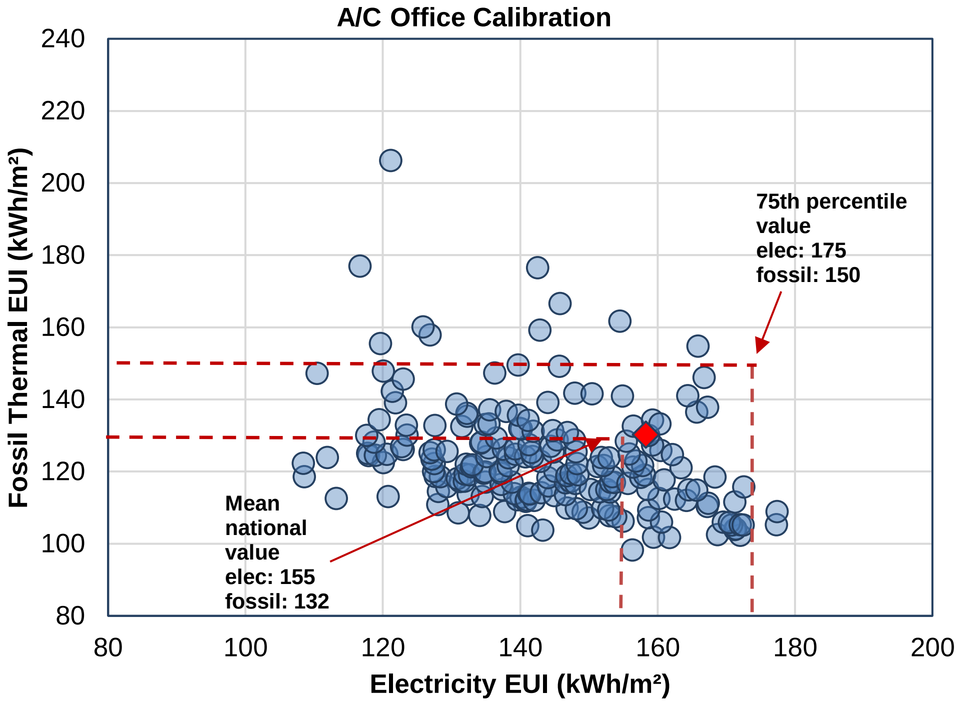


Figure 6-7 Simulation from LHS cases and final model selection (in red). A/C Office

For the office case, the mismatch between the simulation models and the national mean value is lower than in the school case. In this case, models tend to have a better performance suggesting that assumed physical properties and systems' performance are slightly better than in the average A/C office, suggesting a poor sub-sector performance.

Table 6-1 Case studies baseline characteristics

Baseline characteristics	Primary School	A/C Office
Year of construction	1960s	1960s
Number of floors	2	3
Floor space (m^2)	1,990	2,590
Orientation (°)+	227	31
Air tightness (ach) +	1.0	1.0
Exterior Walls+	Cavity Wall-Brick walls 100 mm brick with 25mm air gap U-value=1.66 (W/m^2K)	Cavity Wall-Brick walls 100 mm brick with 25mm air gap U-value=1.61 (W/m^2K)
Roof+	200mm concrete block U-value=3.12 (W/m^2K)	200mm concrete block U-value=3.12 (W/m^2K)
Ground floor+	150mm concrete slab U-value=1.31 (W/m^2K)	150mm concrete slab U-value=1.31 (W/m^2K)
Windows+	Single-pane clear (5mm thick) U-value=5.84 (W/m^2K)	Single-pane clear (5mm thick) U-value=5.84 (W/m^2K)
Glazing ratio	28%	41%
HVAC System+	Gas-fired boiler 515 kW η = 0.82 No cooling system	Gas-fired boiler 750 kW η = 0.70 Air-cooled Chiller 272 kW COP=2.0
Emission system	Heating: HT Radiators 90/70°C Cooling: Natural ventilation	Heating: CAV 80/50°C Cooling: CAV 7/12°C
Heating Set Point (°C) +	19.3	21.9
Cooling Set Point (°C) +	--	24.0
Occupancy (people/m^2)+*	2.1	8.2
*Equipment (W/m^2)**+	2.0	14.9
*Lighting level (W/m^2)**+	12.2	21.4
EUI electricity (kWh/m^2-y)	45.6	158.3
EUI gas (kWh/m^2-y)	142.3	130.2
Annual energy bill (£/y)	19,449	59,625
Thermal discomfort (hours)	1,443	1,413
CO2 emissions (Ton)	214.8	285.6

*Just for main areas. School: Classrooms and Staff offices. A/C Office: Open plan office space

+Calibrated parameters

A detailed analysis of energy and economic baseline values is presented in the following section. In addition, baseline exergy and exergoeconomic values are presented in Section 6.2.3.

6.2.2 Baseline energy and economic values

6.2.2.1 Energy indicators

I. Primary school energy use

The school's EUI or operational energy is found at 187.9 kWh/m²-year (2.2% higher than national mean value); with gas as the main energy source (75.7%). By end-use, heating represents 58.1% of the total energy demand, meaning that a calculated 515 kW gas fired boiler uses 781.7 GJ/year of natural gas. This is followed by 238.2 GJ/year for DHW (17.7%) and 59.0 GJ/year of electricity for interior lighting (13.7%). Fans, mainly used for mechanical cooling and extraction also have an intensive use, demanding 66.1 GJ/year, representing 4.9% of the total energy demand. Figure 6-8 presents a detailed end-use of monthly energy use by square meter. Low consumption can be seen during the summer months due to limited activities in the building.

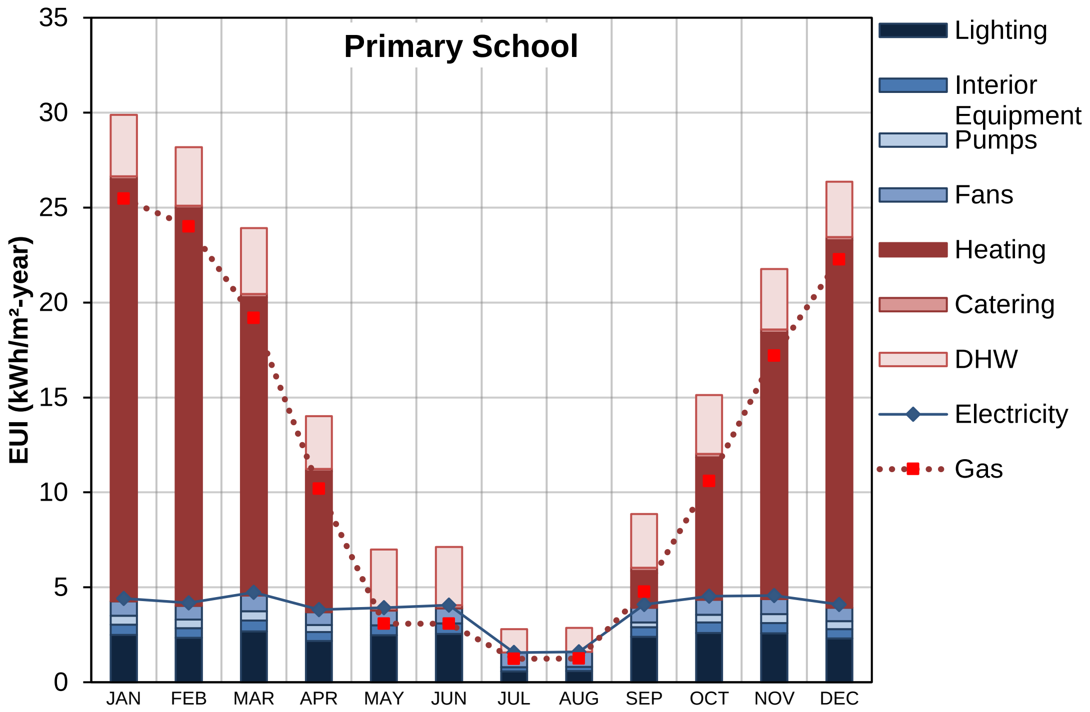


Figure 6-8 Monthly Energy Use Indicators by end-uses for the baseline primary school

II. A/C Office energy use

The results show different monthly end-use patterns than those found in the school archetype, especially because of the office cooling demand during summer months Figure 6-9). The office's EUI is found at 288.5 kWh/m²-year (0.5% higher than the national mean value), with similar demands for gas and electricity (gas: 45.1%, electricity: 54.9%). The 750 kW gas boiler requires 1099.3 GJ/year to cover the heat demand, while the 272 kW air-cooled chiller, supplying cold water to CAV systems consumes 101.9 GJ/year of electricity. These shares represent 40.9% for heating purposes and just 10.9% for cooling. Other end-uses with high demands are interior equipment with 689.7 GJ/year (24.0%) and lighting with 572.8 GJ/year (21.3%). Pumps and fans, mainly used for HVAC systems to move hot/cold water and air distribution respectively, consume 110.6 GJ/year.

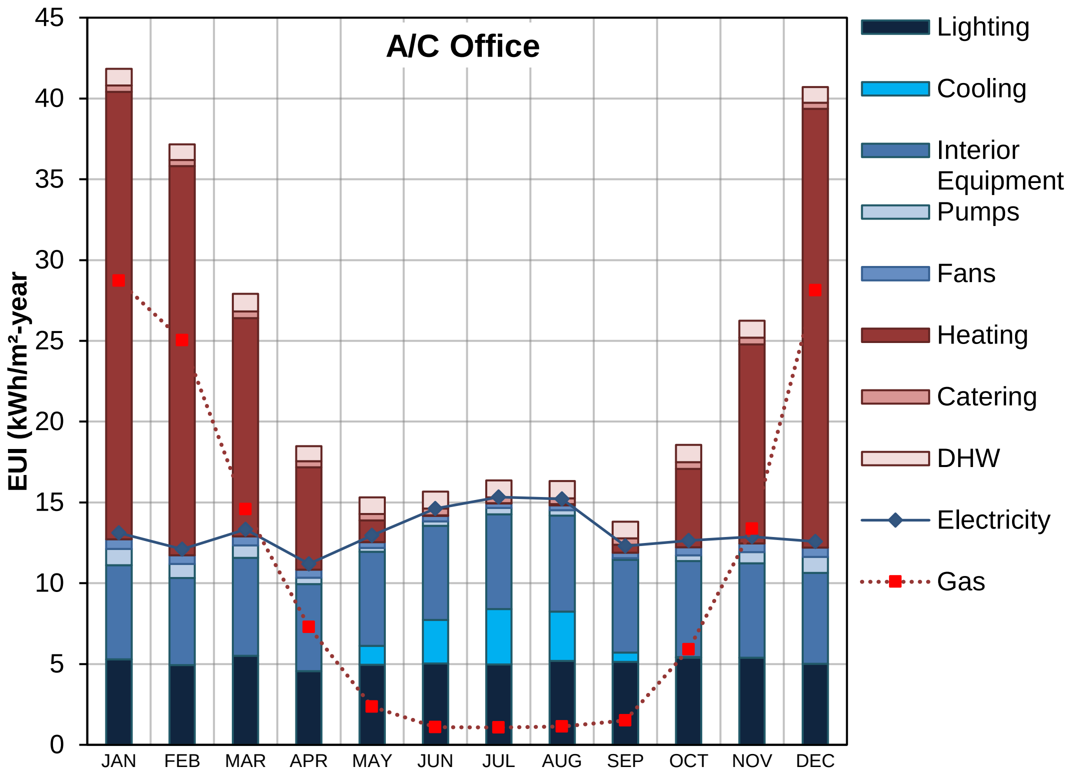


Figure 6-9 Monthly Energy Use Indicators by end-uses for the baseline office building

6.2.2.2 Economic indicators

I. Primary School economic values

The outputs from the economic model deliver an annual energy bill of £19,449.3 for the primary school, where £10,949.6 is needed to cover electricity demand and £8,499.6 for natural gas. A monthly breakdown can be seen in Figure 6-10. In addition, the LCC (over 50 years) obtained by the tool is found at £500,425 (£251.5/m²). This value will serve as a baseline for future comparison of BER measures.

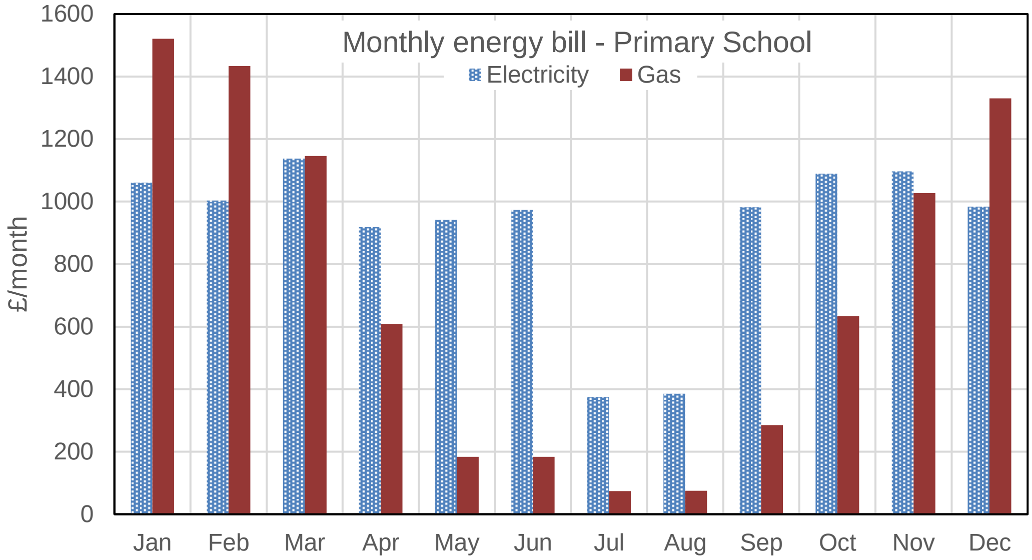


Figure 6-10 Monthly energy bill breakdown. Primary school archetype

II. A/C Office economic values

For the office, the annual energy bill is found at £59,625.3, with annual expenditures for electricity of £49,503.2, and £10,122.2 for gas. A monthly breakdown can be seen in Figure 6-11. The obtained LCC for 50 years is £1,534,146 (£592.33/m²).

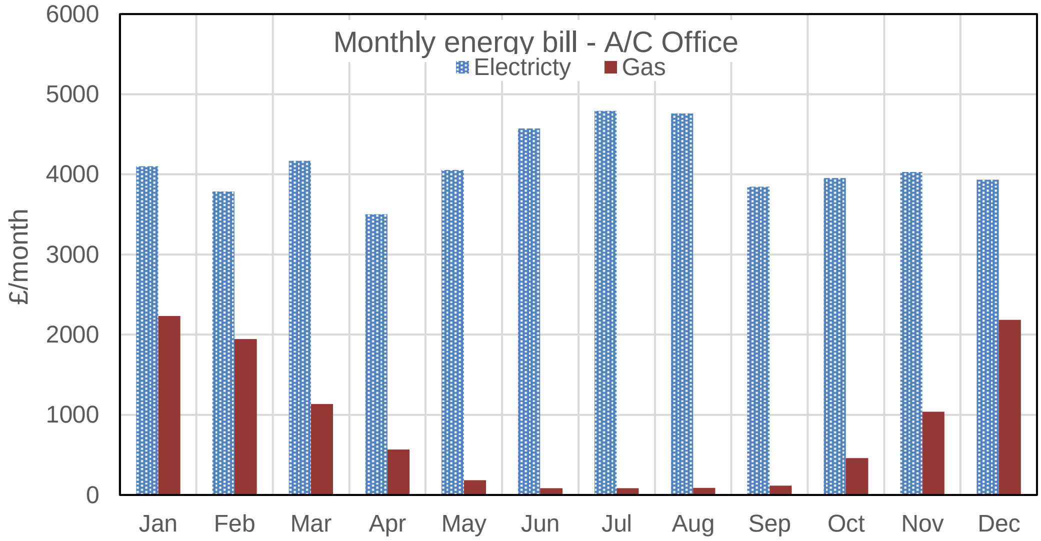


Figure 6-11 Monthly energy bill breakdown. A/C Office archetype

6.2.2.3 Baseline thermal occupant comfort and carbon emissions

The function of the buildings is to provide a comfortable space for the effective productivity of occupants. Therefore, occupant thermal comfort is considered as one of the most important indicators. In this sense, using the tool's occupant thermal model based on the ASHARE 55 guideline, the non-comfortable hours are found at 1,443 and 1,414 hours per year for the school and office respectively. This is considering all the analysed zones (classrooms, offices, common areas, etc.). Particularly for the school case, areas with staff members and extramural activities (evening classes, summer school) are also considered in the thermal comfort analysis, leading to potentially higher values compared to if only classrooms thermal zones under a typical timetable (8am to 3pm) are considered.

To calculate emissions, primary energy sources have to be considered by including energy for conversion, production, and transportation. Also, a disaggregation by fuel type has to be considered as each energy source has embedded different emission factors (Table 5-5). With this in mind, the total primary energy use in the school building represents 3696.6 GJ/year or 553.9 kWh/m²-year, meaning a total annual GHG emissions that of 214.8 tCO_2. For the office this represents 5169.3 GJ/year or 554.3 kWh/m²-year and carbon emissions of 285.6 tCO_2.

6.2.3 Baseline exergy and exergoeconomic values

6.2.3.1 Primary exergy indicators

I. Primary School exergy flows

Primary school requires a total primary exergy input of 1,915.9 GJ/year (264.4 kWh/m²-year). By product type, electric-based equipment requires the largest share of 861.9 GJ (45%), followed by heating with 807.7 GJ (42.2%), and finally DHW with 246.3 GJ (12.8%). Figure 6-12 shows the exergy flows for the three products analysed in the primary school archetype. Exergy flow diagrams give a first insight in the exergy behaviour inside the different building energy systems.

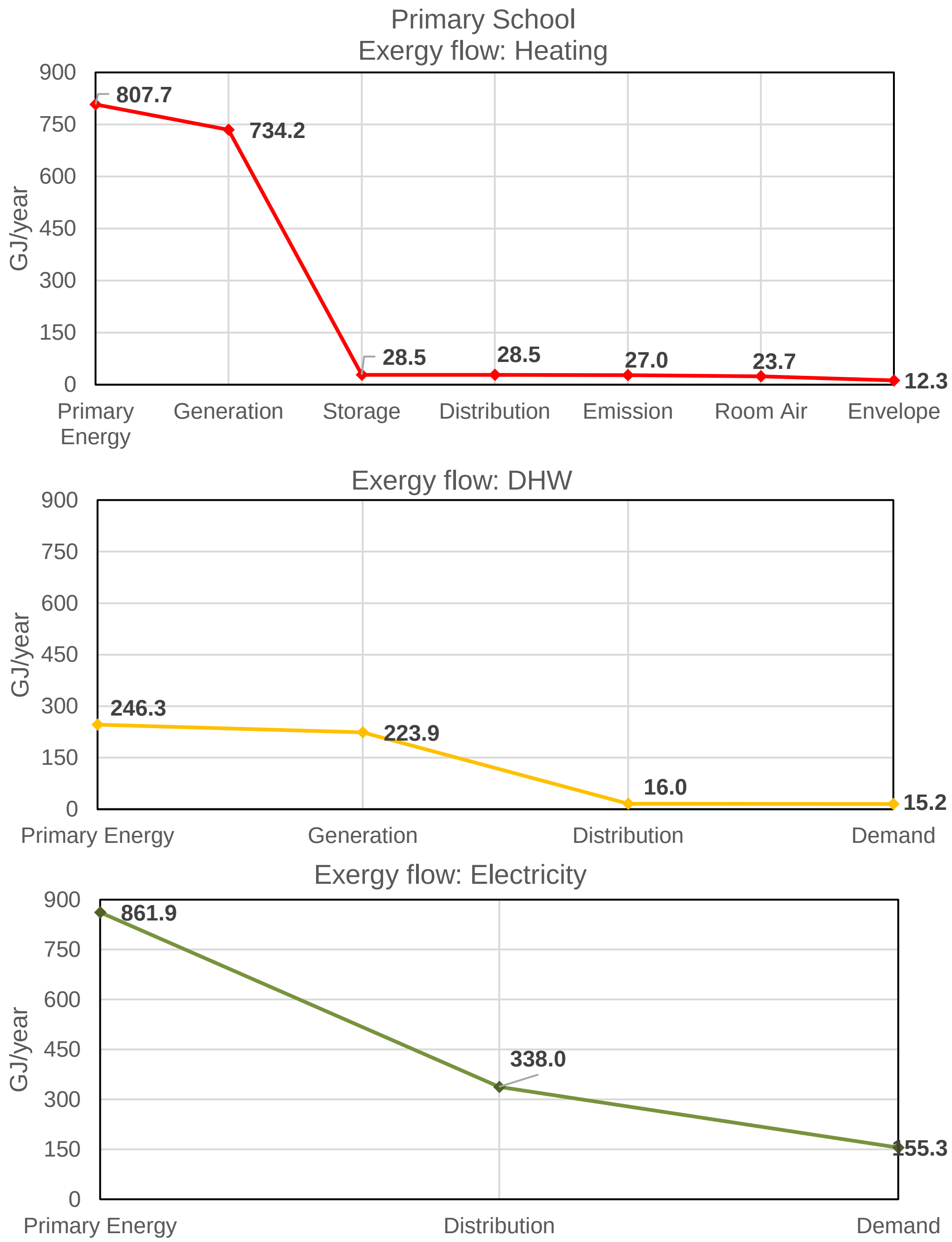


Figure 6-12 Exergy flows by product type. Primary School

II. A/C Office exergy flows

A/C Office requires a total primary exergy input of 4,263.1 GJ/year (550.0 kWh/m²-year). One difference with the school's case is the necessity to analyse the cooling process. By product, as in the case of the school, electric-based equipment requires the largest share of 2,778.8 GJ (65.2%), followed by heating with 1,137.5 GJ (26.7%), cooling with 255.3 GJ (6.0%), and finally DHW with 91.6 GJ (2.1%). Figure 6-13 shows the exergy flows for the four products (including cooling).

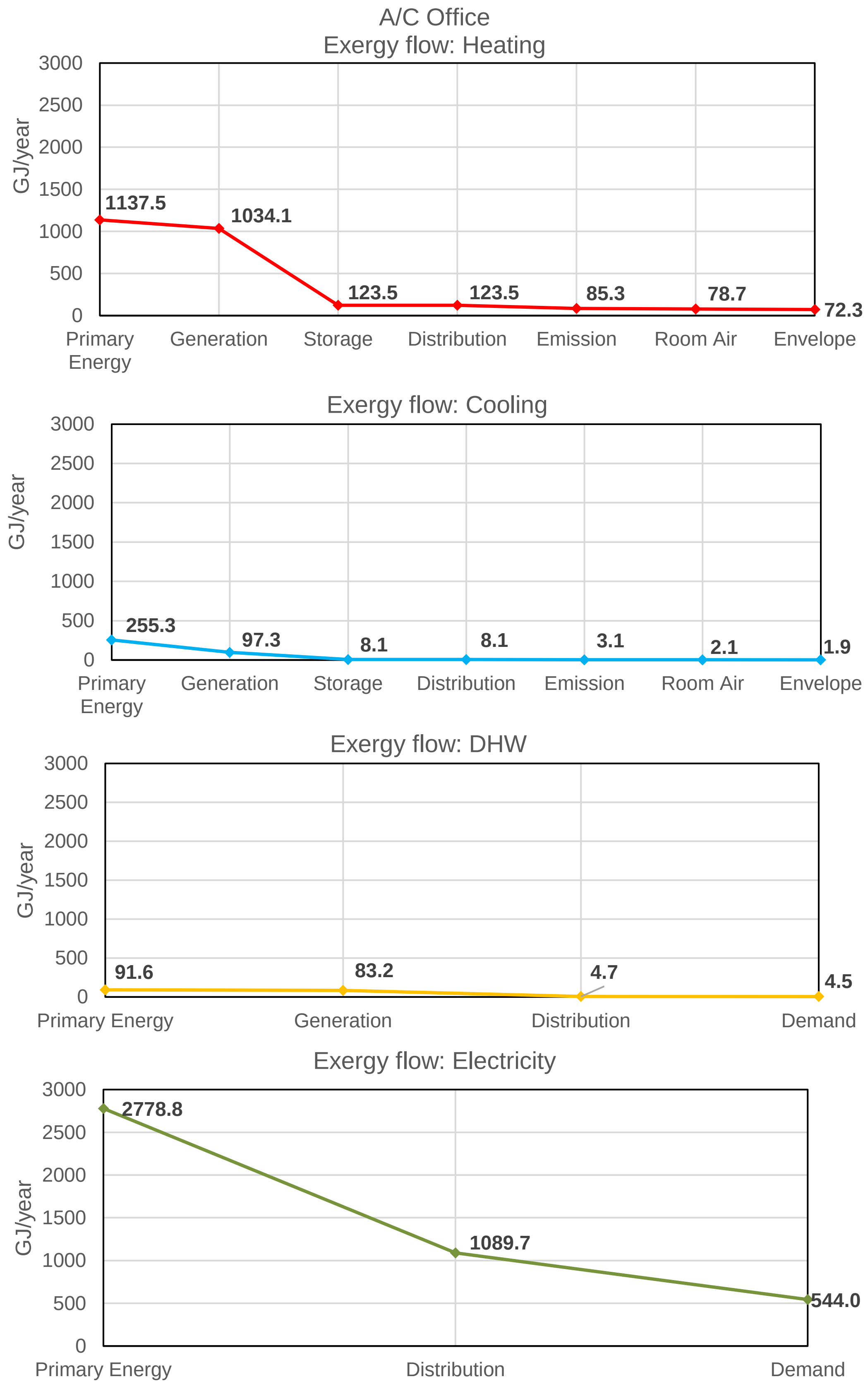


Figure 6-13 Exergy flows by product type. A/C Office

6.2.3.2 Exergy destructions breakdown by sub-systems

By analyzing destructions at each stage of the building's energy supply chain, exergy efficiencies by subsystem and the whole system can be regarded. This gives the possibility to locate the areas with the largest inefficiencies.

I. Primary school thermal (HVAC) exergy destructions

The heating energy system, formed by the conventional gas boiler, presents the largest share of irreversibilities within the building's energy system with 795.4 GJ/year (111.0 kWh/m²-year) as gas is being burned in the gas chamber at 1500 °C to achieve hot water temperatures of around 70 °C. As ExRET-Opt is based on dynamic energy simulation, Figure 6-14 shows the boiler's hourly outlet temperatures along the heating season compared to the ambient temperature. This data is essential to perofrom dynamic exergy caluclations.

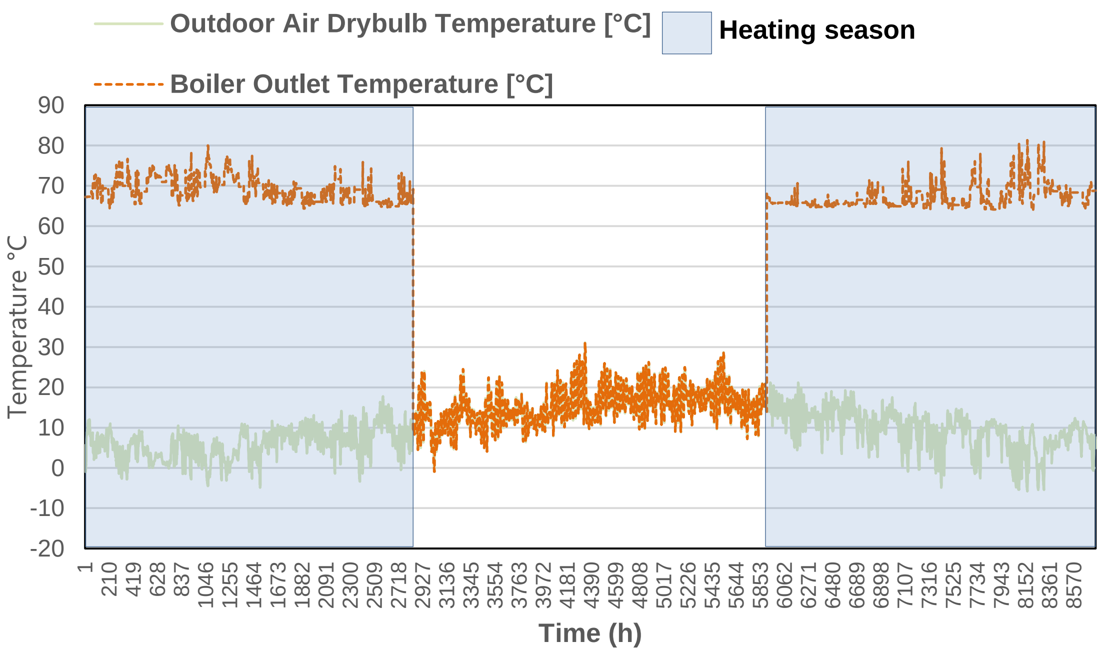


Figure 6-14 Hourly outdoor temperature and boiler outlet temperature (°C). Primary School

To illustrate the advantages of a dynamic exergy modelling within ExRET-Opt, Figure 6-15 shows the hourly exergy destructions at each subsystem of the HVAC energy supply chain. This gives us a direct comparison of the magnitudes of exergy irreversibilities between each part of the building's energy system. Although the dynamic exergy analysis method could be more time consuming than steady-state methods, the adoption of dynamic calculation is important if the cooling season is considered and when climates are not that extreme that building works closer to the reference environment (as in the case of London) (Angelotti et al., 2009). When building internal environment operates close to the reference temperature, exergy outputs are more sensitive to variations in both internal and reference temperatures.

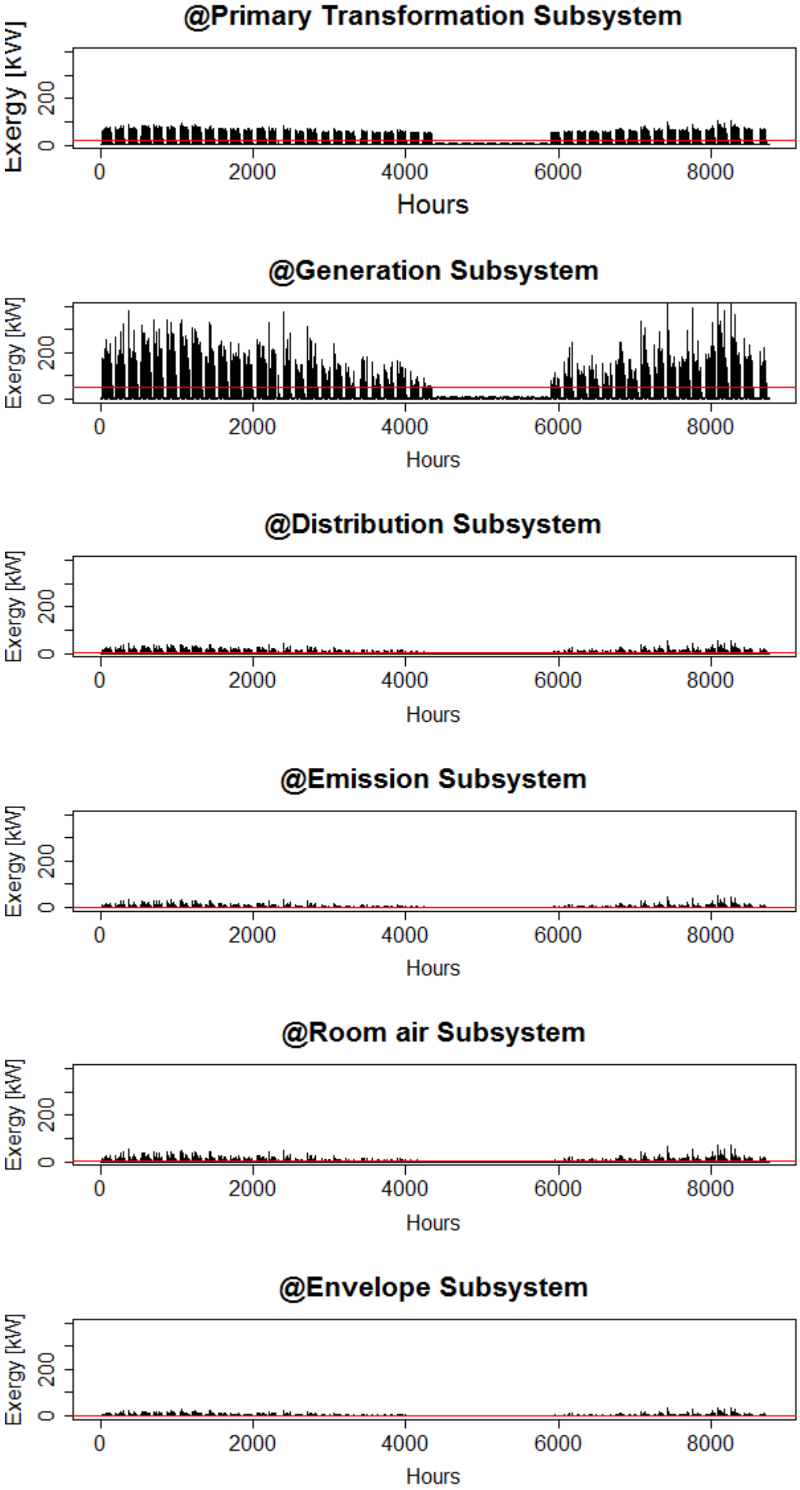


Figure 6-15 Hourly exergy destructions by subsystems. Primary school

A large difference exists between the amount of destructions at the 'Generation' and 'Primary Energy Transformation' subsystems compared to the rest of the energy supply chain. For a more detailed analysis, Figure 6-16 shows the primary school archetype HVAC hourly exergy destructions for the winter-design day (21st February, hour 1248-1272) disaggregated by subsystem. As aforementioned, the largest thermal exergy destructions are caused by and occur at the generation subsystem (gas fired boiler) due to the high-temperature combustion process that takes place.

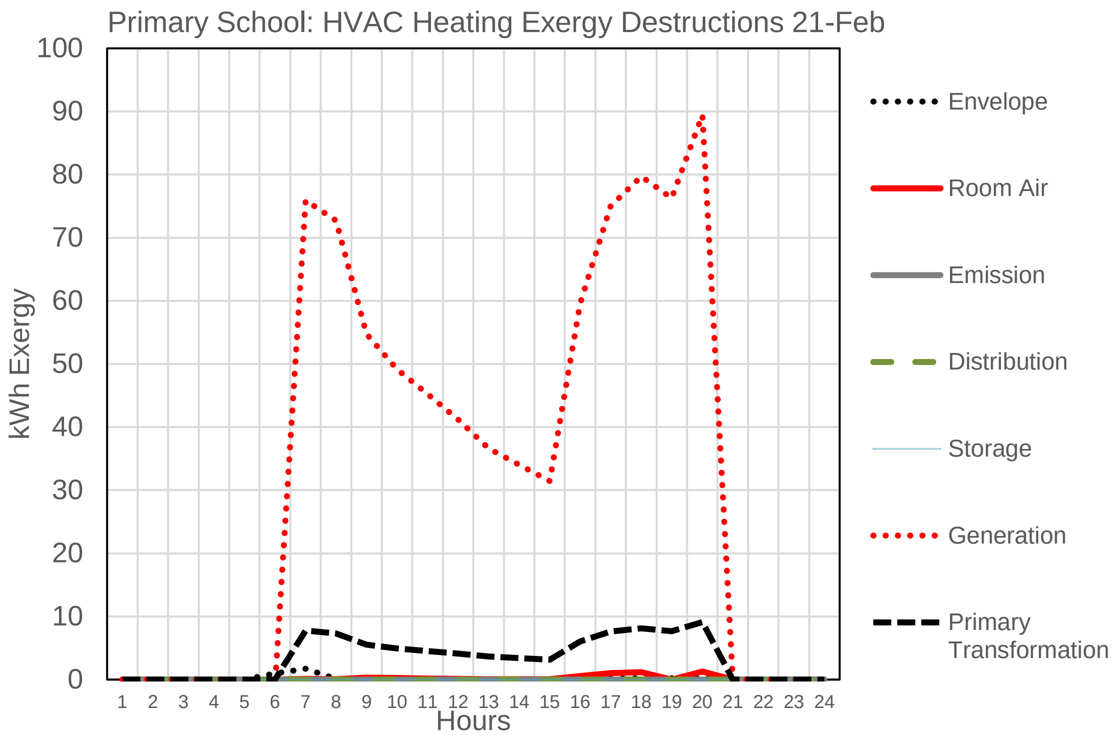


Figure 6-16 Primary school: Winter Design Day. Baseline Exergy destructions by HVAC subsystems

However, the 'Primary Transformation' and the 'Room Air' subsystems also have to be considered. The former presents destructions due to the process of extraction and transportation, which is outside the building's physical boundaries. On the other hand, the 'Room Air' subsystem presents considerable destructions due to a difference between the internal conditions of the room (room temperature) compared to the surface temperature of the emission system (radiators). The bigger the difference, the less exergetically efficient is the system.

Figure 6-17 presents the temperature analysis during occupied hours on the same winter-design day (21st February). Largest temperature differences are presented in the morning as the system starts to operate.

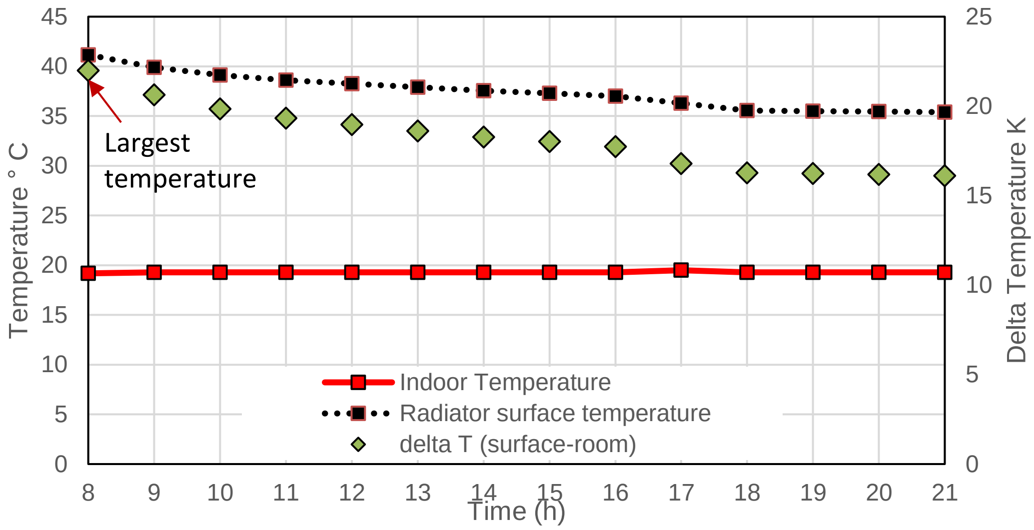


Figure 6-17 Temperature comparison between radiators surface and internal room temperatures. Primary school Ground Floor Classrooms

In the summer, while no mechanical cooling is required, thermal (cold) exergy destructions are regarded as zero.

II. A/C Office thermal (HVAC) exergy destructions

Office's thermal exergy destruction is found with a magnitude of 1,318.7 GJ/year (141.4 kWh/m²-year), resulting in a poor exergy efficiency of 0.069. Unlike the school's case, in the office both heating and cooling processes for space conditioning are presented. Figure 6-18 shows a comparison between the ambient temperature and the boiler, and chiller hourly outlet temperatures, along the heating and cooling season respectively.

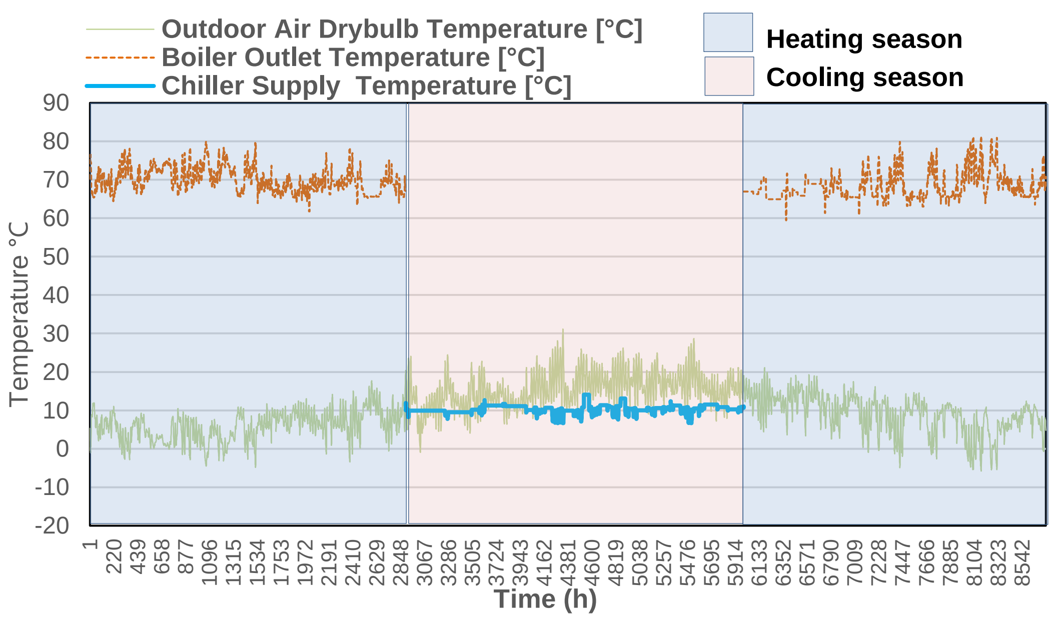


Figure 6-18 Hourly outdoor temperature and boiler and chiller outlet temperature (°C). A/C Office

Figure 6-19 and Figure 6-20 illustrate the office HVAC hourly exergy destructions for the winter and summer design days, respectively.

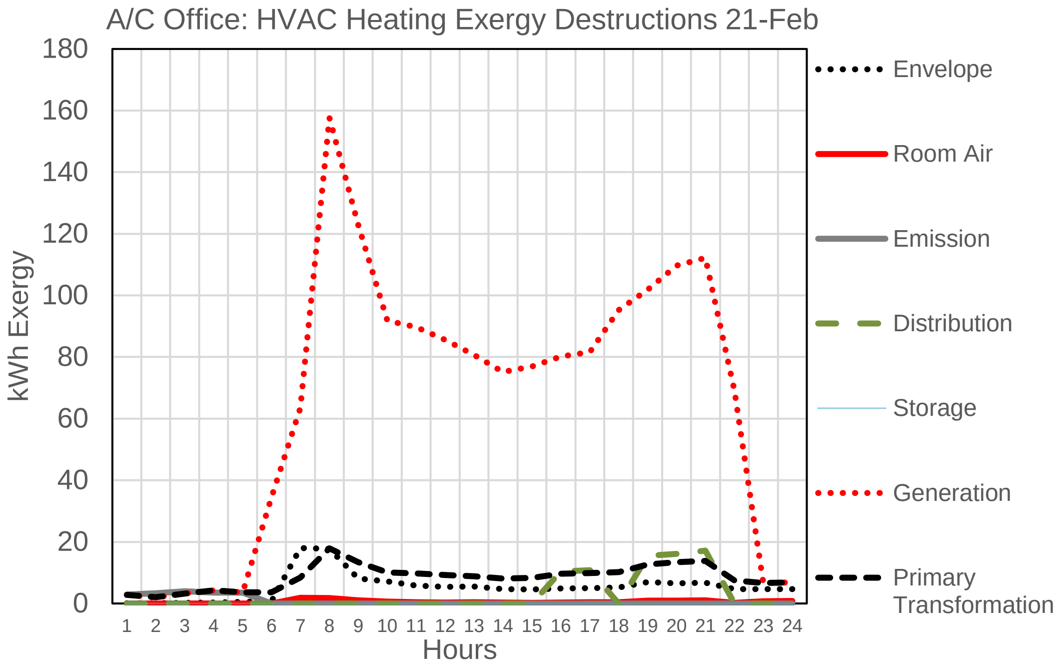


Figure 6-19 A/C office: Winter Design Day. Baseline Exergy destructions by HVAC subsystems

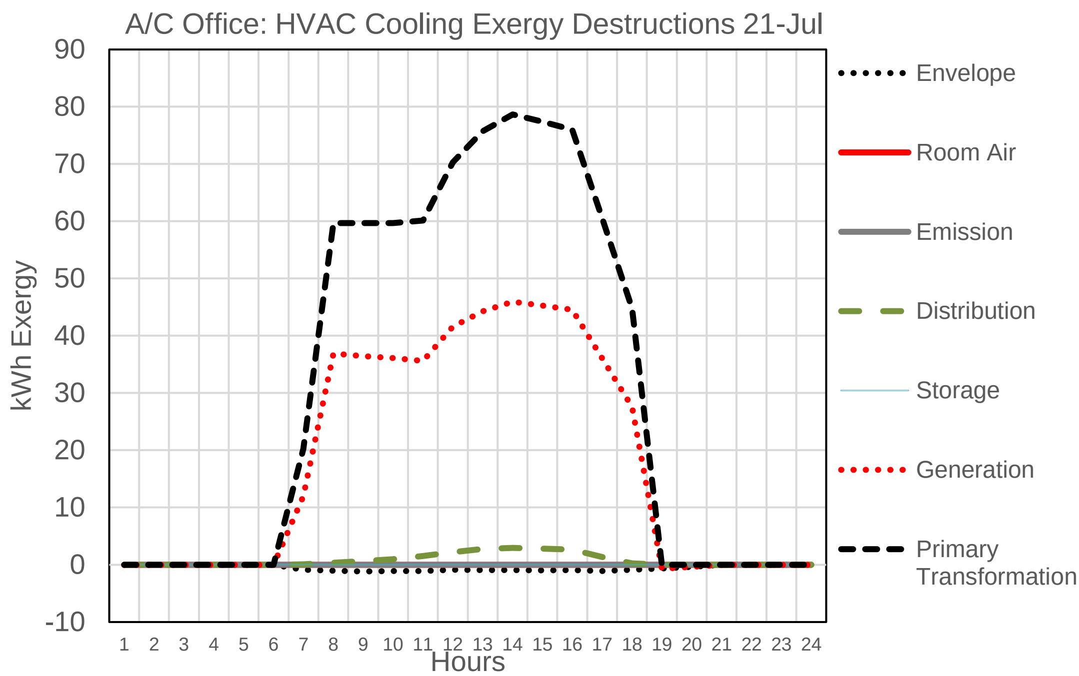


Figure 6-20 A/C office: Summer Design Day. Baseline Exergy destructions by HVAC subsystems

A markedly different pattern can be seen in the two seasons; while the main destructions in colder months are located in the generation subsystem (boiler), during the summer, destructions shift to the 'Primary Energy Transformation', where the conversion process from natural gas to electricity, produces the highest exergy destructions in the supply chain. In this case, the use of a high quality source (electricity) for a low quality demand such as cooling process in a temperate climate is highly penalised by exergy analysis. As seen in Figure 6-20, the dotted line, representing the envelope destructions, is below zero, indicating that the building has exergy that has to be removed from within it into the environment. This usually occurs when a cooling process is required even when the outside temperature is below the room set-point temperature. This phenomenon usually occurs due to high internal heat gains.

In both archetypes, the largest HVAC exergy destructions occur at the primary transformation and the generation stage, representing 98% and 90% of the total exergy destructions for schools and offices respectively (Figure 6-21). This gives an initial insight in the thermodynamic performance of each component within the HVAC energy supply chain and provides a direct comparison of the magnitude of exergy irreversibilities of the two case studies.

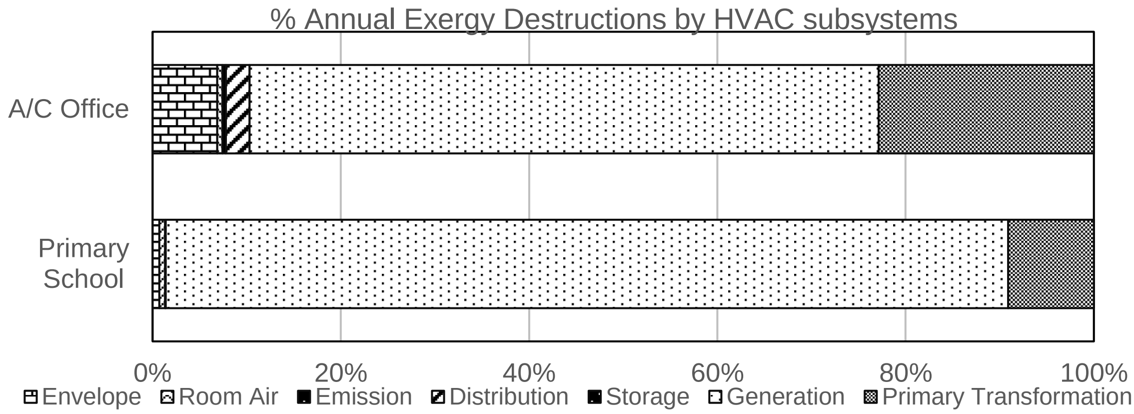


Figure 6-21 Exergy destruction ratio by HVAC subsystems for the primary school and an A/C office building

While a seemingly obvious solution would be to reduce these high irreversibilities, this should be preceded by the improvements of the building's generation systems. However, it is important to note that while some components may have higher exergy destructions rates than others, it is probable that these destructions are caused by exogenous origins, meaning that are mainly caused due to inefficiencies of other components within the system (e.g. at envelope or distribution subsystems). This means that passive measures may also be used for the minimisation of irreversibilities, but could have a lower impact on how the destructions are distributed between the subsystems.

6.2.3.3 Whole building exergy destructions breakdown

With the help of the whole building energy system analysis, a comparison of exergy destructions between the subsystems and the type of buildings can be considered. The annual exergy destructions for the school building, considering HVAC, DHW, and electric-based equipment, accounts for 1,733.1 GJ/year (241.9 kWh/m²-year), giving a total exergy efficiency (ψ_{bui}) of 0.095% for the primary school. The A/C office presents total exergy destructions of 4,340.6 GJ/year (465.5 kWh/m²-year), resulting in an exergy efficiency of 0.153. To highlight the differences between the building types, Figure 6-22 shows the share of destructions per component.

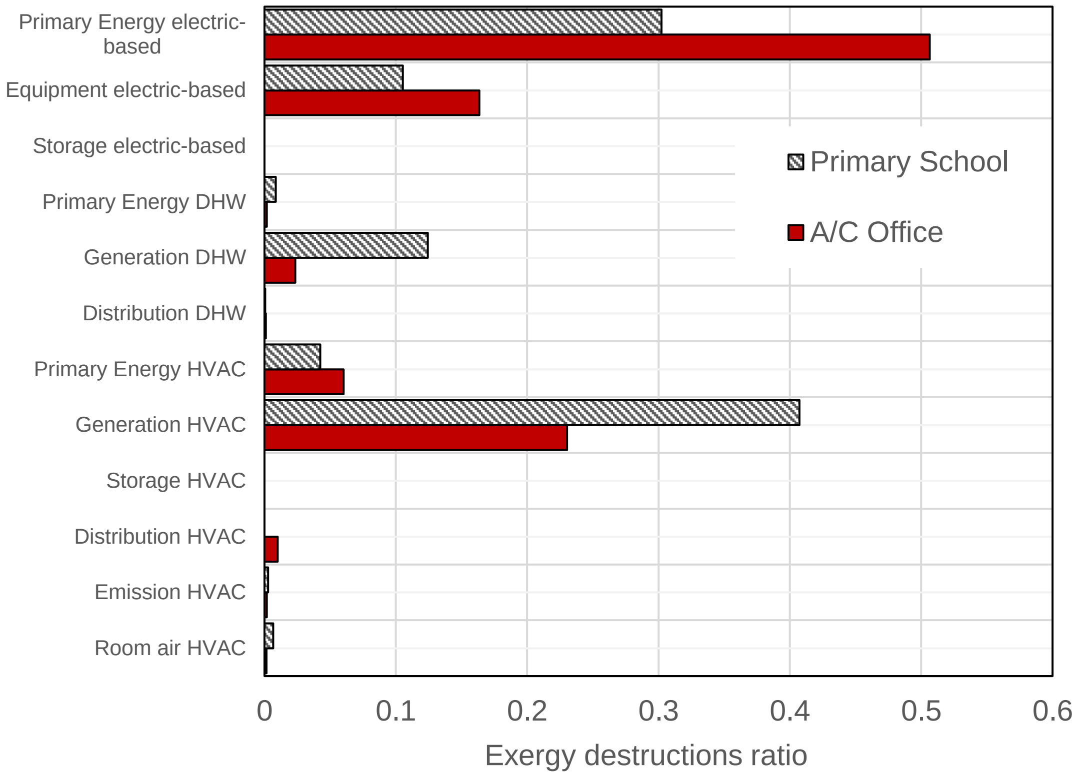


Figure 6-22 Exergy destruction ratio of all energy subsystems for both buildings

In the office case, the largest share of irreversibilities occurs in the primary generation of electricity, used for electric-based appliances, representing more than half of total building irreversibilities throughout the year. The reduction of these irreversibilities could come either from a more efficient electric generation at the power plant, or by the in-site generation of renewable electricity. The next source of exergy destructions is at the HVAC generation subsystem (23%), as a result of burning gas in the boiler for heating purposes, together with the use of electricity to run the chiller. The third source of irreversibilities is the electric appliances (16%), such as computers, lighting, etc., where reductions could come by improving equipment electric efficiencies. Therefore, as the electric-based destructions represent 74%, a large potential exists for reducing irreversibilities and improving the whole building's performance when focusing on this area first.

In the school's case, the HVAC generation subsystem presents the largest destruction with 41%, followed by primary generation of energy for electric equipment (30%) and the generation for DHW demand (13%). Unlike for the office, in order to improve the whole building's performance, a focus should first be on the boiler that would reduce irreversibilities due to heating and domestic hot water demand.

For both buildings, the 'Primary energy transformation' subsystem for the HVAC system, exergy destructions are rather low; although in the office it represents a larger share due to the electricity demand for cooling process during summer. Nevertheless, for both cases, a concern should exist with regards to minimising destructions at the primary energy transformation; however, this is a regulation that has to be looked at a power generation and government level.

6.2.3.4 Exergoeconomic indicators

I. Products' streams exergy price formation

Exergoeconomic analysis will help to determine the real price that the 'consumer' pays for the energy product in its final form: space heating, space cooling, DHW, and end-use electricity. This is done by accounting for exergy destructions at each stage of the energy supply chain, calculating its cost, and obtaining the cost increase per kWh on the product streams. This section illustrates the relationship between the exergy destruction accumulation and the energy stream price increase focusing on HVAC supply chain for both case studies.

Figure 6-23 illustrates the school heating product cost formation throughout the energy supply chain, showing that the heating product at the thermal zone increases from £0.03/kWh (gas price) to £1.79/kWh, with a total relative cost difference r_k of 58.66. This value shows the increase in the product price compared to the price of the entering stream (gas).

The final price represents the real price that occupants are paying for each kWh of heating, as this is not solely composed by the gas price coming from the grid, but also considers capital cost, operation cost, and exergy destruction cost. In the hypothetical case that the building is working under ideal conditions (ideal system) with an exergy efficiency of 1.0 and no capital and maintenance cost, then the final product price would be the same as the entering price (£0.03/kWh), obtaining a total relative cost difference r_k of 1.0. However, under typical conditions, some unavoidable irreversibilities as well as associated cost exist in every real energy system, therefore the costumer will inevitably pay a higher price.

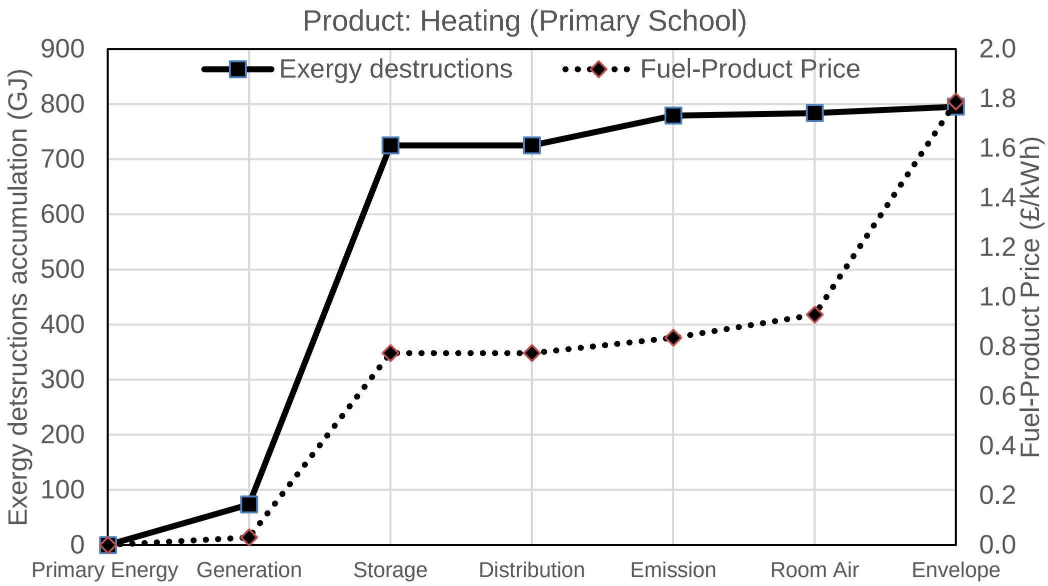


Figure 6-23 Exergy destruction accumulation vs product cost formation for the heating stream. Primary School

As seen in the graph, the largest price increase occurs at the generation (gas boiler) and envelope subsystems, where the higher exergetic costs (larger irreversibilities) are produced. After the exergy passes through the boiler and is converted from gas to hot water at around 70 °C, the exergetic price increases from £0.03/kWh to £0.77/kWh. However, unlike simple exergy analysis, exergoeconomic analysis have located that in addition to the boiler, the envelope thermal properties have to be improved to reduce exergy destructions and thus minimise a price escalation of the heating product. Although the destructions are rather minimal at the envelope, even small inefficiencies escalate the price due to low exergy demand at this stage; therefore, any supply of extra exergy is seen by exergoeconomic analysis as a waste. As seen in the graph, the heating exergy price before it enters the room stands at £0.92/kWh and leaves the envelope at its final price of £1.79/kWh. Therefore, if a reduction in heating product price has to be achieved, the boiler and the envelope thermal properties present the biggest potential for improvement.

For the office case, it is possible to show the streams for the two thermal products: heating and cooling. In Figure 6-24, the office heating product cost formation increases from £0.03/kWh to £0.42/kWh, having a total relative cost difference r_k of 13.0. In this case, the generation and distribution subsystems are the areas of major concern. After the hot water is produced in the boiler, the price increases from £0.03/kWh to £0.25/kWh; however, after the hot water leaves the distribution system, the price has another significant increase, reaching £0.36/kWh. Therefore, in this building, instead of focusing on improving the envelope thermal properties, a focus on improving the pipes or ducts insulation has to be considered first.

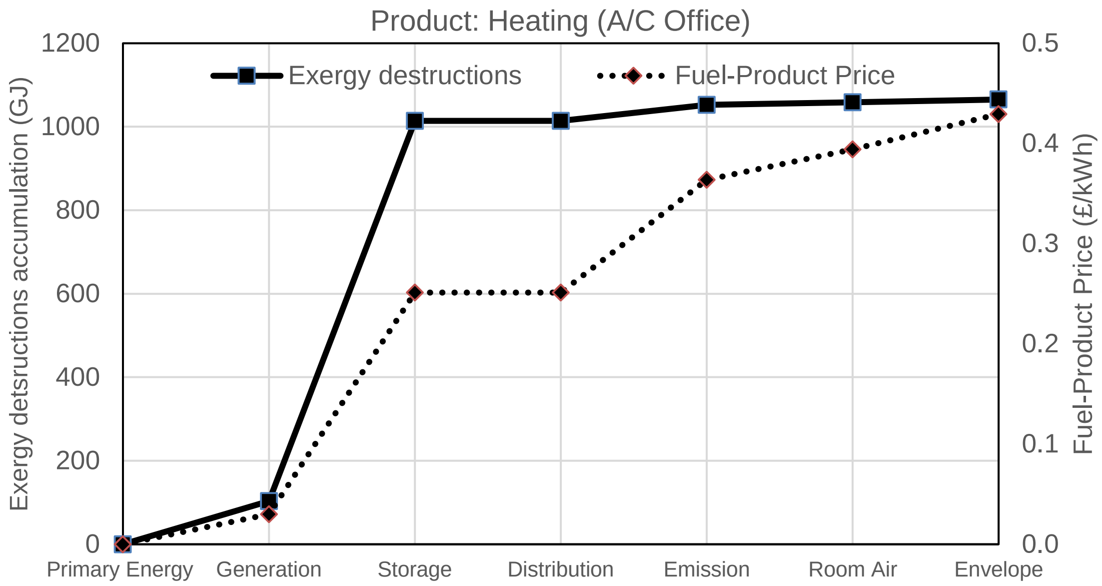


Figure 6-24 Exergy destruction accumulation vs product cost formation for the heating stream. A/C Office

For the cooling product (Figure 6-25), the exergy product cost starts at £0.12/kWh (electricity price) and increases up to £6.28/kWh (r_k = 51.33). This high price per kWh shows that the cooling exergy demand is in fact very low, and any extra exergy expenditure to cover this demand, is seen as excessive. Therefore, any requirement and misuse of energy will result in a major increase in price. This analysis suggests that at least in this particular case study, considering a climate such as London's, cooling has to be covered with passive means as much as possible. However, if the measures, such as natural ventilation, night cooling, external shading, and internal heat gains control are not possible (due the requirement to have a complete closed space where an artificial cooling system is needed), the outputs show that attention has to be put on the generation (low efficient chiller, COP: 2.0), the distribution, and emission subsystems, where the biggest price increases are found. After grid electricity is used on the chillers' compressors to generate chilled water at around 7 °C, the price escalated from £0.12/kWh to £1.44/kWh. However, after the cold exergy passes through the cooling system through the heat exchangers (from water to cold air) and reaches the fan coil unit at the emission subsystem, the price increased to £5.68/kWh. This highly increasing price rate is due to the naturally low exergy demand for cooling and low chiller's COP, where the necessity to use electricity is highly penalised by exergoeconomic analysis.

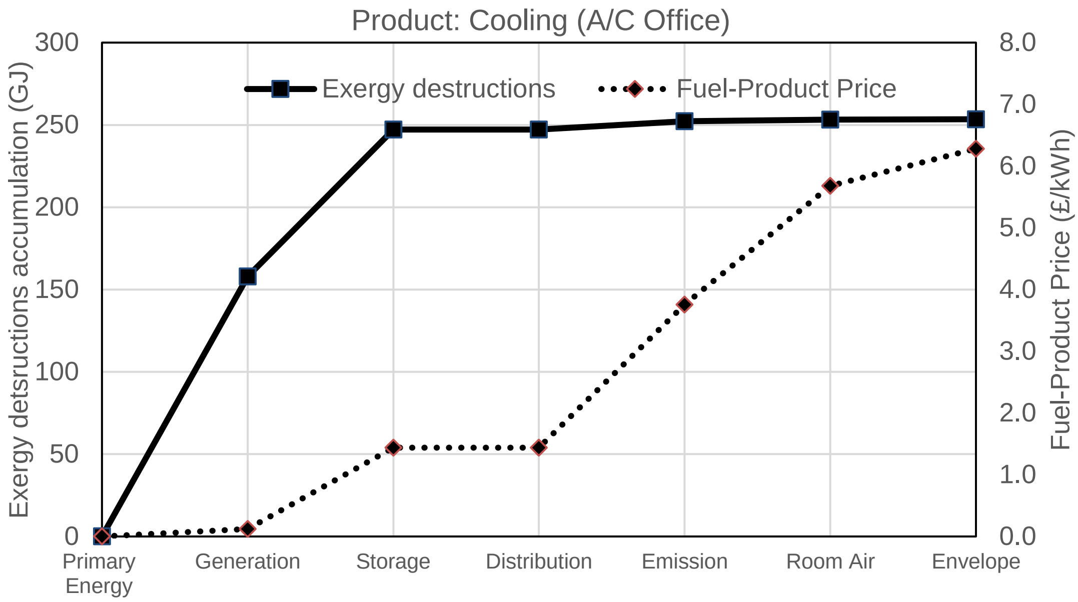


Figure 6-25 Exergy destruction accumulation vs product cost formation for the cooling stream. A/C Office

In many cases, exergy price for heating and cooling products can differ dramatically, as the exergetic cost significantly depends on the temperatures. In this sense, cooling processes, by working closer to ambient temperature (thus having a small ΔT), and any exergy destructions are highly penalised in exergy/exergoeconomic analyses. Added to this, the conversion efficiency of any subsystem can also have a big impact on the final product price. The same fuel-product analysis is also done for the DHW and electric-based exergy flow products. The final baseline outputs are shown in Table 6-3.

II. Exergy destruction cost rate and exergoeconomic cost-benefit

Until now, as no retrofit strategy has been implemented, no capital cost and revenue can be calculated ($\dot{Z}_{sys} = 0\,,\ \dot{R} = 0$). Therefore, as presented in Section 4.2.3.1, the novel expanded exergoeconomic cost-benefit indicator $Exec_{CB}$, developed in this research for the comparison of retrofit measures, is presented for base cases with the same value as the building's exergy destructions cost rate ($Exec_{CB,baseline} = \dot{C}_{D,sys}$). This value will serve as an exergoeconomic benchmark for comparison of retrofit designs, considered in the following sections.

For the school, the $Exec_{CB,baseline}$ or $\dot{C}_{D,sys}$ has a value of £2.72/h (£17,672.9/year) and for the office a value of £6.25/h (£42,893.0/year). This number represents the price the building pays per hour due to exergy destructions, meaning that it considers the real cost of system inefficiencies. In the case of the school, exergy destructions costs represent around 90% of the annual energy expenditure (energy bill), while in the office it is close to 91%, showing that in both cases just around 9% of the total expenditure is being paid to cover the real thermodynamic demand.

Table 6-2 presents the total annual economic cost due to the thermodynamic inefficiencies in all four products' streams for both case studies. For the A/C office, the exergy inefficiencies in the heating and electric energy supply chain have a large impact on the exergoeconomic cost of the building, while in the primary school the heating stream is the product that presents the largest share of expenditure dedicated to cover inefficiencies.

Table 6-2 Exergy destructions economic cost by products

	Heating (£/year)	Cooling (£/year)	DHW (£/year)	Electric appliances (£/year)
A/C Office	11,624.8	6,383.5	1,209.8	23,674.9
Primary School	9,844.1	0	1,738.9	6,044.4

For a more straightforward illustration, Figure 6-26 shows a detailed evaluation of the exergoeconomic cost by locating the destruction cost share of each product per hour. For the school's case, heating and electricity account for almost £2.5/h, where for the office it is approximately £4.5/h.

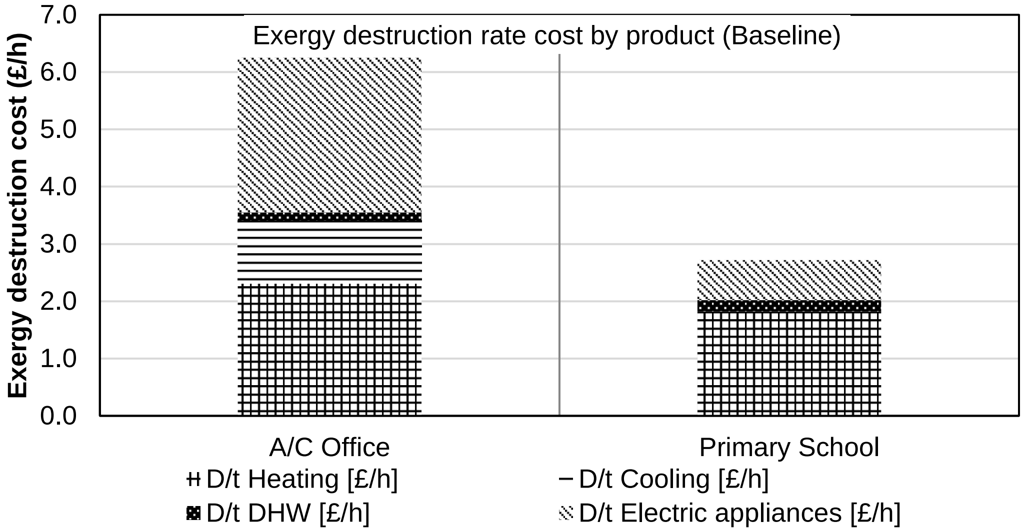


Figure 6-26 Exergy destruction cost rate per product type (Baseline)

By considering a trade-off between the exergy destruction cost, BER project capital cost, and annual revenue, an optimal exergoeconomic-based BER design will present lower values of exergoeconomic cost-benefit indicator $Exec_{CB}$ than the baseline $Exec_{CB,baseline} = \dot{C}_{D,sys}$.

Finally, baseline exergy and exergoeconomic values for both buildings can be seen in Table 6-3.

Table 6-3 Baseline exergy and exergoeconomic values for both case studies

Baseline characteristics	Primary School	A/C Office
Exergy input (fuel) (GJ)	1,915.9	4,263.1
Exergy demand (product) (GJ)	182.8	622.6
Exergy destructions (GJ)	1,733.1	3,640.5
Exergy efficiency HVAC	0.015	0.053
Exergy efficiency DHW	0.062	0.087
Exergy efficiency Electric equip.	0.180	0.195
Exergy efficiency Building	**0.095**	**0.154**
Exergy cost fuel-prod HEAT (£/kWh) {r_k}	0.03—1.79 {58.66}	0.03—0.42 {13.00}
Exergy cost fuel-prod COLD (£/kWh) {r_k}	----- {---}	0.12—6.28 {51.33}
Exergy cost fuel-prod DHW (£/kWh) {r_k}	0.03—0.44 {13.66}	0.03—0.55 {17.33}
Exergy cost fuel-prod Elec (£/kWh) {r_k}	0.12—0.26 {1.16}	0.12—0.24 {1.0}
D (£/h) Exergy destructions cost (energy bill £; %D from energy bill}	2.72 {17,672.9; 90.8%}	6.25 {42,893.0; 71.9 %}
Z (£/h) Capital cost	0	0
Exergoeconomic factor f_k (-)	1	1
Exergoeconomic cost-benefit (£/h)	**2.72**	**6.25**

6.2.4 Effect of different ambient temperature on studied indicators

As exergy analysis is completely dependent on the reference environment, exergy destructions and exergoeconomic values highly depend on the temperature values. As representative archetype buildings from the UK were used and the fact that the calibration process was done by using national statistics, before moving forward with the retrofit study, a further analysis is done by exploring different locations (temperatures) within the country. This process is similar to performing a sensitivity analysis of the reference ambient temperature on the baseline outputs.

Apart from the weather file from London used in the baseline models (1,581 heating degree days (HDD) and 293 cooling degree days (CCD) with a base temperature of 15.5 °C), five different UK locations (Figure 6-27) are investigated in this section: Belfast (HDD: 1,874, CDD: 101), Birmingham (HDD: 1,941, CDD: 170), Cardiff (HDD: 1,736, CDD: 109), Edinburgh (HDD: 2,441, CDD: 64), and Liverpool (HDD: 1,805, CDD: 130). High uncertainties in the results might exist due to temperature values in weather files.

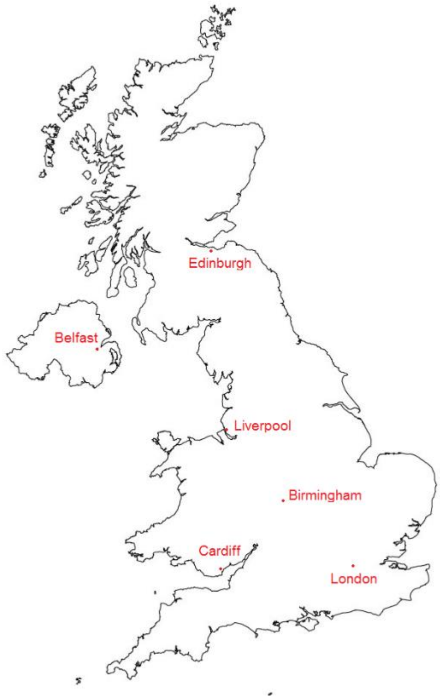


Figure 6-27 UK cities considered for the sensitivity analysis of ambient temperatures

6.2.4.1 Primary School climate sensitivity

Considering the same baseline building model based on a 'Gas Boiler + Radiators' and similar characteristics such as occupant behaviour, power equipment rates, etc., Table 6-4 shows the baseline outputs for energy, economic, thermal comfort, and carbon emissions values.

Table 6-4 Effect of different UK locations on typical energy indicators in a primary school (best performance in green, worst performance in red)

	Total EUI (kWh/m^2-year)	Electric EUI (kWh/m^2-year)	Gas EUI (kWh/m^2-year)	Life Cycle Cost (50 years) (£)	Annual tCO_2	Thermal discomfort (hours)
London	187.9	45.6	142.3	500,468.1	214.8	1,443
Belfast	204.1	45.1	159.0	523,339.3	228.0	1,596
Birmingham	195.8	45.3	150.4	511,533.4	221.2	1,493
Cardiff	197.1	45.4	151.7	513,692.9	222.3	1,514
Edinburgh	196.3	45.3	151.0	512,288.1	221.6	1,531
Liverpool	179.4	45.1	134.3	485,292.7	207.1	1,467

Overall, a similar school based in Liverpool will have the best energetic performance and thus the lowest life cycle cost over the next 50 years. Large differences exist in gas consumption due to its demand for heating purposes. In addition, the small deviations in electricity demand are due to operation differences in pumps and fans used for the HVAC system. However, best thermal comfort levels are achieved in London.

Table 6-5 presents the impact on the exergy and exergoeconomic performance. In this case, Liverpool achieved the least exergy destructions footprint; however, it presented the worst thermodynamic efficiency for the HVAC system. However, when considering the entire building energy system, Liverpool, as a result of lower exergy demands and exergy destructions in other systems, achieved the best overall exergy efficiency and the lowest exergy destruction cost rate.

Table 6-5 Effect of different UK locations on exergy and exergoeconomic indicators in a primary school (best performance in green, worst performance in red)

	Primary exergy input (kWh_{ex}/m^2-year)	Exergy destructions (kWh_{ex}/m^2-year)	Exergy efficiency Ψ HVAC (-)	Exergy efficiency Ψ Building (-)	Exergy destructions cost rate (£/h)
London	267.4	241.9	0.015	0.095	2.7
Belfast	283.6	258.2	0.014	0.089	2.9
Birmingham	275.2	249.7	0.015	0.093	2.8
Cardiff	276.6	251.0	0.015	0.093	2.8
Edinburgh	275.8	250.2	0.015	0.093	2.8
Liverpool	258.0	233.2	0.013	0.096	2.5

The exergy destruction cost rate $\dot{C}_{D,sys}$ by locations and by products is illustrated in Figure 6-28. The only product that presents variations between locations is the heating cost rate. Belfast presents the highest thermal exergy destruction rate for heating with a value of £2.0/h, while Liverpool has the lowest ratio with £1.6/h.

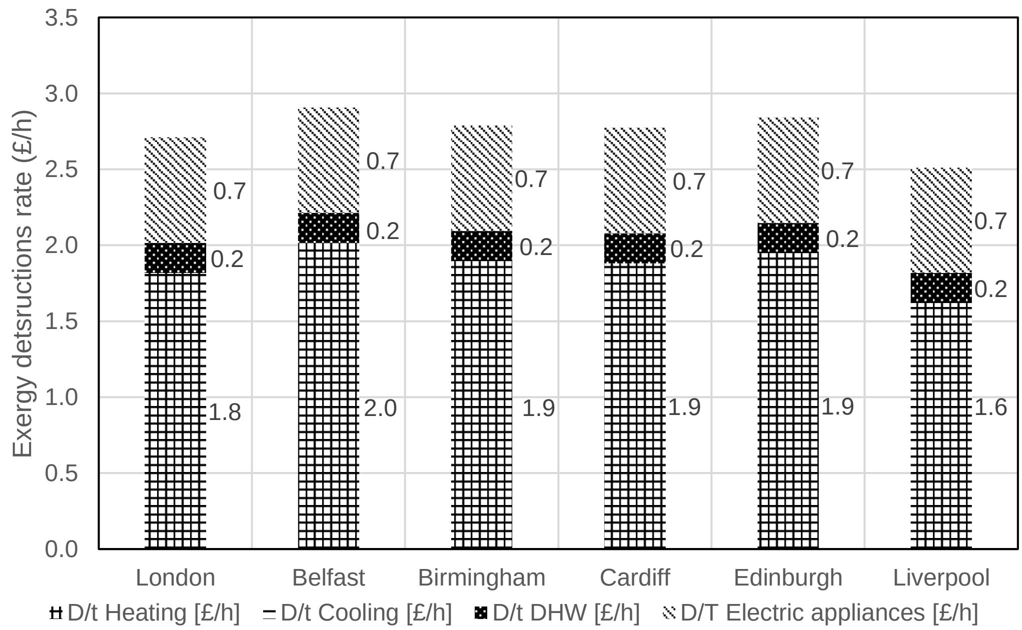


Figure 6-28 Primary School: Exergy destructions cost rate by product in different locations

6.2.4.2 A/C Office climate sensitivity

Considering the same building (gas boiler + air-based chiller) for all locations, Table 6-6 presents an overview of the typical energy performance indicators. The outputs also show Liverpool as the location with better energy performance; however, it presents the largest electric demand. In addition, Liverpool's archetype presents the best thermal comfort conditions, although with no substantial difference in respect to the other locations. The location with the worst energetic performance is Birmingham, while Cardiff achieved the lowest thermal comfort levels.

Table 6-6 Effect of different UK locations on typical energy indicators in an A/C Office (best performance in green, worst performance in red)

	Total EUI (kWh/m²-year)	Electric EUI (kWh/m²-year)	Gas EUI (kWh/m²-year)	Life Cycle Cost (50 years) (£)	Annual tCO_2	Thermal discomfort (hours)
London	288.5	158.3	130.2	1,534,145.9	285.6	1,414
Belfast	299.0	151.3	147.7	1,512,794.1	285.7	1,447
Birmingham	299.1	157.7	141.3	1,551,768.2	290.9	1,442
Cardiff	292.3	155.0	137.3	1,521,506.7	285.0	1,482
Edinburgh	294.0	155.1	138.8	1,525,741.6	286.0	1,410
Liverpool	270.5	159.2	111.3	1,503,604.7	276.4	1,408

As shown in Table 6-7, Liverpool and Cardiff achieved the best overall thermodynamic efficiency. However, as in the school's case, Liverpool presents the lowest values for exergetic performance at the HVAC level. On the other hand, Belfast achieved the best exergy destructions cost rate, while London and Birmingham presented the worst.

Table 6-7 Effect of different UK locations on exergy and exergoeconomic indicators in an A/C Office (best performance in green, worst performance in red)

	Primary exergy input (kWh_{ex}/m^2-year)	Exergy destructions (kWh_{ex}/m^2-year)	Exergy efficiency Ψ HVAC (-)	Exergy efficiency Ψ Building (-)	Exergy destructions cost rate (£/h)
London	550.0	465.5	0.053	0.154	6.3
Belfast	550.4	465.3	0.056	0.155	5.8
Birmingham	560.1	474.9	0.053	0.152	6.3
Cardiff	548.7	463.3	0.059	0.156	5.9
Edinburgh	550.7	465.7	0.056	0.154	6.0
Liverpool	532.6	449.6	0.049	0.156	5.9

Figure 6-29 illustrates a detailed exergoeconomic analysis by products. The outputs show that the lowest heating exergy destruction rate is found in Liverpool (£2.0/h), while Belfast presents the highest (£2.7/h). For the cooling process, the worst exergoeconomic performers are London and Liverpool (£1.1/h) while Belfast presents the best performance (£0.3/h). As mentioned, by considering all the products together, Belfast has the lowest system exergy destruction rate at £5.8/h. This is related to the good performance obtained from the electric exergy performance and low demand for cooling processes. Especially in the UK, a great potential exists for passive means such as natural ventilation or night cooling, which will lower the cooling exergy destructions and exergy costs significantly.

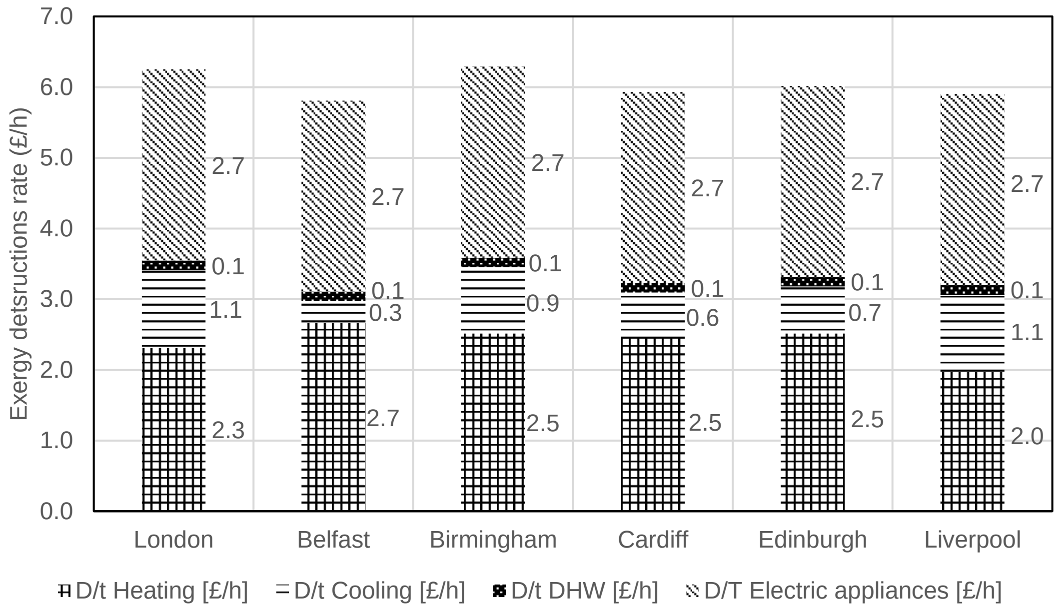


Figure 6-29 A/C Office: Exergy destructions cost rate by product in different locations

6.3 Examination of passive and active BER measures under energy, exergy, economic and exergoeconomic indicators

After the baseline examination presented in Section 6.2.3, where different areas of improvement were identified, in this section, the proposed enhanced BER framework presented in Chapter 4 is fully applied for the analysis of different retrofit measures. This assessment is supported with the utilisation of Mode II within ExRET-Opt. The concepts of exergy and exergoeconomic are applied for the first time in the literature to assess the impact of different active and passive BER measures. The whole range of studied measures with attached costs is presented in Appendix B.5. As stated in the tool description, future energy prices, carbon factors, and government incentives are also considered in order to reduce the level of uncertainty in the outputs. Additionally, exergoeconomic indicators (e.g. $Exec_{CB}$), combined with occupant thermal comfort outputs, are going to be used to develop a deep retrofit designs. In some cases, capital investment and NPV will also be considered to inform whether a specific retrofit measure would be used for a further combined design. To illustrate the outcomes of the series of BER measures applied individually, the results are presented in two parts: first for HVAC systems exclusively and a separate analysis for the rest of measures.

6.3.1 HVAC system retrofits

6.3.1.1 Primary School

For the school's case, H24: PV/T with supplemental electric boiler + CAV presents the best energy performance by lowering the building's EUI from 187.9 kWh/m²-year to 31.56 kWh/m²-year. Heat pumps-based designs, such as H21: GSHP + underfloor heating and H18: GSHP + CAV, presents the next best energetic performances with indexes of 77.6 and 78.8 kWh/m²-year respectively. On the other hand, H28: Biomass Boiler + wall heating presents the worst energy performance by increasing EUI to 210.0 kWh/m²-year. In economic terms, H24: PV/T system presents the lowest Life Cycle Cost due to receiving high rates of government incentives for generating and using both renewable electricity and renewable heat. However, this same system presents the highest capital investment, resulting in a simple payback of 39 years. In this sense, the system with the best return of investment performance is H31: mCHP and Electric Boiler + CAV with a simple payback of 2.8 years.

In terms of annual carbon emissions, H29: Biomass + underfloor achieves the best performance by reducing benchmark values to up to 60.7%, achieving emissions of 84.5 tCO_2/year; while H7: Electric Boiler + CAV presents the worst environmental performance with an increase of 94% compared to the benchmark value, achieving emissions with the magnitude of 471.4 tCO_2/year. Best occupant thermal comfort is achieved by H27: Condensing boiler + walls and underfloor heating, improving thermal conditions by 39.0%. Table 6-8 shows detailed outputs for all HVAC systems.

Table 6-8 Main energy and economic indicators related to HVAC oriented BER measures for a Primary School (best performance in green, worst performance in red)

HVAC code	Total Cost Retrofit Project (£)	Total EUI (kWh/m^2-year)	Annual Income (Savings + incentives) (£)	Annual Energy Bill (£)	Payback (years)	Annual tCO_2	Annual tCO_2 Reduction	Life Cycle Cost (50 years) (£)	NPV (50 years) (£)	Thermal discomfort (hours)
Base	-	187.9	-	19,449.3	-	214.8	-	500,425.4	-	1,443.1
H1	53,684.9	195.8	755.0	18,694.3	71.1	213.1	0.8%	532,847.1	-32,421.7	1,423.6
H2	43,687.8	107.8	5,564.7	13,884.6	7.9	141.9	34.0%	399,440.2	100,985.2	1,311.0
H3	193,697.7	147.8	528.0	18,921.3	366.8	202.9	5.6%	673,909.9	-173,484.5	1,436.2
H4	42,411.5	206.6	-7,787.1	27,236.3	n/a	289.8	-34.9%	741,744.7	-241,319.3	1,299.5
H5	36,221.7	111.5	2,045.4	17,403.9	17.7	173.2	19.4%	482,780.5	17,644.8	1,311.0
H6	189,944.5	152.5	-3,942.3	23,391.5	n/a	242.7	-13.0%	785,304.1	-284,878.7	1,436.2
H7	15,200.0	200.8	-28,813.0	48,262.2	n/a	417.4	-94.3%	1,256,455.,7	-756,030.3	1,299.5
H8	18,200.0	106.6	-6,170.3	25,619.6	n/a	221.6	-3.2%	676,762.5	-176,337.1	1,311.0
H9	200,319.4	149.9	-13,510.1	32,959.4	n/a	311.5	-45.0%	1,041,501.7	-541,076.3	1,436.2
H10	96,057.1	206.6	6,917.4	12,531.9	13.9	106.8	50.3%	415,214.0	85,211.4	1,299.5
H11	71,750.1	111.5	6,771.1	12,678.1	10.6	96.6	55.0%	395,500.6	104,924.7	1,311.0
H12	207,804.6	152.5	2,724.8	16,724.5	76.3	145.4	32.3%	631,012.5	-130,587.1	1,436.2
H13	32,101.2	204.1	-11,598.0	31,047.3	n/a	244.8	-14.0%	829,843.1	-329,417.7	1,299.5
H14	27,746.0	110.6	421.0	19,028.3	65.9	154.6	28.0%	516,390.8	-15,965.4	1,311.0
H15	33,208.6	161.0	-5,424.3	24,873.6	n/a	196.9	8.3%	672,063.4	-171,638.0	1,115.4
H16	51,022.8	121.3	-133.2	19,582.4	n/a	156.8	27.0%	553,128.3	-52,702.9	1,366.3
H17	69,782.5	148.1	-3,659.7	23,108.9	n/a	183.4	14.6%	661,982.1	-161,556.7	896.0
H18	262,036.8	78.8	3,401.4	16,047.9	77.0	163.8	23.7%	665,980.0	-165,554.6	1,316.7
H19	265,036.8	79.6	3,186.8	16,262.5	83.2	165.5	23.0%	674,398.0	-173,972.6	1,313.9

Table 6-8 cont. Main energy and economic indicators related to HVAC oriented BER measures for a Primary School (best performance in green, worst performance in red)

HVAC code	Total Cost Retrofit Project (£)	Total EUI (kWh/m^2-year)	Annual Income (Savings + incentives) (£)	Annual Energy Bill (£)	Payback (years)	Annual tCO_2	Annual tCO_2 Reduction	Life Cycle Cost (50 years) (£)	NPV (50 years) (£)	Thermal discomfort (hours)
H20	230,255.4	90.1	3,095.6	16,353.6	74.4	187.2	12.9%	643,152.3	-142,726.9	1,095.1
H21	257,098.6	77.6	3,898.9	15,550.4	65.9	161.2	24.9%	648,409.3	-147,983.9	1,371.5
H22	275,950.9	80.5	3,711.4	15,737.8	74.4	167.3	22.1%	671,440.1	-171,014.7	899.8
H23	66,859.0	108.3	-6,576.5	26,025.8	n/a	225.1	-4.8%	734,209.0	-233,783.6	1,373.3
H24	1,157,160.0	31.6	29,284.0	-9,834.7	39.5	172.6	19.6%	864,522.5	-364,097.2	1,317.4
H25	44,435.8	200.7	1,367.3	18,082.0	32.5	211.1	1.7%	508,159.9	-7,734.5	895.4
H26	62,599.2	127.1	5,855.3	13,594.0	10.7	148.3	31.0%	410,227.7	90,197.6	1,431.8
H27	81,304.8	155.8	4,127.0	15,322.3	19.7	172.6	19.6%	472,761.3	27,664.1	880.6
H28	60,516.8	210.0	8,110.0	11,339.3	7.5	97.5	54.6%	350,202.7	150,222.7	895.4
H29	79,565.0	132.3	8,566.3	10,882.9	9.3	84.5	60.7%	356,858.0	143,567.4	1,431.8
H30	98,133.5	162.6	8,415.6	11,033.7	11.7	89.3	58.4%	378,670.0	121,755.4	880.6
H31	42,280.0	134.6	15,274.2	4,175.0	2.8	145.0	32.5%	148,256.1	352,169.2	1,424.8
H32	72,692.8	86.8	8,034.8	11,414.4	9.0	115.8	46.1%	363,896.4	136,529.0	1,407.6

For thermal comfort performance, high-exergy HVAC systems with large heating emission areas (wall or underfloor heating) provide the best performance, but require larger investment costs, especially for the emission systems.

When considering Second Law indicators, H32: Condensing gas boiler + CAV + heat recovery system and H16: District heating + underfloor system presents the best thermodynamic performance with exergy destructions reduction of up to 80%; however, both fail to provide major thermal comfort improvements. It is H2: Condensing gas boiler + VAV that requires the lesser exergy input, reducing from a baseline value of 264.4 to 178.0 kWh_{ex}/m^2-year. Nevertheless, it is the designs H32 and H16 with the least overall exergy destructions. H16 improved the overall system exergy efficiency from 0.095 to 0.343, while H32 achieves an efficiency of 0.315. On the other hand, H7: Electric boiler + CAV presents the worst thermodynamic efficiency with 0.031.

In terms of exergoeconomics, H32 presents the least exergy destruction cost with £942.0/year, a significant reduction from the base case of £9,844.1/year. By analysing the final heating product price, H32 and H16 presented the best outcomes with £0.04/kWh and £0.08/kWh, representing just a slight increment from the initial entry price of the stream (gas: £0.03/kWh, district energy: £0.066/kWh, respectively) and a major improvement from the baseline final heating product price of £1.78/kWh.

By analysing the developed exergoeconomic cost benefit indicator $Exec_{CB}$ which considers exergy destruction costs, capital investment and revenue, H32 also achieves the best performance with an $Exec_{CB}$ of £0.71/h (compared to the £2.72/h for the baseline case). The total capital cost for the system is found at £72,692 with a DPB of 10.7 years. As aforementioned, as a product of the RHI government incentive, the system with the highest NPV and lowest DPB is H31: micro-CHP system. On the other hand, for the H24: PV/T system, the amount of electricity generated by the photovoltaic panels that is used exclusively for heating purposes has been highly penalised by exergoeconomic analysis, achieving an $Exec_{CB}$ of £5.96/h. Systems where incentives help to achieve low payback periods, such as biomass boilers, can achieve better exergoeconomic results by using energy sources with lower energy quality levels such as wood pallets.

Table 6-9 shows a recap of the most important exergy and exergoeconomic indicators for each HVAC design.

Table 6-9 Main exergy and exergoeconomic indicators related to HVAC oriented BER measures for a Primary School (best performance in green, worst performance in red)

HVAC code	Primary exergy input (kWh_{ex}/ m²-year)	Exergy dest. (kWh_{ex}/ m²-year)	Exergy efficiency Ψ Building (-)	Exergy dest. Cost Stream: heat (£)	Exergy dest. Cost Stream: cold (£)	Price Fuel Stream: heat (£/kWh)	Price Fuel Stream: cold (£/kWh)	Price Product Stream: heat (£/kWh)	Price Product Stream: cold (£/kWh)	Exergy dest. cost rate (£/h)	BER Capital Cost rate (£/h)	Annual revenue rate (£/h)	$Exec_{CB}$
Base	267.4	241.9	0.095	9,844.1	n/a	0.03	n/a	1.79	n/a	2.72	--	--	2.72
H1	265.4	246.2	0.072	15,691.0	n/a	0.03	n/a	2.37	n/a	3.46	0.23	0.09	3.61
H2	178.0	156.3	0.122	3,019.0	n/a	0.03	n/a	0.63	n/a	1.44	0.19	0.64	0.99
H3	282.4	263.1	0.068	18,063.7	n/a	0.03	n/a	2.64	n/a	3.87	0.83	0.06	4.64
H4	282.4	263.1	0.068	30,103.3	n/a	0.05	n/a	4.39	n/a	6.00	0.18	-0.89	7.07
H5	184.2	162.5	0.118	5,688.5	n/a	0.05	n/a	1.18	n/a	2.10	0.16	0.23	2.02
H6	282.4	263.1	0.068	30,104.8	n/a	0.05	n/a	4.39	n/a	6.00	0.81	-0.45	7.26
H7	520.2	503.7	0.032	56,263.8	n/a	0.12	n/a	10.95	n/a	11.64	0.07	-3.29	14.99
H8	214.9	194.2	0.096	9,847.0	n/a	0.12	n/a	2.65	n/a	3.49	0.08	-0.70	4.27
H9	314.6	295.4	0.061	76,251.7	n/a	0.12	n/a	11.07	n/a	14.13	0.86	-1.54	16.53
H10	314.6	295.4	0.061	25,417.5	n/a	0.04	n/a	3.69	n/a	5.16	0.41	0.79	4.78
H11	197.7	176.0	0.110	4,791.0	n/a	0.04	n/a	0.99	n/a	1.88	0.31	0.77	1.41
H12	301.7	282.5	0.064	24,764.4	n/a	0.04	n/a	3.60	n/a	5.06	0.89	0.31	5.64
H13	301.7	282.5	0.064	43,334.3	n/a	0.07	n/a	6.31	n/a	8.34	0.14	-1.32	9.80
H14	235.8	214.1	0.092	9,926.3	n/a	0.07	n/a	1.69	n/a	2.93	0.12	0.05	3.00
H15	246.0	183.0	0.256	9,007.4	n/a	0.07	n/a	0.15	n/a	3.79	0.14	-0.62	4.55
H16	202.6	133.0	0.343	1,772.1	n/a	0.07	n/a	0.09	n/a	2.40	0.22	-0.02	2.63
H17	229.8	160.2	0.303	5,295.8	n/a	0.07	n/a	0.11	n/a	3.16	0.30	-0.42	3.88
H18	389.1	334.3	0.141	17,166.6	n/a	0.12	n/a	0.29	n/a	5.88	1.12	0.39	6.62
H19	357.3	301.4	0.156	6,309.9	n/a	0.12	n/a	0.19	n/a	3.74	1.14	0.36	4.52

Table 6-9 cont. Main exergy and exergoeconomic indicators related to HVAC oriented BER measures for a Primary School (best performance in green, worst performance in red)

HVAC code	Primary exergy input (kWh_{ex}/ m²-year)	Exergy dest. (kWh_{ex}/ m²-year)	Exergy efficiency Ψ Building (-)	Exergy dest. Cost Stream: heat (£)	Exergy dest. Cost Stream: cold (£)	Price Fuel Stream: heat (£/kWh)	Price Fuel Stream: cold (£/kWh)	Price Product Stream: heat (£/kWh)	Price Product Stream: cold (£/kWh)	Exergy dest. cost rate (£/h)	BER Capital Cost rate (£/h)	Annual revenue rate (£/h)	$Exec_{CB}$
H20	261.4	204.9	0.216	3,657.0	n/a	0.12	n/a	0.16	n/a	3.30	0.99	0.35	3.94
H21	256.2	199.8	0.220	7,431.7	n/a	0.12	n/a	0.20	n/a	4.12	1.10	0.45	4.78
H22	258.7	202.1	0.219	6,873.2	n/a	0.12	n/a	0.19	n/a	4.00	1.18	0.42	4.76
H23	284.2	227.1	0.201	2,099.8	n/a	0.12	n/a	0.14	n/a	2.95	0.29	-0.75	3.99
H24	334.8	302.3	0.097	24,642.0	n/a	0.12	n/a	4.21	n/a	5.59	4.96	3.34	7.21
H25	265.2	200.7	0.243	6,571.1	n/a	0.03	n/a	0.08	n/a	2.47	0.19	0.16	2.50
H26	257.8	186.7	0.276	5,893.3	n/a	0.03	n/a	0.07	n/a	2.39	0.27	0.67	1.99
H27	234.7	164.0	0.301	3,675.3	n/a	0.03	n/a	0.06	n/a	1.96	0.35	0.47	1.84
H28	314.7	250.2	0.205	11,857.1	n/a	0.04	n/a	0.12	n/a	3.69	0.26	0.93	3.02
H29	263.4	192.3	0.270	6,534.3	n/a	0.04	n/a	0.08	n/a	2.77	0.34	0.98	2.13
H30	254.6	183.8	0.278	4,841.0	n/a	0.04	n/a	0.07	n/a	2.44	0.42	0.96	1.90
H31	235.4	173.9	0.261	24,139.8	n/a	0.15	n/a	0.37	n/a	7.53	0.18	1.74	5.97
H32	180.7	123.8	0.315	942.0	n/a	0.03	n/a	0.04	n/a	1.32	0.31	0.92	0.72

In addition, Figure 6-30 illustrates the results for all the analysed HVAC systems by comparing the developed $\boldsymbol{Exec_{CB}}$ with thermal discomfort. These indices are considered two important objectives for cost-effective exergy-efficient building design.

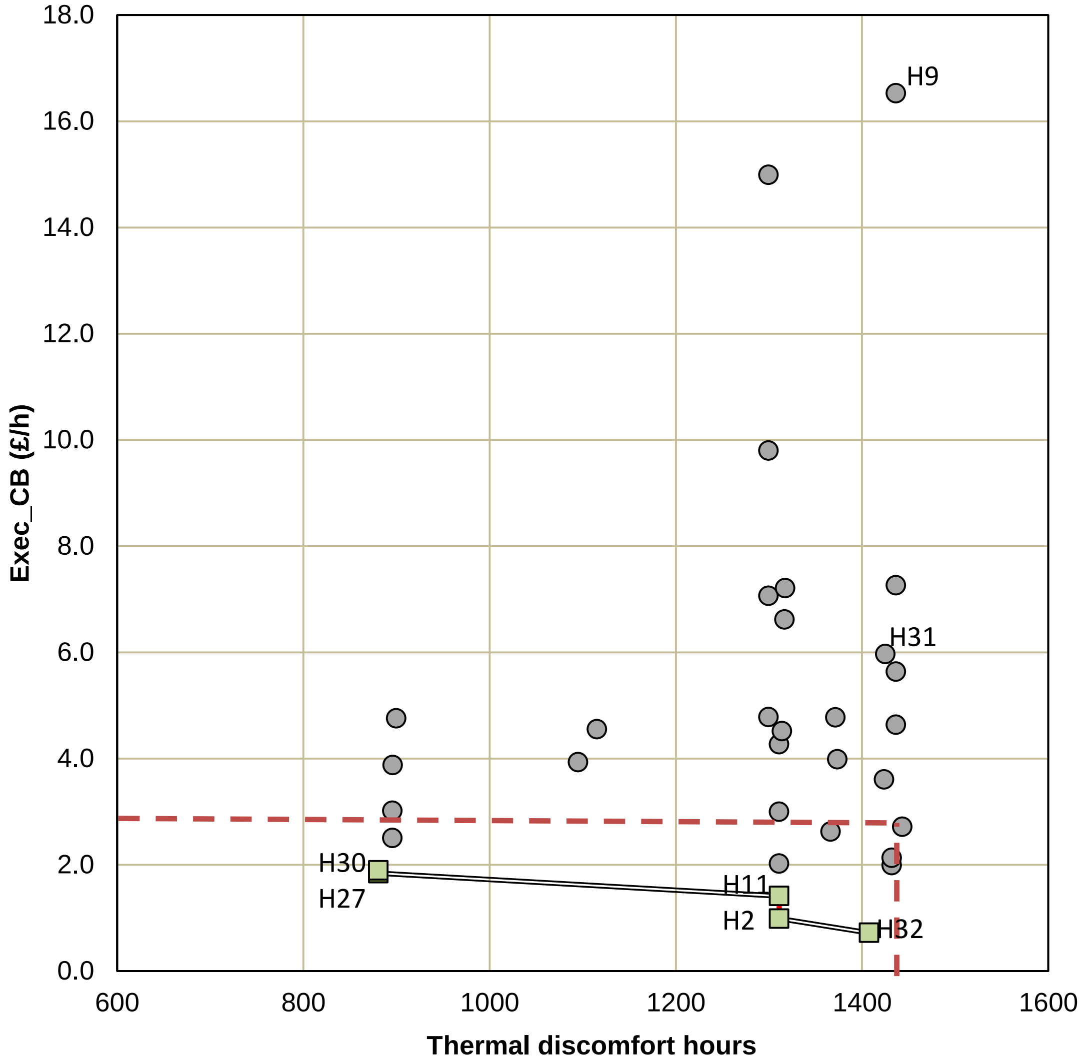


Figure 6-30 Primary School: HVAC systems $Exec_{CB}$ performance against thermal discomfort

The red doted lines represent the baseline values for each index. As seen, just 10 out of 32 designs were able to improve both indicators, and just five solutions are identified in the Pareto front. Biomass-based designs (H11, H27, H30) dominate the Pareto front, representing designs that are both exergoeconomically-efficient and provide improved levels of thermal comfort. H31, which initially presented good energetic and economic performance, failed to improve both indices. Finally, H9 system based on electric heating, presents the worst performance by not improving either indicator.

6.3.1.2 A/C Office

For the office case, H24: PV/T with supplemental electric boiler + old chiller + CAV present the best energy performance by lowering the building's EUI from 288.5 to 166.6 kWh/m²-year. Similar to the primary school case, system designs based on heat pumps also achieves considerable reductions. On the other hand, only one design presents a worse energy performance compared to the baseline, being H14: District system + VAV which demands 297.5 kWh/m²-year, mainly due to poor performance in the cooling season. In economic terms, similarly to the school's case, H24 presents the lowest Life Cycle Cost, thanks to the support of the government incentives. The main drawback associated with this design is the high capital investment required (£873,200 with a DPB of 19.7 years). Systems such as H20: GSHP + wall heating/cooling, H31: Micro-CHP with a fuel cell and electric boiler and old chiller, and H32: Condensing gas boiler and old chiller with a CAV + a heat recovery, all present payback periods of less than 6 years.

In terms of annual carbon emissions, H32 achieves the most GHG reductions (24.1%), with emissions of 216.7 tCO_2/year. On the other hand, H8: Electric Boiler + chiller +VAV presents the worst environmental performance with an increase of 27.2% compared to the benchmark value, achieving emissions with a value of 363.3 tCO_2/year. When analysing occupant thermal comfort, HVAC retrofits achieved better conditions than those found in the school's case. H29: Biomass Boiler + chiller + underfloor system presents just 167.8 of uncomfortable hours, a reduction of 88.1%. However, all the systems based on CAV emission system achieved the worst thermal comfort performance by not improving comfort conditions. Table 6-10 shows detailed outputs for all systems applied to A/C Office case.

Table 6-10 Main energy and economic indicators related to HVAC oriented BER measures for an A/C Office (best performance in green, worst performance in red)

HVAC code	Total Cost Retrofit Project (£)	Total EUI (kWh/m²-year)	Annual Income (Savings + incentives) (£)	Annual Energy Bill (£)	Simple Payback (years)	Annual tCO_2	Annual tCO_2 Reduction	Life Cycle Cost (50 years) (£)	NPV (50 years) (£)	Thermal discomfort (hours)
base	--	288.54	--	59,625.3	--	285.6	--	1,534,145.93	--	1,413.8
H1	130,395.3	240.29	4,685.7	54,939.6	27.8	255.9	10.4%	1,539,517.12	-5,371.2	1,413.7
H2	97,674.6	267.42	-7,259.6	66,884.9	n/a	304.4	-6.6%	1,815,265.99	-281,120.1	621.5
H3	402,080.4	247.57	-1,615.3	61,240.6	n/a	287.6	-0.7%	1,964,028.75	-429,882.8	559.2
H4	107,661.1	245.06	-1,233.1	60,858.4	n/a	282.3	1.2%	1,669,849.66	-135,703.7	1,413.7
H5	86,317.8	271.38	-12,164.5	71,789.9	n/a	326.3	-14.2%	1,930,501.04	-396,355.1	621.5
H6	393,849.5	250.83	-5,659.2	65,284.5	n/a	305.6	-7.0%	2,060,128.38	-525,982.5	559.2
H7	63,682.0	243.16	-16,414.2	76,039.6	n/a	328.8	-15.1%	2,017,983.52	-483,837.6	1,413.4
H8	70,581.3	268.68	-24,393.2	84,018.6	n/a	363.3	-27.2%	2,229,943.98	-695,798.1	621.9
H9	416,602.0	250.83	-14,692.1	74,317.4	n/a	339.2	-18.8%	2,314,517.72	-780,371.8	559.2
H10	215,844.3	245.06	9,807.4	49,817.9	22.0	217.9	23.7%	1,490,261.76	43,884.2	1,413.7
H11	140,360.2	271.38	-3,193.7	62,819.0	n/a	272.9	4.4%	1,751,875.44	-217,729.5	621.5
H12	433,017.0	250.83	1,554.0	58,071.3	278.6	261.6	8.4%	1,912,362.01	-378,216.1	559.2
H13	54,242.6	251.77	-4,210.6	63,835.9	n/a	263.3	7.8%	1,694,869.80	-160,723.9	1,413.7
H14	35,262.3	297.53	-12,935.2	72,560.5	n/a	286.5	-0.3%	1,901,020.34	-366,874.4	621.5
H15	62,769.5	219.54	2,616.0	57,009.3	24.0	234.9	17.7%	1,527,458.14	6,687.8	1,378.9
H16	109,109.7	258.66	-3,863.6	63,489.0	n/a	254.7	10.8%	1,738,932.63	-204,786.7	224.9
H17	153,524.7	271.39	-6,071.8	65,697.2	n/a	262.5	8.1%	1,838,643.88	-304,497.9	263.9
H18	316,901.0	174.62	8,694.4	50,930.9	36.4	236.1	17.3%	1,616,497.92	-82,352.0	1,060.8
H19	319,901.0	177.25	7,873.9	51,751.4	40.6	239.7	16.1%	1,640,506.77	-106,360.8	1,054.7

Table 6-10 Main energy and economic indicators related to HVAC oriented BER measures for an A/C Office (best performance in green, worst performance in red)

HVAC code	Total Cost Retrofit Project (£)	Total EUI (kWh/m²-year)	Annual Income (Savings + incentives) (£)	Annual Energy Bill (£)	Simple Payback (years)	Annual tCO_2	Annual tCO_2 Reduction	Life Cycle Cost (50 years) (£)	NPV (50 years) (£)	Thermal discomfort (hours)
H20	49,415.0	170.7	11,232.0	48,393.3	4.4	230.8	19.2%	1,292,873.19	241,272.7	1,321.9
H21	95,426.0	163.59	11,740.6	47,884.7	8.1	221.2	22.5%	1,324,223.21	209,922.7	785.7
H22	139,841.0	164.69	11,598.4	48,026.9	12.1	222.7	22.0%	1,370,776.76	163,369.2	898.1
H23	127,288.9	200.65	-3,118.9	62,744.3	n/a	271.3	5.0%	1,737,328.28	-203,182.4	664.9
H24	873,200.0	116.55	59,296.5	328.8	14.7	289.1	-1.2%	851,782.74	682,363.2	739.2
H25	102,438.9	269.43	-1,802.4	61,427.7	n/a	286.3	-0.3%	1,679,455.09	-145,309.2	1,201.9
H26	150,684.6	262.61	-2,463.2	62,088.6	n/a	286.7	-0.4%	1,743,053.30	-208,907.4	168.9
H27	195,099.6	278.34	-3,952.2	63,577.6	n/a	296.2	-3.7%	1,824,259.44	-290,113.5	205.0
H28	126,263.8	274.82	4,120.8	55,504.6	30.6	243.3	14.8%	1,550,062.49	-15,916.6	1,201.9
H29	175,150.7	267.16	2,642.1	56,983.2	66.3	248.8	12.9%	1,635,322.51	-101,176.6	167.8
H30	219,565.7	283.88	2,166.0	57,459.3	101.4	252.0	11.8%	1,690,467.74	-156,321.8	205.0
H31	36,280.0	254.25	7,546.7	52,078.6	4.8	271.8	4.8%	1,375,009.24	159,136.7	704.9
H32	66,692.8	185.88	11,646.7	47,978.7	5.7	216.7	24.1%	1,298,890.23	235,255.7	1,134.6

The best exergetic performance is obtained by H32: Boiler + electric boiler and old chiller + heat recovery system, achieving an HVAC exergy efficiency of 0.198 and the lowest primary exergy input, reducing it from a baseline value of 550.0 to 415.9 kWh_{ex}/m^2-year. Other systems with good performance are H21: Ground source heat pump + underfloor and H22: Ground source heat pump + underfloor and wall heating with an exergy efficiency of 0.185.

In terms of exergoeconomics, H21 and H22 presents the lowest heating exergy destruction cost with £737.3/year and £892.1/year respectively, a significant reduction from the base case of £11,624.8/year. However, for cooling, the design with the least exergy destruction cost is H26: Cond. gas boiler + chiller + underfloor with a total value of £58.8/year, representing a major improvement as the baseline value stood at £6,383.5/year. When analysing the final product price of the heating stream, H32 obtains the lowest value with 0.07 £/kWh; however, for the cooling product it was still high at 25.63 £/kWh, due to the fact that the old chiller was not retrofitted and the potential of using the recovery system for cooling was being wasted. H26 presents the lowest final product price for cooling with a value of 0.13 £/kWh, as this design took advantage of highly efficient chillers with large radiator areas.

However, it is the system H32 that achieves the best cost-benefit exergoeconomic performance with an $Exec_{CB}$ of £2.25/h (well below the £6.25/h of the baseline case). The total capital cost for H32 is £66,693 with a DPB of 6.4 years. In addition, designs based on GSHP present the lowest exergy destructions and primary exergy input. The GSHP with underfloor heating (H21) also achieves good exergoeconomic performance with an $Exec_{CB}$ of £4.64/h, but requiring a much higher capital investment at £409,564, providing a DPB of 34.9 years. On the other hand, the exergy analysis performed on H24: PV/T system, highly penalises it due to the fact that electricity is being used for heating and cooling purposes (regardless if it comes from a renewable source) resulting in a $Exec_{CB}$ of £9.11/h. Table 6-11 shows a summary of the most important exergy and exergoeconomic indicators for each HVAC design.

Table 6-11 Main exergy and exergoeconomic indicators related to HVAC oriented BER measures for an A/C Office (best performance in green, worst performance in red)

HVAC code	Primary exergy input (kWh_{ex}/ m²-year)	Exergy dest. (kWh_{ex}/ m²-year)	Exergy efficiency Ψ Building (-)	Exergy dest. Cost Stream: heat (£)	Exergy dest. Cost Stream: cold (£)	Price Fuel Stream: heat (£/kWh)	Price Fuel Stream: cold (£/kWh)	Price Product Stream: heat (£/kWh)	Price Product Stream: cold (£/kWh)	Exergy dest. cost rate (£/h)	BER Capital Cost rate (£/h)	Annual revenue rate (£/h)	$Exec_{CB}$
base	**550.0**	**465.5**	0.154	11624.8	6383.5	0.03	0.12	0.43	6.28	6.25	-	-	6.25
H1	**494.1**	**409.5**	0.171	7174.3	3770.3	0.03	0.12	0.28	3.81	4.92	0.56	0.53	4.94
H2	**586.0**	**495.3**	0.155	5094.0	26683.1	0.03	0.12	0.36	11.02	8.36	0.42	-0.83	9.61
H3	**626.4**	**548.0**	0.125	8681.5	3151.1	0.03	0.12	0.67	3.51	5.14	1.72	-0.18	7.05
H4	**502.1**	**417.5**	0.168	13631.9	3770.3	0.05	0.12	0.52	3.81	6.30	0.46	-0.14	6.91
H5	**592.7**	**502.0**	0.153	9631.4	26683.1	0.05	0.12	0.67	11.02	9.42	0.37	-1.39	11.18
H6	**631.9**	**553.5**	0.124	14578.4	3151.1	0.05	0.12	1.19	3.51	6.48	1.69	-0.65	8.81
H7	**632.4**	**551.6**	0.128	27208.3	3773.2	0.12	0.12	1.34	3.82	9.87	0.27	-1.87	12.02
H8	**597.1**	**508.0**	0.149	23514.3	26683.3	0.12	0.12	1.52	11.02	12.44	0.30	-2.78	15.53
H9	**723.8**	**645.4**	0.108	35380.1	3868.6	0.12	0.12	2.90	3.51	11.02	1.79	-1.68	14.48
H10	**519.5**	**435.0**	0.163	11518.0	3770.3	0.04	0.12	0.44	3.81	5.84	0.92	1.12	5.65
H11	**607.1**	**516.4**	0.149	8122.3	26683.1	0.04	0.12	0.57	11.02	9.06	0.60	-0.36	10.03
H12	**571.6**	**493.1**	0.137	12023.5	3151.1	0.04	0.12	0.98	3.51	5.92	1.86	0.18	7.60
H13	**517.1**	**433.1**	0.162	19878.6	7154.4	0.07	0.07	0.76	6.87	8.21	0.23	-0.48	8.92
H14	**614.3**	**527.0**	0.142	19691.3	40774.4	0.07	0.07	0.97	15.91	13.24	0.15	-1.48	14.87
H15	**464.0**	**381.9**	0.177	8516.7	4493.2	0.07	0.07	0.28	25.73	6.01	0.27	0.30	5.98
H16	**514.4**	**435.1**	0.154	12919.2	10195.1	0.07	0.07	0.44	19.05	8.11	0.47	-0.44	9.02
H17	**531.9**	**452.4**	0.15	15473.9	10553.1	0.07	0.07	0.50	14.09	8.75	0.66	-0.69	10.11
H18	**690.2**	**599.8**	0.131	37993.3	9630.0	0.12	0.12	0.86	30.98	12.77	1.36	0.99	13.13
H19	**699.5**	**606.9**	0.132	38315.5	10083.3	0.12	0.12	0.87	30.85	12.93	1.37	0.90	13.40

Table 6-11 cont. Main exergy and exergoeconomic indicators related to HVAC oriented BER measures for an A/C Office (best performance in green, worst performance in red)

HVAC code	Primary exergy input (kWhex/ m²-year)	Exergy dest. (kWhex/ m²-year)	Exergy efficiency Ψ Building (-)	Exergy dest. Cost Stream: heat (£)	Exergy dest. Cost Stream: cold (£)	Price Fuel Stream: heat (£/kWh)	Price Fuel Stream: cold (£/kWh)	Price Product Stream: heat (£/kWh)	Price Product Stream: cold (£/kWh)	Exergy dest. cost rate (£/h)	BER Capital Cost rate (£/h)	Annual revenue rate (£/h)	$Exec_{CB}$
H20	**449.7**	**369.1**	0.179	2806.9	3399.6	0.12	0.12	0.20	12.97	4.75	0.21	1.28	3.68
H21	**431.9**	**352.2**	0.185	737.3	3474.3	0.12	0.12	0.14	1.76	4.28	0.41	1.34	3.35
H22	**432.8**	**352.8**	0.185	892.1	2696.1	0.12	0.12	0.15	2.70	4.18	0.60	1.32	3.45
H23	**522.2**	**439.0**	0.159	10314.2	4078.0	0.12	0.12	0.39	3.30	6.52	0.55	-0.36	7.42
H24	**774.0**	**653.8**	0.155	41438.1	6672.1	0.12	0.12	2.42	63.88	12.14	3.74	6.77	9.11
H25	**547.4**	**444.5**	0.188	8837.1	616.8	0.03	0.12	0.19	0.59	4.88	0.44	-0.21	5.53
H26	**544.6**	**439.6**	0.193	7600.7	58.8	0.03	0.12	0.18	0.13	4.61	0.65	-0.28	5.54
H27	**563.9**	**459.4**	0.185	9768.5	967.4	0.03	0.12	0.22	0.28	5.17	0.84	-0.45	6.45
H28	**576.2**	**473.3**	0.179	14585.6	616.8	0.04	0.12	0.30	0.59	6.02	0.54	0.47	6.09
H29	**569.7**	**464.7**	0.184	12570.4	97.6	0.04	0.12	0.29	0.13	5.61	0.75	0.30	6.05
H30	**593.5**	**489.0**	0.176	16129.7	967.4	0.04	0.12	0.34	0.28	6.39	0.94	0.25	7.08
H31	**569.0**	**456.9**	0.197	30937.1	5324.7	0.15	0.12	0.79	3.20	11.21	0.16	0.86	10.51
H32	**415.9**	**333.7**	0.198	1426.1	629.8	0.03	0.12	0.07	25.64	3.30	0.29	1.33	2.25

Relating exergy consumption to occupant thermal comfort, it is found that high-exergy systems (condensing gas and biomass boilers) with underfloor heating (H26, H29 respectively) provide the best thermal comfort performance. Figure 6-31 shows the results for all the analysed HVAC systems, displaying the best solutions in the Pareto front. All the systems located inside the dotted square represent an improvement in both the exergoeconomic cost-benefit and occupant thermal comfort indicators.

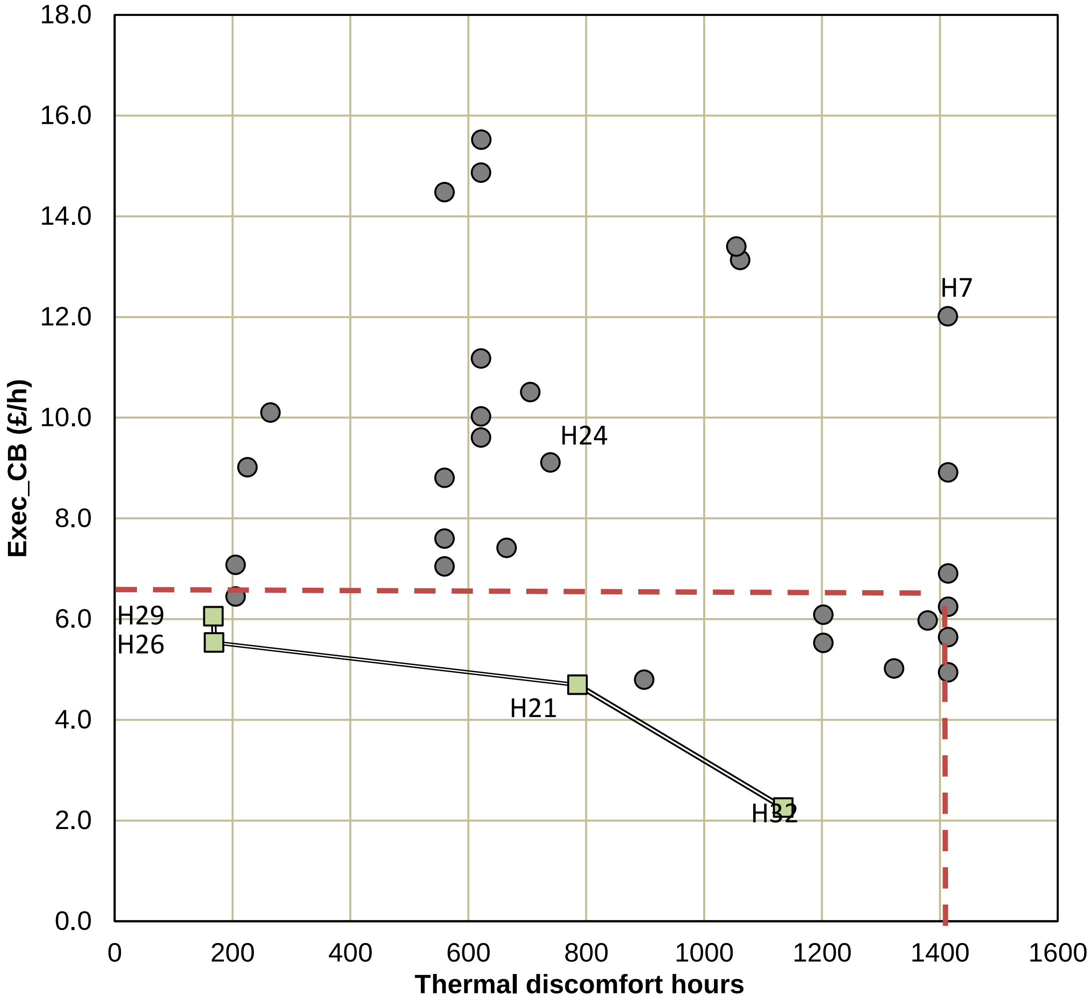


Figure 6-31 A/C Office: HVAC systems $Exec_{CB}$ performance against thermal discomfort

As illustrated, again just 10 out of 32 designs were able to improve both indicators, with just four solutions in the Pareto front. In this case, there is no single primary system that dominates the Pareto front; however, the underfloor heating/cooling system is in three out of four designs (H21, H26, H29). H24, which initially presented good energy performance and the lowest life cycle cost, failed to improve both indices. Finally, it is H9 system based on electric heating/cooling +CAV that presents the worst performance by not improving either indicator.

6.3.2 Non-HVAC retrofits

To provide a clearer indication of the impact of the rest of retrofit solutions, these have been differentiated into passive measures *(insulation, glazing, sealing, and set-points)* and active measures *(lighting and renewable systems).* It is expected that non-HVAC solutions do not achieve any significant system exergy efficiency improvement; however, it has a high potential to reduce the total exergy destructions footprint by lowering the building's energy/exergy demand. They also hold great potential for improving the building's economics and improving occupant thermal comfort. Given the model's complexity and interaction among different simulation tools, the framework may not capture all the issues of comfort, maintenance and actual building energy and economic performance.

Due to the number of measures, it is infeasible to present detailed output tables as shown in the last section for the HVAC systems. Nevertheless, these are attached in Appendix D. In the following sections, a more focused analysis is done by identifying the best solutions per technology/measure under the same indicators analysed in the previous section.

6.3.2.1 Primary School

For the school's case, and leaving other model's properties at baseline values, almost all insulation measures presented an improvement in the analysed indicators due an improvement in envelope characteristics. Polyurethane (0.14m) achieve the minimum energy use demand with a reduction of 14.8% (159.3 kWh/m²-year), thus reducing building's exergy destructions by 12%. In economic terms, with investments close to £200k, corkboard (0.065m) and EPS (0.06m) presents the most favourable NPVs with DPB as low as 13 years. Again, 0.14m of Polyurethane achieved the best comfort conditions with an improvement of 11%. For exergoeconomic indicators, 'glass fibre' with a thickness of 0.085m produces the best overall performance, where aside from achieving a DBP of 13 years with an investment of £20,105, it presents the lowest $Exec_{CB}$ among insulation measures with a value of £2.25/h. Added to this, an improvement of 10% in thermal comfort conditions, 12% in energy savings, and 10% in irreversibilities minimisation is also accomplished. The U_{values} (W/m²-K) for this measure stand at 0.33 for the wall, 0.37 for the roof and 0.32 for the ground floor, where no element compiles with Part L2 building regulations.

Glazing systems failed to provide any considerable energy savings and also performed poorly in terms of economic indicators, where seasonal occupancy does not justify its installation without the support of other measures. Nevertheless, the best overall performance is achieved for the triple-glazing system with a 6mm gap of Argon gas, delivering a reduction in energy demand of only 1.9%. In addition, all measures prove to be economically infeasible and do not provide any improvement in thermal comfort. Exergoeconomically, none of the systems are able to improve the baseline $Exec_{CB}$ due to high investment cost, low reductions of exergy destructions and low generated revenue.

For airtightness measures, as expected the maximum improvement of infiltration rates (of 90% from 1.0 *ach* to 0.1 ach) provide the largest energy savings by reducing the demand by 11.5% and delivering the best thermal comfort conditions. However, considering a trade-off between investment and energy savings, a 30% in airtightness improvement reach a 3.8% of energy savings with a positive NPV. Measures above this point do not provide any larger economic benefits. Exergetically, a similar behaviour can be seen, as an improvement of 90% of airtightness provides the largest reduction of primary exergy input and exergy destructions; however, as this comes with a large capital investment, and with the envelope as a part of the 'building energy system', the final product cost of heat increases with tighter envelopes. However, this highly depends on the chosen ventilation system. If the ventilation system is properly selected and maintained, an airtight building could provide high levels of thermal comfort (Lowe, 2000), while being a cost-effective solution. When considering the $Exec_{CB}$, an improvement of 70% in infiltration rates produces the best $Exec_{CB}$ with a value of £2.54/h, while improving thermal comfort by 4%; however, after improving the infiltration up to 30%, no major improvement can be seen for the $Exec_{CB}$ (Figure 6-32).

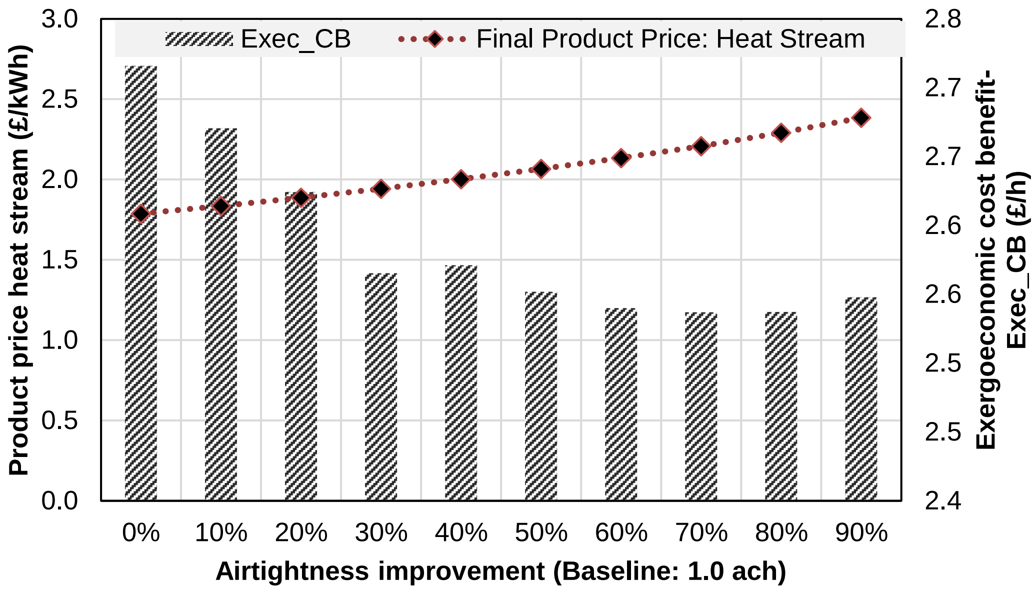


Figure 6-32 Heat stream final product price and Exec_CB for envelope airtightness improvement in a Primary School

Low set-points (18°C) naturally achieve better energy, exergy and exergoeconomic performance ($Exec_{CB}$= £2.31/h); however, this comes with a decrease in comfort conditions by 1%. On the other hand, a set-point of 22 °C has a poor exergoeconomic performance ($Exec_{CB}$= £3.70/h), but increases thermal comfort by 21%.

Among lighting technologies, LED system achieved the best energy results with the reduction of energy use by 3.9%. However, no lighting measure achieved a positive NPV. Exergetically, LED lighting system achieved a reduction of 9.9% in both primary exergy input and total building exergy destructions, showing the share of electric exergy on the overall system. However, while large investment, necessary to install this type of measure, minimises exergy destruction cost in great quantities, the exergoeconomic indicators do not improve significantly, compared to the baseline values.

For renewable measures, PV panels, covering 75% of the roof area, achieved the best energy performance, reducing the demand of electric energy from the grid, resulting in an overall EUI improvement of 37.5%. However, as this measure requires an investment of £1,027,764, even considering government incentives, the NPV would not break even in the next 50 years. Just the 20 kW stand-alone wind turbine is able to provide a positive NPV among the renewable measures[10].

As exergy analysis does not consider renewable exergy electricity as 'free' electricity, primary exergy input and exergy destructions were not minimised due to the fact that electricity was still being used for the same end-use purposes. In this sense, exergy analysis promotes a smart relation between the quality of the supply and the quality of the demand. For example, even if renewable electricity is being used for heating purposes, the analysis will show an inefficient system. A differentiation can be achieved with exergoeconomics, as electric energy sources have different price per kWh to those coming from the grid; however due to high investment cost of renewable technologies, improvements are difficult to achieve. Therefore, energy stream cost formation, instead of coming from thermodynamic inefficiecnies could come from high capital cost investments. In this sense, only the R4: 20 kW turbine achieved an improvement of the $Exec_{CB}$ at £2.70/h. The installation of stand-alone PV panels without the improvement on other areas or the smart redirection of the electricity to appropriate end-uses, will always provide poor exergoeconomic results.

To show an overall analysis of all non-HVAC BER applied to the school archetype, Figure 6-33 illustrates the results compared to the baseline case, locating those that have a better exergoeconomic cost benefit performance and occupant thermal comfort performance.

[10] However, due to the limitations of the model, the option of wind technology has to be taken with care, as the effect that the wind environment could be unsuitable for a wind turbine (as in the specific case for London, UK).

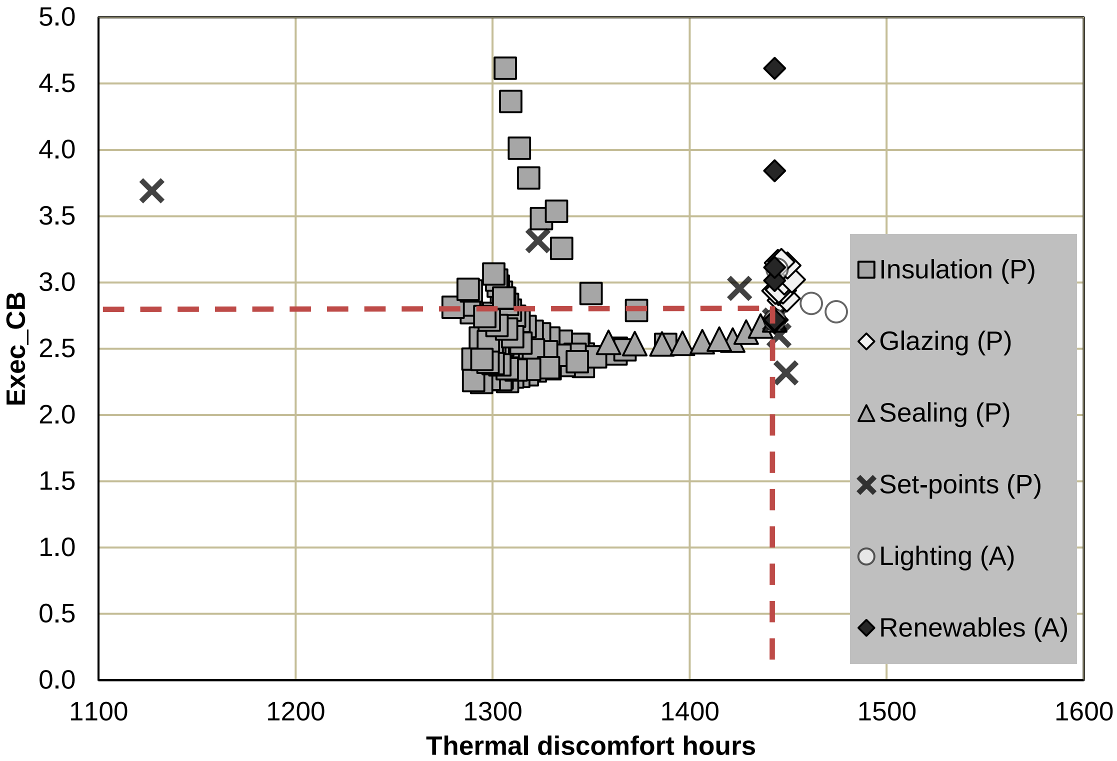


Figure 6-33 Primary School: All BERs (no HVAC) $Exec_{CB}$ performance against thermal discomfort

6.3.2.2 A/C Office

For measures applied to the A/C Office case study, insulation technologies such as 0.30m of corkboard (I6) and 0.15m of polyurethane (I1) achieved energy savings of around 10% and reduction in exergy destructions of 6%. However, economically, the best performer was 0.03m of EPS (expanded polystyrene), with a capital cost of £14,349 and a DPB of 11.6 years. This solution minimises energy use by 7% and exergy destructions by 4%. The insulation technologies that provide the best thermal comfort are 0.05m of XPS (Extruded polystyrene) and 0.05m of EPS (expanded polystyrene), with an improvement of 5%. In general, the application of insulation measures does not impact significantly discomfort reduction, mainly due to the appearance of overheating hours in the cooling season, therefore switching uncomfortable conditions from winter to summer. Exergoeconomically, the best insulation is 0.13m EPS, having a $Exec_{CB}$ as low as £5.67/h, representing reduction of £0.58/h below the baseline case. The envelope U_{values} (W/m²-K) for this solution are: 0.38 for the wall, 0.43 for the roof and 0.25 for the ground floor. Just the ground floor compiles with Part L2 building regulations. Other insulation technologies with good exergoeconomic performance are glass fibre and phenolic foam board

Glazing systems presented a better performance than those found in the case of the school as they also had an impact during the cooling months. Triple glazing systems with 6mm gaps[11] of Argon or Air achieved the highest energy savings among the glazing measures, with reductions of up to 8.2%. However, economically none of the glazing systems reached a positive NPV during the project's lifetime (50 years), mainly because of high capital investment cost (DPBs were no less than 80 years and $Exec_{CB}$ were higher than the baseline for all the cases). The best exergoeconomic indicator was achieved by double glazing with 13mm air gap (G2) with an $Exec_{CB}$ of £6.29/h.

On the other hand, a hypothetical reduction of the infiltration rate achieved better economic and exergoeconomic results than those found in other passive measures. By tightening the envelope up to 90% from the baseline case, energy savings of 25.5% can be achieved. However, an improvement of 60% achieved the highest NPV with an investment of £54,327 and a DPB of 17.7 years. Exergoeconomically, a linear relationship exists between the airtightness reduction and exergoeconomic cost benefit, with 90% improvement, presenting the best outcome with $Exec_{CB}$ of £4.65/h (Figure 6-34). It also presents lower product prices for both heating and cooling streams, with final product prices of £0.29/kWh and £3.76/kWh respectively. Unlike in the school's case, an airtight envelope with high energy and exergy efficient HVAC design could provide a good overall performance throughout the year.

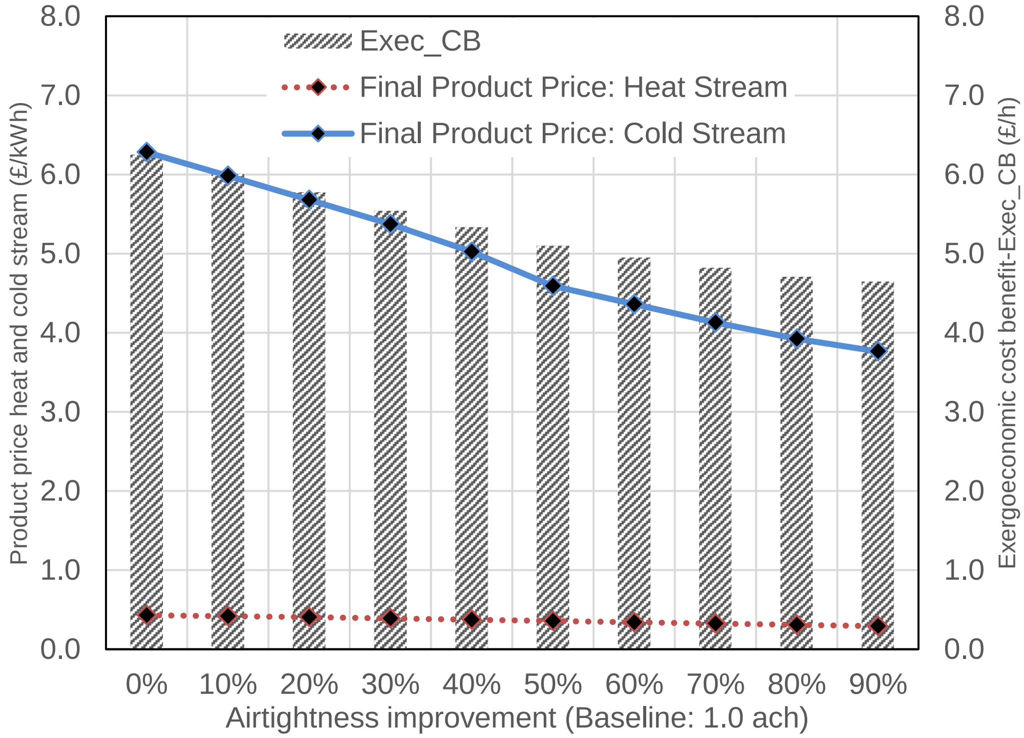


Figure 6-34 Heat and cold streams final product price and Exec_CB for envelope airtightness improvement in a Primary School

[11] In practical cases, a 6 mm air or Argon gap could be less than optimal. Currently, optimal gaps are around 12 and 10mm respectively. These features will be updates in a future version of ExRET-Opt

Changing set-points is always a trade-of between obtaining better thermal comfort and achieving energy savings. Set-points of 22 °C for heating, and 23°C for cooling provided the best comfort performance but did not produce any significant exergoeconomic change, both measures having an $Exec_{CB}$ of £6.24/h.

For the active measures, L3: LED-based lighting achieved the largest minimisation for energy use (7.4%) and exergy destructions (15%), by also providing the best $Exec_{CB}$ indicator (£4.95/h). This involves a capital investment of £177,344, resulting in a DPB of 23.7 years and an NPV of +£100,278.

For renewable systems, the only technology that achieved a positive NPV value and an improvement in $Exec_{CB}$ (£6.19/h) was R4: 20 kW wind turbine. Irreversibilities' reductions were minimal as electricity was being used for the same end-use processes, where just a slight decrease can be seen at the 'Primary Energy Transformation' subsystem, due to the lower fossil fuel utilisation for electricity generation.

Figure 6-35 shows the results for all the non-HVAC measures applied to the office archetype, locating those that have better exergoeconomic and thermal comfort performance. For the exclusive case of this office archetype, it is clear that minimising infiltration rate has the biggest impact on both indicators.

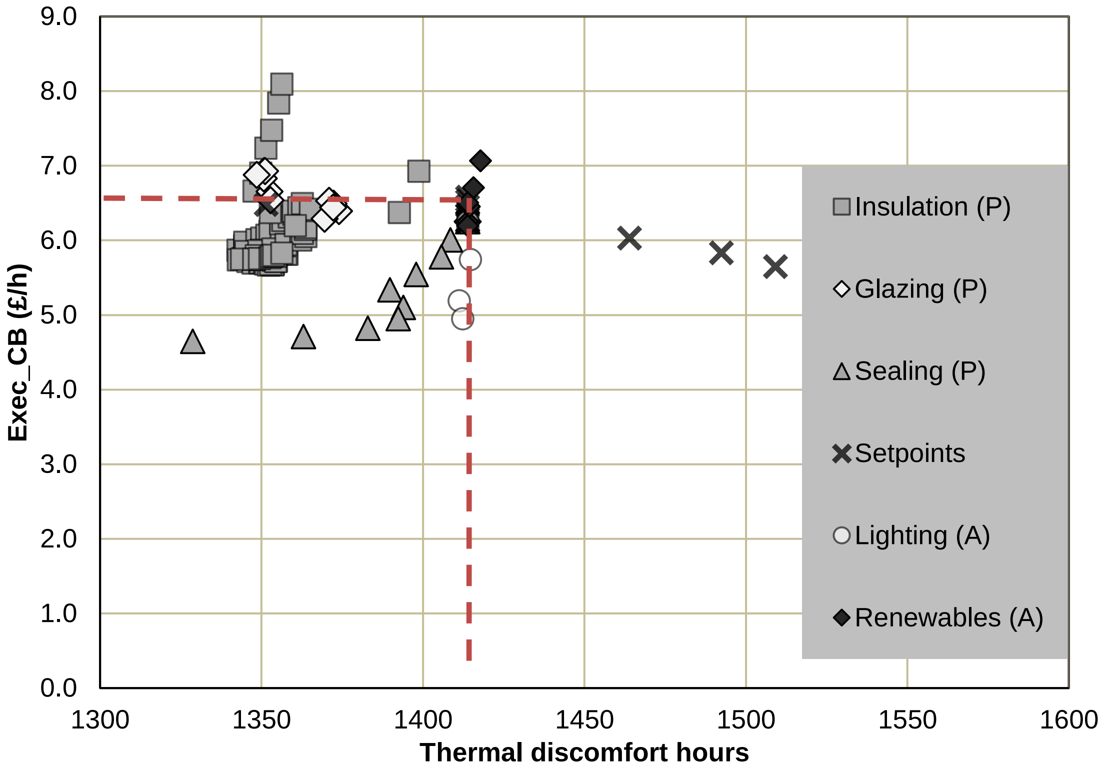


Figure 6-35 A/C Office: All BERs (no HVAC) $Exec_{CB}$ performance against thermal discomfort

The parametric analysis done in this section shows the individual impact on different energy, exergy and other indicators of a large range of BER measures limited to two non-domestic archetype buildings. This analysis, especially with the aid of exergy and exergoeconomic analysis, will serve as a basis for developing deep measures that consider the aforementioned indicators.

6.4 Development and analysis of deep BER measures

6.4.1 Description of the deep retrofit scenarios

Having pinpointed in the baseline case the sources of high energy use, exergy loss, and exergy destruction costs, the next step consists of developing a deep retrofit scenario, considering the integration of different measures. Since the benefit of a combined retrofit scenario is not the sum of individual benefits, due to a complex interaction of the building physics and its systems, deep energy/exergy retrofit packages were designed with the intention to obtain new, improved outputs. These designs are based on the main investigated indicators: expanded cost-benefit indicator ($Exec_{CB}$), internal thermal comfort, capital cost, and CO_2 emissions.

6.4.1.1 Primary School deep BER

Based on the systems found in the Pareto front (Figure 6-30), when comparing thermal comfort and exergoeconomics cost benefit indicator, the biomass boiler with VAV emission system (H11) is selected for the school HVAC system, where besides from providing the best comfort conditions it also provided the highest reductions in CO_2 emissions (58%). Also, insulation for the hot water distribution pipes is considered. For the envelope, 0.085m of glass fibre insulation and an improvement of the infiltration rate of 70% is proposed. Although glazing systems seemed not to provide cost-effective solutions, the selection of double glazing with 13mm air gap for the deep BER is made due to thermal comfort improvement potential. The BER design is complemented with LED lighting system, 25% roof area of PV panels, and a 20-kW wind turbine. When the HVAC system is auto-sized by the simulation model considering all these elements, the boiler results in a design capacity of 194 kW - a significant reduction from the baseline gas boiler of 515 kW. However, the total capital cost of the deep measure is equal to £734,968. A schematic layout of the building system and subsystems is illustrated in Figure 6-36.

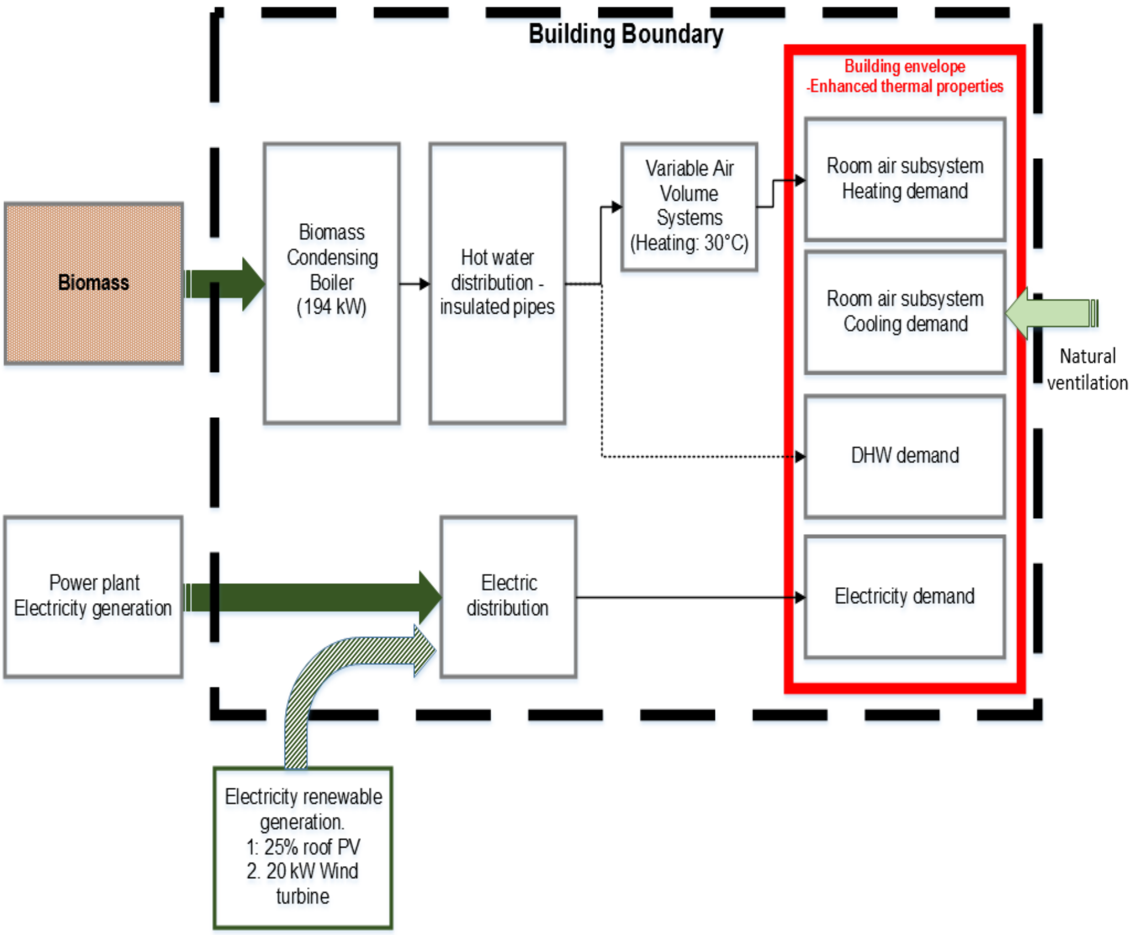


Figure 6-36 Schematic layout of the energy system for the Primary School base case

6.4.1.2 A/C Office deep BER

For the office building HVAC system, also based on those systems found in the Pareto front (Figure 6-31) when comparing comfort conditions and exergoeconomic cost benefit, the GSHP with underfloor heating/cooling (H21) is selected as it provides a better thermal comfort than the system with the MVHR system (H32). In addition to this, it also achieved 22.5% of CO_2 reductions. Improved insulation on the distribution systems is also considered as part of the retrofit. For the envelope thermal properties, 0.07m of EPS, double glazing with 13mm of air gap, and a reduction of 60% of the infiltration rate is considered. As in the case of the school, LED lighting, 25% roof PV system and a 20 kW wind turbine are included. When sizing the GSHP system for both heating and cooling mode, it results in an equipment of 127 kW, with a capital cost of £153,389. This replaces a 750 kW boiler and a 252 kW air-based chiller system used in the base case. The capital cost of the whole design stands at £980,401. A schematic layout of the building system and subsystems is illustrated in Figure 6-36.

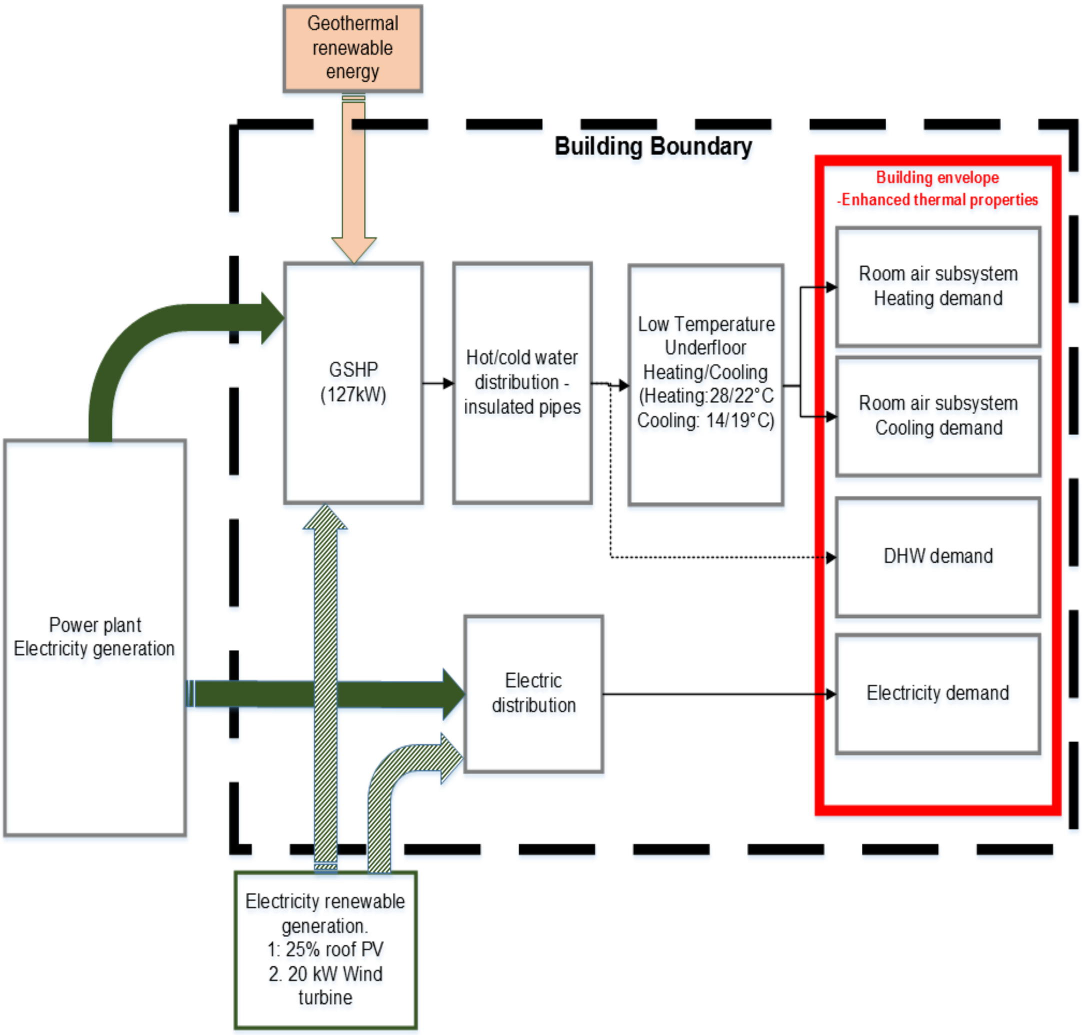


Figure 6-37 Schematic layout of the energy system for the A/C Office base case

Table 6-12 shows the measures per technology type that comprises of the deep retrofit packages as well as the required investment. The design for the school requires an investment of £369.3/m², while for the office stands at £378.5/m². The school's HVAC system represents 8% of the total investment, while technologies such as insulation, and renewable systems account for the majority of capital costs. On the other hand, the HVAC office retrofit share represents 24.4% of the total investment, being almost as large as the investment for renewable technologies. The capital cost ratio between the passive and active measures is found to be around 20% for both retrofit designs.

Table 6-12 Deep energy retrofit characteristics for both buildings

Technology	Primary School	Investment (£)	A/C Office	Investment (£)
HVAC system	Biomass Boiler (194 kW)	40,288	GSHP (127 kW)	153,389
Emission system	VAV	18,200	LT Underfloor	95,426
Insulation	Glass fibre Thickness: 8.5 cm	20,813.4	Expanded polystyrene Thickness: 7cm	19,514
Glazing system	Double pane 13mm (air gap)	47,324.5	Double pane 13mm (air gap)	141,201
Sealing (ach)	0.3	56,925	0.4	54,327
Set points (Heat/Cool)	22 (no cooling)	--	21 and 24	--
Lighting	LED	128,830	LED	177,344
Renewable systems	PV: 25% roof (216 m²–43 kWp) Wind: 20 kW	342,588 80,000	PV: 25% roof (285 m²–57 kWp) Wind: 20 kW	259,200 80,000
Total		734,968		980,401
Passive/Active Investment Ratio		0.17		0.22

6.4.2 Results: Performance of the deep-BER designs

Both packages achieve energy savings of around 70%. In addition, reductions of exergy destructions are achieved at a rate of 49.7% for the school and 42.2% for the office. The share of renewable energy used to cover building's demand is larger for the school, where 42% of the total energy demand is covered by the electricity generated from the PV panels and the wind turbine. In the case of the office, this value stands at 21.6%.

Nevertheless, neither package achieves a positive NPV (50 years), having discounted paybacks above the analysis period (school: 84 years, office: 61 years). However, an interesting result in the school case is presented, as after accounting for the energy bill savings and government incentives, thanks to the use of the biomass boiler and PV panels, a positive income of £2,121/year is obtained. This means, that if a share of the investment cost can be covered by external funding bodies (public or private NGOs), the deep BER measure could become financially attractive.

In terms of thermal comfort, the school retrofit achieves a 66% improvement, from 1,443 uncomfortable hours to 490 hours. On the other hand, the office design only improves it by 22%, from 1,414 uncomfortable hours to 1,101 hours. Although a considerable improvement was perceived in winter months for the office case, the large levels of insulation levels produce overheating during the summer, switching uncomfortable conditions to these months.

Exergetically, both designs achieve exergy destruction reduction of more than 40%. However, the school's biomass-based system barely improved the total exergy efficiency performance, improving HVAC thermodynamic efficiency from 0.015 to 0.026 and the whole building exergy efficiency from 0.095 to 0.125. This is because biomass, depending on its renewability factor, can be regarded as a high-quality energy source, having quality levels greater than natural gas or electricity (Table 4-3). On the other hand, the office design achieved an improvement on HVAC exergy efficiency from 0.053 to 0.184, and an improvement on building exergy efficiency from 0.154 to 0.204. This increase is due the utilisation of geothermal renewable energy for the operation of the heat pump; however, the utilisation of grid electricity from fossil-fuel power stations is still penalised by exergy analysis.

Exergoeconomically, the school's deep BER design is able to reduce the final product price for the heat stream from £1.79/kWh to £1.27/kWh. Figure 6-38 shows the cost increase per kWh of the heating product stream for the retrofitted school building. Compared to the results illustrated in Figure 6-23, which show the cost stream for the baseline case, these new outputs show a reduction of the final product price by 29%. However, still special attention has to be put on the distribution system and beyond, where the product price begins to increase at higher rates. This can be explained as the hot water produced by the boiler at around 80 °C, which uses a high-quality energy source (biomass), is being irrationally used by the VAV system, where large temperature drops in the heat exchanging process between the distribution and the emission systems are found. Therefore, any temperature reduction in the subsequent subsystems, which indeed produce exergy destructions, is regarded at a high exergy destruction cost rate.

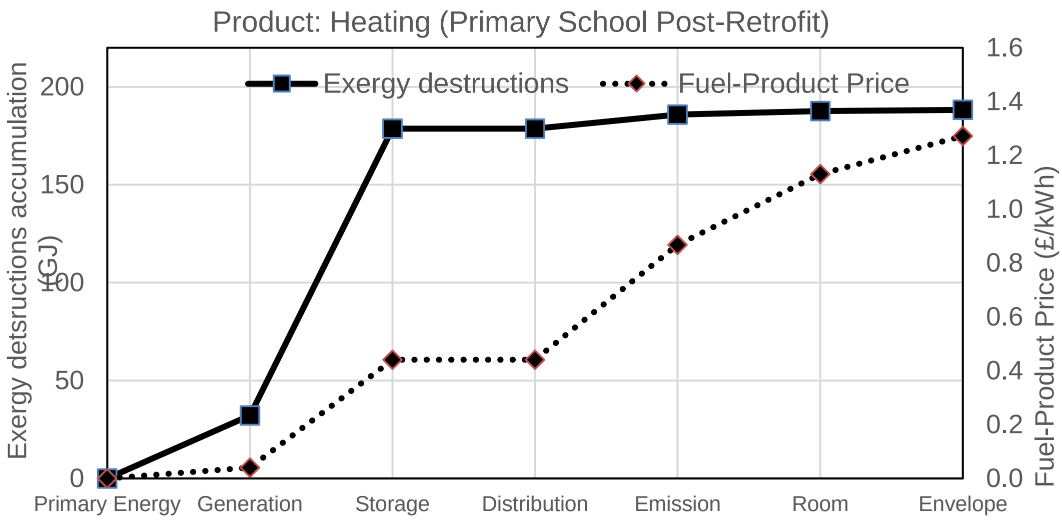


Figure 6-38 Exergy destruction accumulation vs price increase for heating stream post retrofit. Primary School

The same pattern can be observed in the office HVAC system products. For heating (Figure 6-39), a reduction of the heat final product price from £0.42/kWh to £0.19/kWh is achieved, as a result of the reduction of energy/exergy demand and exergy destructions combined with the utilisation of a higher thermodynamic efficient system such as the GSHP. However, the largest increase in price occurs at the generation subsystem, where electricity is converted to hot water.

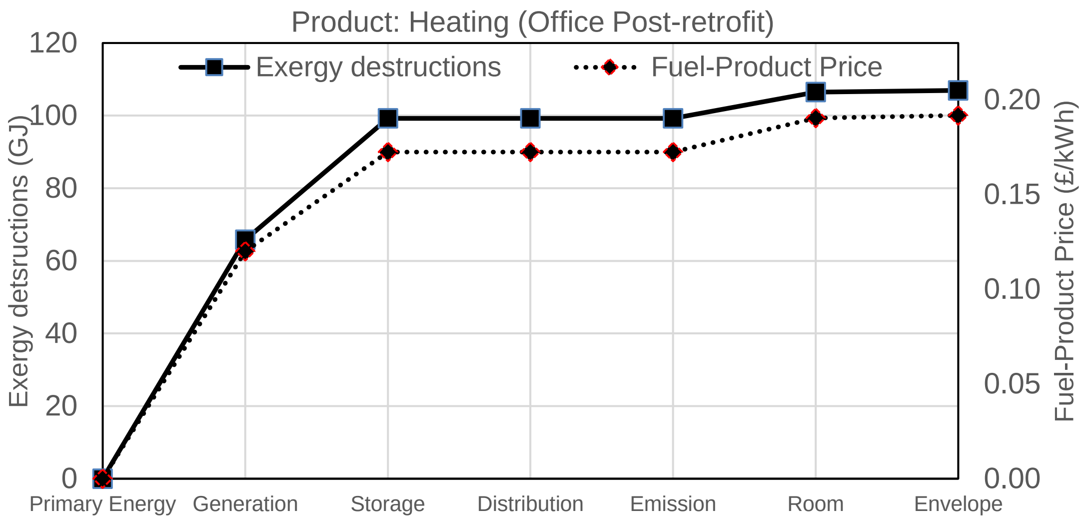


Figure 6-39 Exergy destruction accumulation vs price increase for heating stream post retrofit. A/C Office

For the cooling process (Figure 6-40), an even more significant reduction is achieved by lowering the product price from £6.28/kWh to £1.85/kWh, due to the same motives explained for the heating stream. However, the cooling product price suffers its largest increase after the cold water passes the distribution system, where a minimum increase in the cold water temperature is highly penalised by exergoeconomics, due to the amount of electricity that was previously required to produce the cold water.

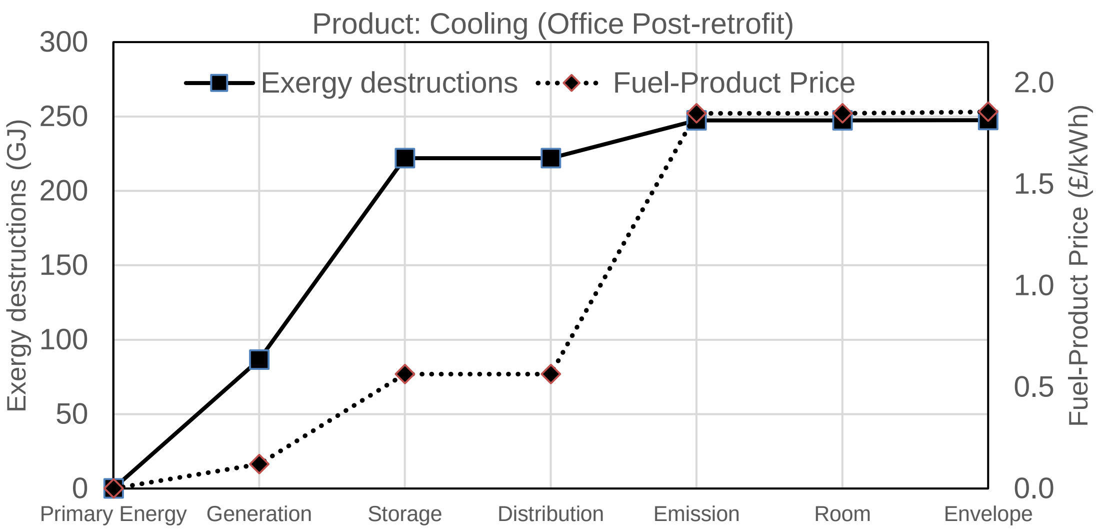


Figure 6-40 Exergy destruction accumulation vs price increase for cooling stream post retrofit. A/C Office

These products price reductions for both buildings have an impact on the exergy destruction cost rate. As shown in Figure 6-41, exergy destruction costs, compared to the baseline, are reduced from £2.72/h to £1.22/h for the school and from £6.25/h to £4.23/h for the office.

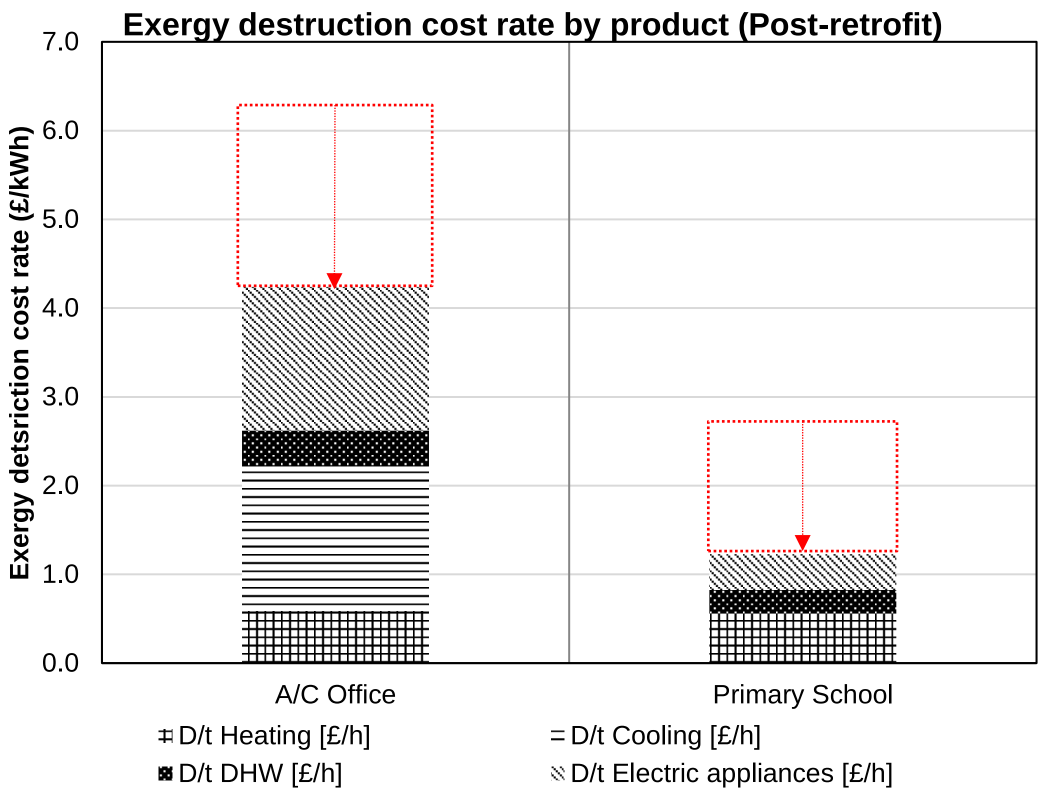


Figure 6-41 Exergy destruction cost rate per product type (Post-retrofit)

As a result of reducing the exergy destruction cost rate, the $Exec_{CB}$ indicator also presented a lower value than the baseline exergy destructions cost, even considering the high investment costs (£369/m² and £379/m² for the school and office, respectively) and a lower than expected annual revenue. For the school, $Exec_{CB}$ is £1.91/h, while for the office it is £4.42/h. Finally, Table 6-13 summarises all the main energy, exergy, exergoeconomic, and non-energy outputs for the combined measures compared against the baseline scenarios

Table 6-13 Comparison of energy, exergy, and exergoeconomic values for pre-retrofit and post-retrofit buildings

	Primary School			A/C Office		
Properties	**Base Case**	**Deep Retrofit**	**% Variation**	**Base Case**	**Deep Retrofit**	**% Variation**
Energy use (EUI) (kWh/m^2-year)	187.9	79.9	-57.5	288.5	120.6	-58.2
Net energy use[12] (EUI) (kWh/m^2-year)	187.9	46.3	-75.3	288.5	94.6	-67.2
Annual emissions (tCO_2)	214.8	20.9	-90.3	285.6	133.9	-53.1
Thermal Discomfort (hrs)	1,443	490	-66.0	1,414	1,101	-22.1
Energy bill (after incentives) (£)	19,449	-2,121	-110.1	59,625	24,495	-58.9
NPV (50 years)	--	-42954	--	--	-154,818	--
Exergy input (GJ/year)	1,916	997	-48.0	5,129	3,141	-38.7
Exergy destructions (GJ/year)	1,733	872	-49.7	4,341	2,500	-42.4
Exergy efficiency HVAC	0.015	0.026	+1.1	0.053	0.184	+13.1
Exergy efficiency DHW	0.062	0.057	-0.5	0.087	0.028	-5.9
Exergy efficiency Electric equipment	0.180	0.195	+1.5	0.195	0.222	+2.7

[12] Renewable energy generated in site and use in the building is not accounted for

Table 6-13 cont. Comparison of energy, exergy, and exergoeconomic values for pre-retrofit and post-retrofit buildings

	Primary School			A/C Office		
Properties	**Base Case**	**Deep Retrofit**	**% Variation**	**Base Case**	**Deep Retrofit**	**% Variation**
Building Exergy efficiency	0.095	0.125	+3.0	0.154	0.204	+5.0
Exergy price fuel-prod HEAT (£/kWh) (r_k)	0.03->1.79 (58.66)	0.04->1.27 (30.81)	-29.1	0.03->0.42 (13.00)	0.12->0.19 (0.59)	-54.8
Exergy price fuel-prod COLD (£/kWh) (r_k)	----- (---)	----- (---)	-24.1	0.12->6.28 (51.33)	0.12->1.85 (14.47)	-70.5
Exergy price fuel-prod DHW (£/kWh) (r_k)	0.03->0.44 (13.66)	0.04->0.58 (13.62)	+31.8	0.03->0.55 (17.33)	0.12->1.65 (12.8)	+200.0
Exergy price fuel-prod Elec (£/kWh) (r_k)	0.12->0.26 (1.16)	0.12->0.24 (1.01)	-7.6	0.12->.24 (1.0)	0.12->0.21 (0.76)	-12.5
D cost destructions (£/h)	2.72	1.22	-55.1	6.25	4.23	-32.3
Capital investment (£)	--	£734,968	--	--	£980,401	--
Z (£/h)	--	3.15	--	--	4.20	--
Annual revenue (£/h)	--	2.46	--	--	4.01	--
$Exec_{CB}$ *(£/h)*	2.72	1.91	-29.8	6.25	4.42	+29.3
Exergoeconomic factor f_k *(-)*	--	0.72	--	--	0.49	--

6.4.3 Sensitivity analysis (post-parametric study)

A sensitivity analysis, studying the effect of wall insulation thickness, is performed for the deep BER solutions analysed in the last section. This is done to explore a further manual design optimisation of BER characteristics. For this particular analysis, just the building wall insulation is varied, leaving the rest of the envelope intact together with all the rest of the energy systems.

6.4.3.1 Primary School

As a result of increasing the glass fibre insulation thickness, an increment in total capital investment is obtained, even considering the biomass boiler size reduction due to lower energy demands. The results show an increment of £500 per each cm increase. Added to this, a slight reduction in discomfort hours is also obtained (Figure **6**-**42**).

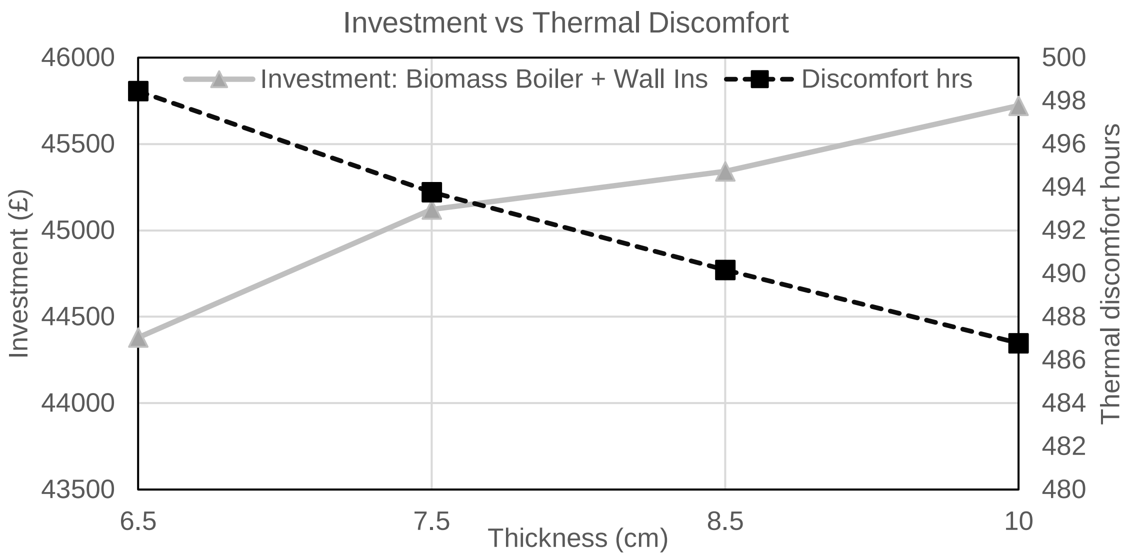


Figure 6-42 **Sensitivity analysis of glass fibre wall insulation for the School case. Investment and Discomfort hours**

As illustrated in Figure 6-43, by increasing the insulation, a minimisation in both the energy use and exergy destructions is achieved (Fig. 21). In this case, the exergy destruction cost rate for heating, ranges from £0.57/h for the lower insulation thickness of .065m, to £0.53/h for 0.10m.

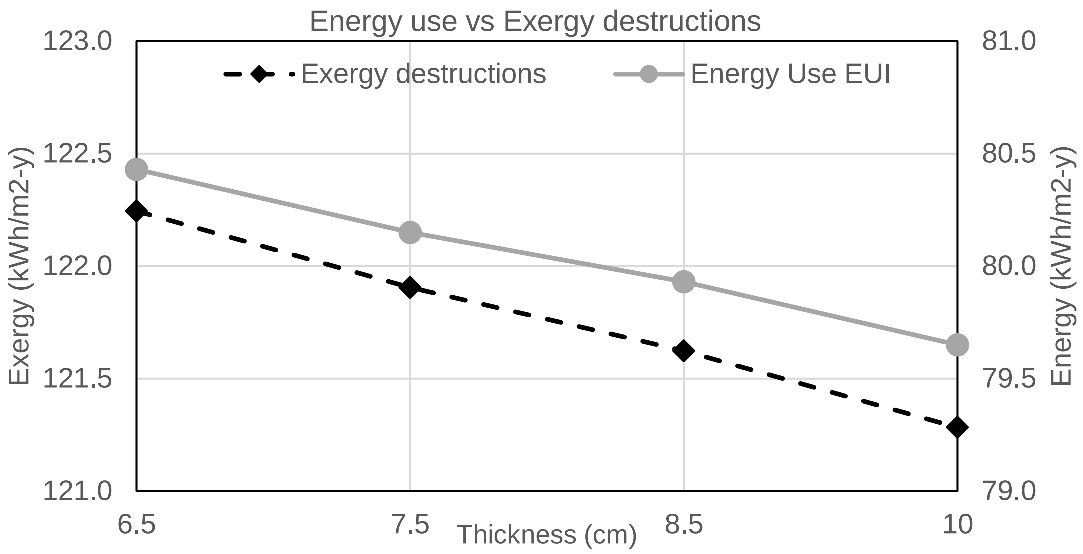


Figure 6-43 Sensitivity analysis of glass fibre wall insulation for the School case. Energy use vs Exergy destructions

6.4.3.2 A/C Office

For the office, the outputs are slightly different to those presented for the school. By increasing the insulation, the total investment cost is actually reduced, as the capital cost savings from downsizing the GSHP equipment exceed the extra investment, required for thicker insulation. Originally at 0.07m of EPS, the GSHP had an installed capacity of 127 kW, while for 0.15m of EPS, the GSHP size is reduced to 119 kW, thus requiring a lower investment cost. However, this increase in insulation negatively impacts thermal comfort due to overheating during the summer months (Figure 6-44). DBPs are very similar for both extreme cases, ranging from 64 years for the lowest thickness to 60 years for the highest insulation level.

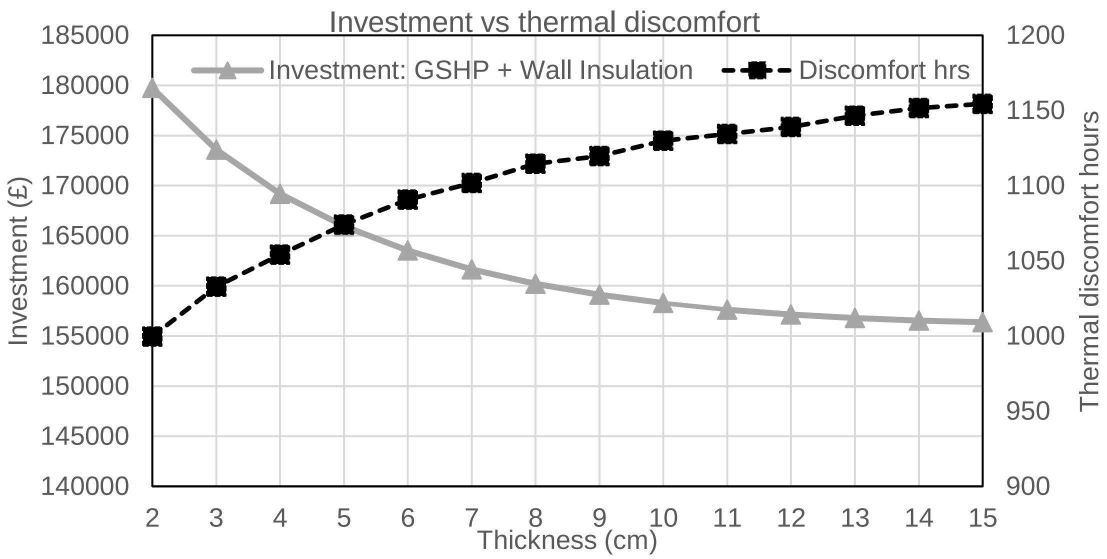


Figure 6-44 Sensitivity analysis of EPS wall insulation for the Office case. Investment and Discomfort hours

Figure 6-45 shows different behaviours for energy use and exergy destructions. On the one hand, the increase of insulation leads to the reduction in total energy use, where savings in electricity for the operation of the heat pump in heating mode are greater than the increase of electrical demand for cooling. On the other hand, it is the opposite in the exergy terms. An increase in electrical demand for cooling presents larger irreversibilities than exergy savings in the heating process. This is due to the lower exergetic efficiency for cooling processes in a temperate climate such as London. Therefore, other passive strategies such as natural ventilation or night cooling should be pursued to lower exergetic demand and increase in thermodynamic efficiency.

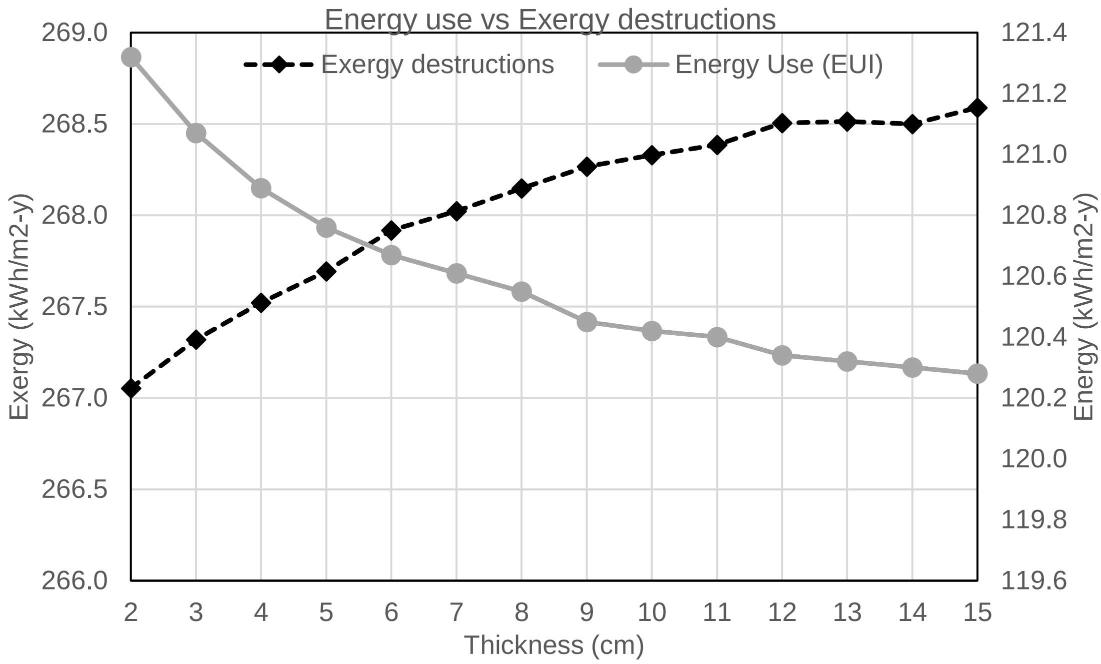


Figure 6-45 Sensitivity analysis of glass fibre wall insulation for the Office case. Energy use vs Exergy destructions

By decreasing insulation thickness from 0.07m to 0.02m, an increase in exergy efficiency from 0.183 to 0.189 is achieved. In addition, the exergy destruction cost for the heating and cooling products combined is proportional to the thickness insulation increase, going from £1.83/h for 0.02m, to £2.19/h for 0.15m.

6.5 Discussion of findings

This chapter presented a way by which exergy and exergoeconomics could be integrated as a valuable decision-making support tool for the improvement of building energy retrofit design and overall building energy performance. The case studies, represented by generic UK non-domestic buildings, helped to demonstrate the first application of the exergy/exergoeconomic retrofit-oriented framework. The framework is supported by the dynamic simulation tool ExRET-Opt, allowing dynamic exergy analysis and an exergoeconomic evaluation. Dynamic physics-based modelling can give more meaningful results than steady-state models, as the former not only considers dynamic temperatures (essential for exergy analysis), but also provides less uncertainties as future changes in environmental factors and technologies can be assessed.

6.5.1 Exergy and exergoeconomic performance of typical UK non-domestic buildings

First, benchmark values for both case study buildings were obtained demonstrating the tool's pre-processing phase. In this phase, the calibration module proved to be of great importance to minimise model's uncertainties and to obtain realistic results. Nevertheless, the obtained exergy/exergoeconomic benchmark values represent novel outputs that can be regarded as representative of the UK non-domestic sector. For a building that demands both artificial heating and cooling as in the office case, a markedly different pattern can be seen in the two seasons. While the main destructions in colder months are located in the generation subsystem (boiler), during the summer the main destructions shift to the 'Primary Energy Transformation', where the conversion process from natural gas to electricity produces the highest exergy destructions in the supply chain. In this case, the use of a high-quality source (electricity) for a low-quality demand such as cooling demand in a temperate climate was severely penalised by exergy analysis. This first insight has resulted in the ability to calculate what can be called as the overall thermodynamic efficiency for this type of buildings. Outputs show that a typical school exergy efficiency (ψ_{bui}) stands at 0.095, while a typical A/C office at 0.153. This represents a low thermodynamic efficiency where improvement could come either from a more efficient electric generation at the power plant, electric equipment, or by the in-site generation of renewable electricity used appropriately for high quality demands.

In addition, the benchmark exergoeconomic indices resulted in the calculation of the product cost formation. These outputs help to understand how the energy price increases throughout the energy supply chain until it reaches the demand side. For example, for the school, the heating product that reaches a thermal zone increased from an initial gas price value of £0.03/kWh to a final heating product value of £1.79/kWh, representing a total relative cost difference r_k of 58.66. On the other hand, for the office case, it was possible to calculate the streams for the two thermal products: heating and cooling. The office heating product cost formation increased from £0.03/kWh to £0.42/kWh, (r_k =13.0), while for the cooling product, the exergy product cost started at £0.12/kWh (electricity price) and increased up to £6.28/kWh (r_k = 51.33). This high product price showed how small the cooling demand is in exergy terms. This analysis suggests that at least in this particular case study, considering a temperate climate such as London's, cooling has to be covered with the passive means as much as possible or by installing highly efficient artificial cooling generation (e.g. absorption chillers).

This cost formation analysis locates exact location where the energy stream price increases. In a building that has not been through a refurbishment process, the increase generally comes due to high rates of exergy destructions. In a hypothetical ideal thermodynamic system (irreversibilities-free, ψ_{bui} =1.0), the total relative cost difference r_k would be 1.0. However, due to real systems' exergy destructions, consumers inevitably pay a higher product price than the entering value.

Thanks to the calculation of the products' cost formation and the building's exergy destruction cost, the novel expanded exergoeconomic cost-benefit indicator $Exec_{CB}$, developed in this research for the comparison of retrofit measures, was presented. When it comes to the base case, the exergoeconomic cost-benefit index is represented by the building's exergy destructions cost rate only ($Exec_{CB,baseline}$= $\dot{C}_{D,sys}$), as no capital investment and therefore retrofit revenue exists. For the school, the $Exec_{CB,baseline}$ or $\dot{C}_{D,sys}$ value was found at £2.72/h, while for the office a value of £6.25/h was obtained. These values represent the amount of economic value that the building/consumer is paying by the hour just to cover thermodynamic inefficiencies. In the case of the school, exergy destructions costs represent around 90.8% of the annual energy bill expenditure, while in the office it is close to 91.2%, showing that in both cases just 9% of the expenditure is being paid to cover the real thermodynamic demand. This value can be regarded as a real economic efficiency indicator of a building.

6.5.2 Effect of different reference environments on exergoeconomic indicators

Considering the same baseline building energy models, a sensitivity analysis of the reference temperature was carried out by modelling different climatic regions within the UK's context. Apart from London, five different locations within the UK context were explored (Belfast, Birmingham, Cardiff, Edinburgh, and Liverpool). The aim was to analyse the impacts of different reference temperature on the results. Although several studies exist that analyse the impact of the reference environment on exergy outputs, no study exists that examines its effects on exergoeconomic outputs.

Overall, although the differences in outputs were not significantly large, Liverpool presented the worst exergy efficiency for the HVAC system for both building types; however, when considering the entire building energy system (HVAC, DHW and electric equipment), it presented the lower exergy demand and the lowest exergy destructions which resulted in the highest exergy efficiency values and lowest exergy destruction cost rates among the analysed cities. This slightly better performance is mainly driven due to better electric exergy performance and low demand for cooling processes, having the potential of covering cooling demand with passive means.

Regardless of the outcomes of the sensitivity analysis, the importance of the reference temperature on exergy and exergoeconomic indicators was highlighted, concluding that robust weather data is necessary to reduce uncertainty in the design outputs. This is especially important for exergy analysis which is highly dependent on the reference environment.

6.5.3 The different impact of active and passive BER measures on exergy and exergoeconomic outputs

Later, after pinpointing major thermodynamic inefficiencies along the building's energy supply systems, a parametric study of different active and passive BER was performed. In order to analyse and compare different BER measures, apart from traditional indices, the novel exergoeconomic cost benefit indicator, which considers the cost rate of exergy destruction, capital costs, and revenue costs due to energy savings, was applied. This indicator appears promising, as it considers the whole spectrum of energy, economics (capital investment and revenue), exergy destructions, and exegetic cost formation. Overall, the proposed exergoeconomic cost-benefit indicator presented a good correlation with typical economic indicators, suggesting that the former could also be reliable for decision making.

In typical practice, it is believed that buildings with better performance are those that tend to have a good passive design and a tighter envelope. But the results obtained for the specific case studies showed that active components, such as efficient HVAC systems configurations based on GSHP and district systems connected to low temperature emissions systems, could have better exergoeconomic performance if applied and sized correctly, and are therefore more likely to improve overall thermodynamic performance. For this reason, before any major passive refurbishment is undertaken, findings suggest that active measures should be considered first.

However, for both cases, the system that improved the most the exergoeconomic cost-benefit indicator was the MVHR system. MVHR systems have the potential to deliver the highest rates of efficiency; however, its performance depends on the amount of electricity necessary to move the fans. If more exergetic electricity is required than the exergy recovery from the warm air, the so called 'low exergy' solution would not represent any improvement. Additionally, some technologies that are typically believed to be efficient and provide large reductions in carbon emissions (e.g. air/air heat pumps using electricity from the grid) struggle to reduce exergy destructions because of low COP values found in a temperate weather such as London. Some systems that can be considered as 'low exergy' solutions such as PV/T systems were highly penalised by exergoeconomic analysis due to the fact that electricity was being used for heating and cooling purposes. This shows that electricity needs to be used correctly, considering a supply-demand quality match in the design. Using electricity for space conditioning is a practice that should be avoided and heavily penalised by appropriate taxation.

The advantage of presenting two different non-domestic building types allows comparing different measures and helps realise how complex the non-domestic buildings' sector can be, where a single solution to cover all needs does not exist. For example, for the school's case, lowering the demand by improving the envelope thermal properties has the capacity to reduce the exergy destructions footprint; however, the 'optimal' HVAC system found in the analysis which was based on a biomass boiler + VAV units, failed to provide any significant performance improvement in thermodynamic efficiency due to a poor system design. Nevertheless, systems, such as GSHP, heat recovery-based systems, and district heating appear to have the best improvement potential but suffer from larger capital costs, making the solutions economically infeasible.

On the other hand, the office case presents different results as it differentiates by having a cooling process. The outputs point out that retrofitting the thermal envelope could have a negative impact because of the increased likelihood of overheating during summer. Outputs show that low-exergy systems, such as GSHP and heat recovery systems, combined with large surface emissions areas, have the potential to be implemented even with the current market conditions. On the other hand, other promising low exergy systems fail to provide cost-beneficial solutions. For example, district systems do not seem to be economically viable due to lack of government incentives. Therefore, exergy-based taxation and incentives could help unlock unconventional technologies and provide more flexibility in the design process, where high performance buildings combined with low exergy supply structures are intrinsic for the future of sustainable development in the building sector. Other similar low exergy systems that showed high capital prices in the current market were heat pumps that work with low temperature lifting.

Additionally, and regardless of the building type, the model exergy outputs showed that the renewable electricity generated by CHPs, PV/T systems, and wind turbines need to be used correctly, considering a supply-demand quality match in the design. Using electricity for space conditioning is a practice that should be avoided in any design and heavily penalised by appropriate taxation.

Other interesting results from the exergy and exergoeconomic analyses suggest high potential for achieving exergy-efficient buildings by considerably reducing the energy demand for electrical appliances. This could be done by either improving the end-use equipment efficiency or by producing renewable electricity (solar or wind) with an exclusive use for electric equipment. Therefore, redirecting the renewable electricity for heating or cooling process has to be avoided at all costs. However, the issue of dealing with high demands for artificial lighting is still complex. While it can be reduced by installing more efficient lighting (e.g. LED), as tested in this chapter, or ideally, by maximising the use of daylighting; this becomes more difficult when dealing with the existing buildings. Nevertheless, daylight, in terms of exergy, represents the highest thermodynamic efficiency, and thus has to be highly promoted. The problem with the rest of the electrical appliances, such as inefficient computers, printers, television sets, microwaves, electric ovens, etc., should also be regarded as a major issue with the only solution from an end-use perspective, being the installation of higher electric-efficient equipment.

6.5.4 Developing BER measures with exergy and exergoeconomic indicators

Finally, the chapter showed the development of deep BER based on exergoeconomic indicators together with other typical indices (NPV, thermal comfort, CO_2 emissions). The office case achieved improvements in energy use of 67%, CO_2 emissions of 53%, thermal comfort of 22%, and reductions of exergy destructions by 42%. Also, overall exergy efficiency was improved from 0.150 to 0.204. The school case presented similar results with the potential to even generate income thanks to the government incentives (e.g. RHI for biomass boilers). School building's exergy efficiency was improved from 0.095 to 0.125. In both cases, final product price for heating and cooling were notably reduced. Although the price of the fuel and the product depend on market conditions, with the support of exergy and exergoeconomic analyses, the price reduction was obtained by utilising highly efficient technologies.

Nevertheless, to achieve this performance, high capital investments were required, demonstrating that low exergy equipment is still expensive under current market conditions. As demonstrated in similar energy retrofit studies showed in the literature review, deep-BER solutions find it difficult to be economically feasible depending on several techno-economic factors. In this research, both proposed deep-BER scenarios developed with the support of the novel exergoeconomic indicator, failed to provide good economic outcomes, as payback periods were found over 60 years (school: 84 years, office: 61 years). Although the selection of a BER project mainly depends on managements' preferences and selection criteria, projects with long payback periods are typically not implemented.   In this sense, even though with the support of both thermodynamic laws for the assessment and design of BER measures, the designed deep-BER measures obtained long payback periods showing how typical economics and the current market environment do not account for exergy savings and exergy efficiency. However, an interesting result was obtained for the school deep BER design. After accounting for the energy bill savings and government incentives, due to the use of the biomass boiler and PV panels, a positive annual income was obtained (+£2,121/year). This means, that if a share of the investment cost can be covered by external funding bodies (public or private NGOs), the deep BER measure could become financially attractive.

Nevertheless, biomass boilers are low thermodynamic efficiency systems. This supports the case for developing exergy-based taxation and incentives, which will encourage the design of buildings with better thermodynamic performance. Also, it could help unlock unconventional technologies and provide more flexibility in the design process, where high performance buildings combined with low exergy supply structures are key for a future sustainable development of the building sector. For example, outputs demonstrated that district systems or low temperature lifting GSHP do not seem to be economically viable due to high technological price and lack of government subsidies. Therefore, it is suggested that incentives be shifted to energy systems with higher thermodynamic performance.

Selecting the measures for building's energy retrofit that are able to deliver high exergy efficiency, combined with low capital cost and high return on investment is still a challenge. While appropriate energy policies and incentives are not developed, other methods are necessary to obtain better thermodynamic-efficient designs. In this regard, and based in engineering design, the combination of thermodynamic analysis coupled with multi-objective optimisation algorithms could hold the key to obtaining cost-effective solutions under current energy policy and market conditions.

Chapter 7 Optimising deep-BER designs by using exergy-based multi-objective optimisation and genetic algorithms (NSGA-II)

This chapter presents the application of ExRET-Opt optimisation mode, where the simulation tool and retrofit module are coupled into an optimisation platform. It allows the modeller to perform a deeper design exploration under different search constrains. The expectation is to achieve better solutions in accordance with the same indicators investigated in the previous chapter. The optimisation process, based on a type of genetic algorithm (NSGA-II), can tackle single or multiple objective functions at the time. This study performs a multi-objective optimisation problem by examining three conflicting criteria: a) minimisation of total building exergy destructions, b) minimisation of occupant thermal discomfort hours, and c) maximisation of project's NPV. Therefore, this study can be considered as a hybrid thermodynamic optimisation, as NPV outputs are related to First Law (energy) values, while exergy destructions to Second Law values. After the optimisation procedure is performed, a large range of Pareto solutions are obtained. Therefore, to support the decision making process in selecting a final BER design, the application of a Multi-Criteria Decision Making (MCDM) method, based on compromise programming, is proposed by demonstrating its usefulness and importance in ranking designs when several optimal solutions exist. As the final retrofit design decisions usually require qualitative aspects of human judgement, the integration of the MCDM method in the whole simulation process aims to support design teams or decision makers in making informed decisions based on different criteria and thus improving the final selection of a BER measure. Finally, an ultimate optimal solution is selected to compare the outputs with those from the baseline case and the deep-BER design developed in the previous chapter.

7.1 Study Design: Configuration of MOO parameters

The optimisation process is applied to the same calibrated baseline archetype buildings investigated in the last chapter (Section 6.2). As the investigation of the impact of all possible combinations among retrofit measures, using the parametric (scenario-by-scenario) approach, is both impractical and time consuming, the multi-objective optimisation and multi-criteria (MOO-MCDM) module is required at this stage. The simulation workflow and modelling environments regarding the optimisation process and multi criteria method were already illustrated in Section 5.2.5. The basic algorithm is based on a fast and elitist non-dominated sorting genetic algorithm (NSGA-II), able to work with both continuous and discrete variables, aiming to obtain solutions considering any objective function(s) by the user. On the other hand, the MCDM method is based on compromise programming and the Tchebyshev distance for the scan of solutions under different weighting coefficients for the analysed objectives.

A fundamental task in the MOO design process is the configuration of parameters and identification of optimal computing settings to improve calculation time and accuracy of the results. The following sections will show the design and settings applied to this particular study.

7.1.1 Decision variables and design space

The BER measures embedded in ExRET-Opt and applied in the last chapter can be catalogued between micro and macro parameters. From the range of retrofit measures that can be catalogued as micro parameters are set-points and infiltration rates, which belong to the composition of a greater parameter. Parameters that are considered macro or lumped are HVAC systems, insulation technologies, glazing systems, lighting systems and renewable energy generation technologies. The difference between both types can be seen in the way the measures are encoded within the tool. While the first are just represented as a changing single variable, the second is a complete piece of code formed by many static variables programmed in an .idf file. As Calleja Rodríguez et al. (2013) mentions, the biggest strength of macro parameters is the ability to group several micro parameters into one variable, and thus decrease the search space as much as possible.

7.1.1.1 Design space

As expected, the search space or all possible retrofit design combinations for the school and the office archetypes are over billion different configurations. The main reason for this large search space, is that in this study each part of the envelope (wall, roof, ground floor) is considered as an independent object, where different insulation technologies and thicknesses can be applied along the different parts of the envelope. The decision variables for the optimisation process are defined in Table 7-1.

Table 7-1 Decision variables and vector ID

Decision variables - BER measures	Number of possible solutions	Vector ID
HVAC system	33	X^{HVAC}
Wall insulation	96	X^{wall}
Roof Insulation	96	X^{roof}
Ground Insulation	91	X^{ground}
Sealing (infiltration rate)	10	X^{seal}
Glazing	13	X^{glaz}
Lighting	4	X^{light}
Photovoltaic panels	4	X^{PV}
Wind turbines	3	X^{wind}
Heating set-point	5	X^{heat}
Cooling set-point*	5	X^{cool}

*Considered only for the A/C Office (cooling case)

Therefore, all possible combinations for the school case are 863,480,217,600, while for the office there are 4,317,401,088,000 options. The office presents more combinations (five times larger) due to the utilisation of an extra design variable: cooling set-point. Since running both full-parametric projects with a 3.50 GHz 8-core computer would be unfeasible due to time-constraints, the use of the optimisation module is necessary to drastically reduce the number of simulations needed to at least achieve close to optimal results.

7.1.2 Objective functions

As mentioned, an energy optimisation problem requires at least two conflicting problems. In this study three objectives that have to be satisfied simultaneously are going to be investigated for both case study buildings. These are the minimisation of overall exergy destructions, reduction of occupant thermal discomfort, and maximisation of project's Net Present Value:

I. Building annual exergy destructions (kWh/m^2-year):

$$Z_1(x)\, min = \; Ex_{dest,bui} \; = \sum Ex_{prim}(t_k) - \sum Ex_{dem,bui}\,(t_k) \tag{7.1}$$

II. Occupant discomfort hours:

$$Z_2(x) min = \; \left(\left| PMV \right| > 0.5 \right) = \; \left| (0.303\, e - 0.036M \; + \; 0.028)\, L \right| \; > 0.5 \tag{7.2}$$

III. Net Present Value$_{50\ years}$ (£):

$$Z_3(x) max = \; NPV_{50years} \; = -TCI + \left(\sum_{n=1}^{N} \frac{R}{(1+i)^n} \right) + \; \frac{SV_N}{(1+i)^N} \tag{7.3}$$

However, for simplification and to encode a purely minimisation problem, the NPV is set as negative (although the final results will be presented as normal positive outputs). Therefore:

$$Z_3(x) min = \; -NPV_{50years} \; = -\left\{ -TCI + \left(\sum_{n=1}^{N} \frac{R}{(1+i)^n} \right) + \; \frac{SV_N}{(1+i)^N} \right\} \tag{7.4}$$

The calculation and description of all objectives was already presented in section 4.1.4 (exergy destructions), section 4.2.1 (NPV), and section 5.2.5.2 (occupant thermal comfort). Although the experiment is conducted with a hybrid thermodynamic approach, meaning that the tool is going to optimise variables from the two laws, namely exergy destructions and NPV, additional analysis is made for other important indicators such as energy use, exergy efficiency, exergoeconomic cost-benefit, carbon emissions, and occupant thermal comfort.

7.1.3 Constraints

Furthermore, it was chosen to subject the optimisation problem to three constraints. First, as a pre-established budget is one of the most common typical limitations in real practice, it was decided to use the initial total capital investment as a constraint, using the values obtained for the deep BER designs (Section 6.4) as maximum figures. These investments were £734,968 for the Primary school, and £980,401 for the A/C Office. As a result, DPB is also considered as a constraint, sought for solutions with a DBP of 50 years or less, giving positive NPV values. Finally, a third constraint is the maximum discomfort hours, subjecting the model not to worsen the initial baseline conditions. The aim is to test the model to deliver cheaper solutions with better energetic, exergetic economic, and thermal comfort performance. Hence, the complete optimisation problems for the school and office can be formulated as follows:

a) Primary School

Given a ten-dimensional decision variable vector

$x = \{X^{\mathrm{HVAC}}, X^{\mathrm{wall}}, X^{\mathrm{roof}}, X^{\mathrm{ground}}, X^{\mathrm{seal}}, X^{\mathrm{glaz}}, X^{\mathrm{light}}, X^{\mathrm{PV}}, X^{\mathrm{wind}}, X^{\mathrm{heat}}\}$, in the solution space X, find the vector(s) x^* that:

Minimise: $Z(x^*) = \{Z_1(\mathrm{x}*), Z_2(\mathrm{x}*), -Z_3(\mathrm{x}*)\}$

Subject to follow inequality constraints: $\begin{cases} TCI \leq £734{,}968 \\ DPB \leq 50\ years \\ Discomfort \leq 1{,}443 \end{cases}$ {constraints}

b) A/C Office

Given an eleven-dimensional decision variable vector

$x = \{X^{\mathrm{HVAC}}, X^{\mathrm{wall}}, X^{\mathrm{roof}}, X^{\mathrm{ground}}, X^{\mathrm{seal}}, X^{\mathrm{glaz}}, X^{\mathrm{light}}, X^{\mathrm{PV}}, X^{\mathrm{wind}}, X^{\mathrm{heat}}, X^{\mathrm{cool}}\}$, in the solution space X, find the vector(s) x^* that:

Minimise: $Z(x^*) = \{Z_1(\mathrm{x}*), Z_2(\mathrm{x}*), -Z_3(\mathrm{x}*)\}$

Subject to follow inequality constraints: $\begin{cases} TCI \leq £980{,}401 \\ DPB \leq 50\ years \\ Discomfort\ \leq 1{,}413 \end{cases}$ {constraints}

7.1.4 NSGA-II parameters

A fundamental task for the process is the identification of the optimal computing settings to improve calculation time and accuracy. As GA requires a large population size to efficiently work to define the Pareto front within the entire search space, the following settings were defined for both studies:

Table 7-2 Algorithm parameters and stopping criteria for optimisation with GA

Parameters	
Encoding scheme	Integer encoding (discretisation)
Population type	Double-Vector
Population size	100
Crossover Rate	100%
Mutation Rate	20%
Selection process	Stochastic – fitness influenced
Tournament Selection	2
Elitism size	Pareto optimal solutions
Stopping criteria	
Max Generations	100
Time limit (s)	10^6
Fitness limit	10^{-6}

The optimisation procedure will then perform ~10,000 simulations, or will terminate either if the objective functions converge or a time limit is reached.

7.2 Optimisation results

Following 170 hours of simulation, 9,585 and 10,060 simulations were gathered for the school and office respectively. This represents less than 0.00001% of the entire search space. To present the results, first an analysis for each objective is done to obtain the best individual solutions. Later, comparison by pair of objectives is made by locating 2D Pareto fronts for each combination. Finally, an analysis of the three sets of objectives is done by locating the Pareto surfaces.

7.2.1 Single-objective analysis

Table 7-3 and Table 7-4 present the results and BER designs when each objective is optimised independently for the school and office respectively.

Table 7-3 BER retrofit design for single-objective optimisation. Primary School

Objectives	X^{HVAC}	X^{wall} Wall Insulation (m) {U_{value}}	X^{roof} Roof Insulation (m) {U_{value}}	X^{ground} Ground Insulation (m) {U_{value}}	X^{seal} Infiltration reduction % (ach)	X^{glaz} (glass-gap-glass, in mm)	X^{light} Light techn.	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)	X^{cool} (°C)	$Ex_{dest,bui}$ (kWh/m²-year)	*Discomfort* (hours)	$NPV_{50years}$ (£)
[min] $Ex_{dest,bui}$	H28: Biomass + Wall Heating	EPS (0.11m) {U: 0.27}	Phenolic (0.04m) {U: 0.45}	XPS (0.02m) {U: 0.75}	70% (0.3 ach)	Double Glazed Air (6-13-6)	T8 LED	0	0	20	---	**119.5**	1,369	+23,493
[min] *Discomfort*	H10: Biomass Boiler + CAV	Cellular Glass (0.13m) {U: 0.27}	EPS (0.15m) {U: 0.22}	Glass Fibre (0.065m) {U: 0.39}	40% (0.6 ach)	Double Glazed Krypton (6-13-6)	T12 LFC	0	0	19	---	228.4	**355**	+19,333
[max] $NPV_{50years}$	H31: mCHP + CAV	Aerogel (0.005m) {U: 1.01}	Polyurethane (0.09m) {U: 0.25}	EPS (0.02m) {U: 0.75}	40% (0.6 ach)	Single glazing	T12 LFC	0	0	20	---	154.1	1,389	**+276,182**

Table 7-4 BER retrofit design for single-objective optimisation. A/C Office

Objectives	X^{HVAC}	X^{wall} Wall Insulation (m) {U_{value}}	X^{roof} Roof Insulation (m) {U_{value}}	X^{ground} Ground Insulation (m) {U_{value}}	X^{seal} Infiltration reduction % (ach)	X^{glaz} (glass-gap-glass, in mm)	X^{light} Light techn.	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)	X^{cool} (°C)	$Ex_{dest,bui}$ (kWh/m²-year)	*Discomfort* (hours)	$NPV_{50years}$ (£)
[min] $Ex_{dest,bui}$	H32: Condensing gas boiler + CAV and MVHR	Cellular Glass (0.14m) {U: 0.25}	XPS (0.14m) {U: 0.23}	Cork Board (0.02m) {U: 0.42}	50% (0.5 ach)	Triple Glazed Air (6-6-6)	T8 LED	0	0	20	26	**238.4**	1,294	+4,671
[min] *Discomfort*	H29: Biomass Boiler + Underfloor	XPS (0.14m) {U: 0.22}	Cellular Glass (0.06m) {U: 0.56}	Cellular Glass (0.10m) {U: 0.15}	0% (1 ach)	Single glazing	T8 LED	0	20	19	24	361.6	**111**	+28,663
[max] $NPV_{50years}$	H32: Condensing gas boiler + CAV and MVHR	EPS (0.12m) {U: 0.25}	EPS (0.15m) {U: 0.22}	Glass Fibre (0.085m) {U: 0.24}	10% (0.9 ach)	Single glazing	T8 LED	0	0	20	26	251.1	1,391	**+326,306**

7.2.1.1 Primary School

As shown in Table 7-3, the minimisation of exergy destructions involves the utilisation of a biomass boiler connected to a wall heating system. This design is combined with low levels of envelope's thermal insulation and complemented with a highly efficient lighting system. It does not consider the installation of any renewable generation system. This design produces a reduction in exergy destructions from 241.9 to 119.5 kWh/m^2-year with a minor reduction in discomfort hours from 1,443 to 1,369 hours. It also achieves a reduction in energy use from 188 to 72.3 kWh/m^2-year and a reduction of GHG of 76.3%. This specific BER design requires an investment of £300,855 resulting in a discounted payback (DPB) of 45.5 years. However, building exergy efficiency decreases to 0.083, but the exergoeconomic cost-benefit improves from £2.7/h to £1.6/h.

The results from the optimisation of comfort conditions require the implementation of a biomass boiler with a CAV system, complemented with higher insulation levels compared to the last case. This design decreases uncomfortable hours from 1,443 to 355 hours. It also achieves a 5.6% improvement in exergy destructions, 18.5% in energy use, and reductions in GHG emissions of 55.9%. This requires an investment of £228,759 and has a DPB period of 44.9 years; however, it has an overall exergy efficiency of 0.066 with an exergoeconomic cost-benefit indicator of £3.6/h.

The optimisation of the NPV requires a design with the most favourable economic conditions, thus resulting in the least initial investment among single optimised projects with just £125,635. This results in a NPV of £276,182 and a DPB of 9.5 years. The design is based on a microCHP system connected to an electric boiler and CAV systems; however, in this case the insulation levels are lower and no retrofit measure on the glazing system is implemented. Energy use stands at 120.3 kWh/m^2-year (36% reduction), with annual GHG emissions' reduction of 39.7% and an improvement in exergy destructions of 36.3%. The system exergy efficiency results in 0.086 with an exergoeconomic cost-benefit indicator of £5.4/h.

It was mentioned in the previous chapter that if a reduction in the baseline heating destruction cost rate has to be achieved, the generation system (e.g. boiler) and the envelope thermal properties present the biggest potential for improvement. However, even though a minimisation of exergy destructions is achieved, the annual exergy destruction cost rate is incremented when minimising discomfort and maximising NPV. Figure 7-1 shows a comparison of exergy destruction cost by product for each minimisation design compared to the baseline case. The graph also pinpoints the exergoeconomic cost benefit value by indicating those that present better performance compared to the baseline (green area). In this case, just the BER design, based on minimisation of irreversibilities, achieved a performance improvement.

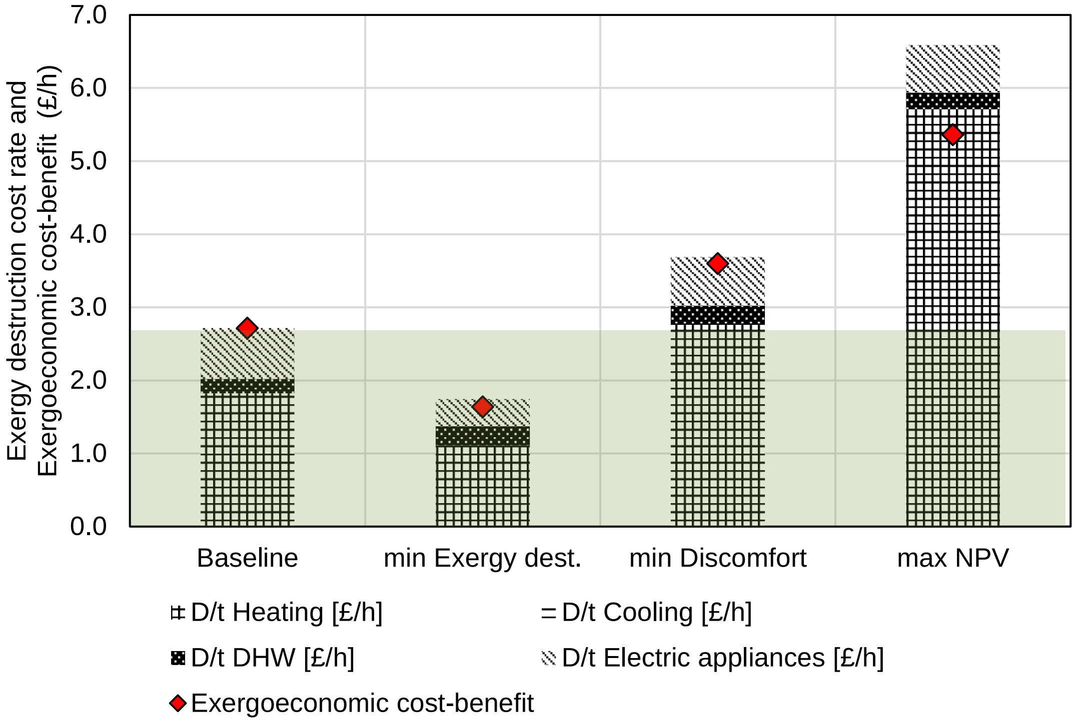


Figure 7-1 Exergy destruction cost rate and exergoeconomic cost-benefit comparison between baseline and single optimised objectives. Primary School

7.2.1.2 A/C office

For the single minimisation of exergy destructions in the office case, the BER design presents a condensing gas boiler with a CAV plus a MVHR system. The re-utilisation of low-grade waste heat is the main reason for the irreversibilities' reductions within the heating/cooling system. In addition, the design is complemented with high levels of insulation in the walls and the roof combined with the installation of triple glazing with 6mm air gap. This project reduces exergy destructions from 465.5 to 238.4 kWh/m^2-year together with a slight improvement of thermal comfort hours (8.4%). The project requires an initial investment of £638,776 obtaining a DPB of 49.8 years. Other improved indicators are energy use (56.7%) and GHG emissions (45.9%). In terms of the Second Law values, the overall exergy efficiency is improved from 0.154 to 0.220 and the exergoeconomic cost benefit is minimised from £6.25/h to £2.66/h.

When optimising comfort conditions, the model provides a BER design based on a biomass boiler connected to an underfloor heating/cooling system. This produces a major improvement in comfort, by minimising annual discomfort hours from 1,413 to just 111 hours. The project's initial investment is found at £515,357 achieving a DPB of 45.0 years. The project also achieves reductions of 22.3% for exergy destructions, 30.8% for energy use, and GHG emissions of 36.4%. The system exergy efficiency is found at 0.204 with an exergoeconomic cost-benefit indicator of £6.0/h.

Similarly, to the reduction of exergy destructions, optimising NPV values results in the implementation of a condensing gas boiler with CAV, plus a MVHR system complemented with high levels of building envelope's thermal insulation; however, minor improvements of the infiltration rate (from 1.0 to 0.9 *ach*) and no retrofit on the glazing system is suggested. Similarly, to the school's case, this results in the project with the least initial investments, having a value of £272,703. This gives a NPV of £326,306 with a DPB of 14.7 years. In addition, this design minimises exergy destructions close to the obtained optimal output, with a value of 251.1 kWh/m^2-year; however, occupant thermal comfort is barely improved by 1.6%. Other significant outputs are the reductions in energy use by 50.4% and GHG emissions by 42.7%. Unexpectedly, it has a better thermodynamic performance achieving an overall exergy efficiency of 0.225 and an exergoeconomic cost-benefit of £1.45/h.

Figure 7-2 shows a comparison of exergy destruction cost by product for each optimisation design compared to the baseline case along the exergoeconomic cost benefit value. Unlike the school's case, all the individual minimisation designs achieved an improvement in exergoeconomic cost-benefit value. In this case, the BER design based on the single maximisation of NPV delivers the best outcomes.

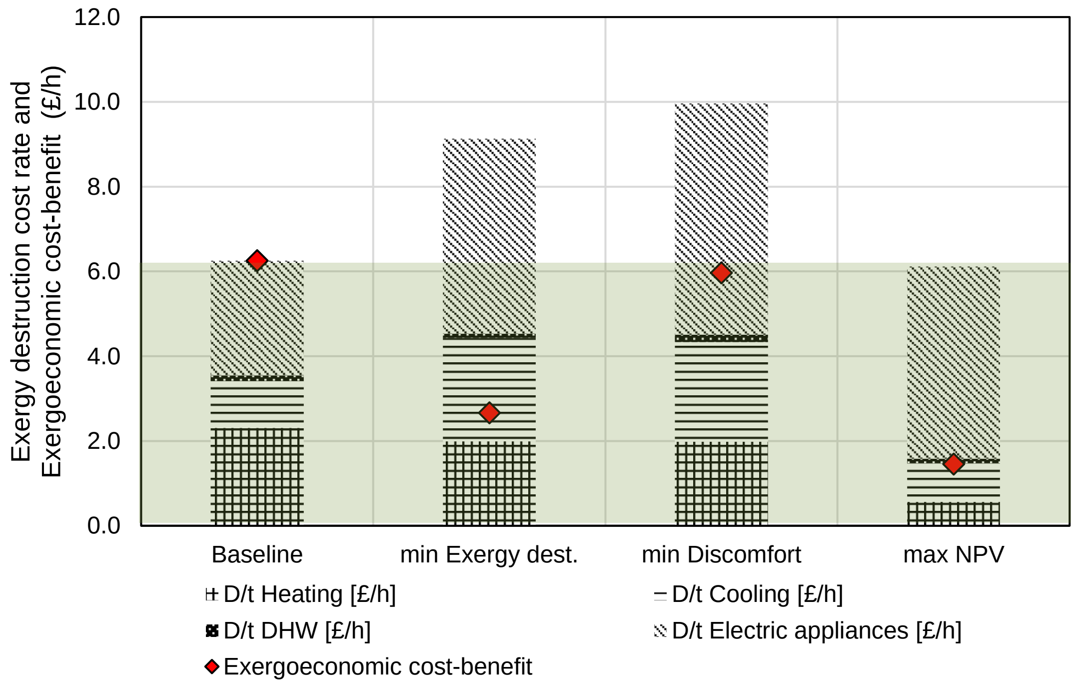


Figure 7-2 Exergy destruction cost rate and exergoeconomic cost-benefit comparison between baseline and single optimised objectives. A/C Office

7.2.2 Dual-objective analysis

In this section, the performance of the system can be presented as a trade-off between the pairs of objectives to easily illustrate Pareto solutions. This represents an analysis of the three sets of dual objectives: 1) Exergy destructions – Comfort, 2) Exergy Destructions – NPV, and 3) Comfort – NPV. Next graphs illustrate the simultaneous minimisation of the two objectives for the two case studies. All simulated solutions, such as the solutions constrained by the selected criteria (maximum discomfort, positive NPV, and maximum capital investment), the identification of the baseline case, and the Pareto front are represented. Each solution in the Pareto front has associated different BER strategies.

7.2.2.1 Primary School

Figure 7-3 illustrates the simultaneous minimisation of exergy destructions and discomfort hours, localising the constraint solutions and the Pareto front (formed by eleven designs). Models with better outputs in the objectives that are not part of the Pareto front are due to the established constraints, either related to thermal comfort, capital investment, or cost-benefit. When analysing the Pareto front, the most common HVAC systems are H10: Biomass boiler with CAV system and H28: Biomass boiler with wall heating, both with a frequency of 27.3%. For insulation, no measures with exact technology and thickness are repeated; however, the most common technology is EPS for the wall, polyurethane and EPS for the roof, and polyurethane for the ground floor. In respect to the infiltration rate, 0.7 *ach* is the most common value. For active systems, the T8 LED lighting system, with no PV panels and wind turbines are the most frequent variables.

The minimum value for exergy destructions is achieved by the system H28, while the minimum value for discomfort by the H10. The whole description of the BER designs for both optimised extremes can be seen in the graph. Also, the BER design that represents the model closer to the 'utopia point' is presented. The utopia point is represented by a theoretical solution that has both optimised values.

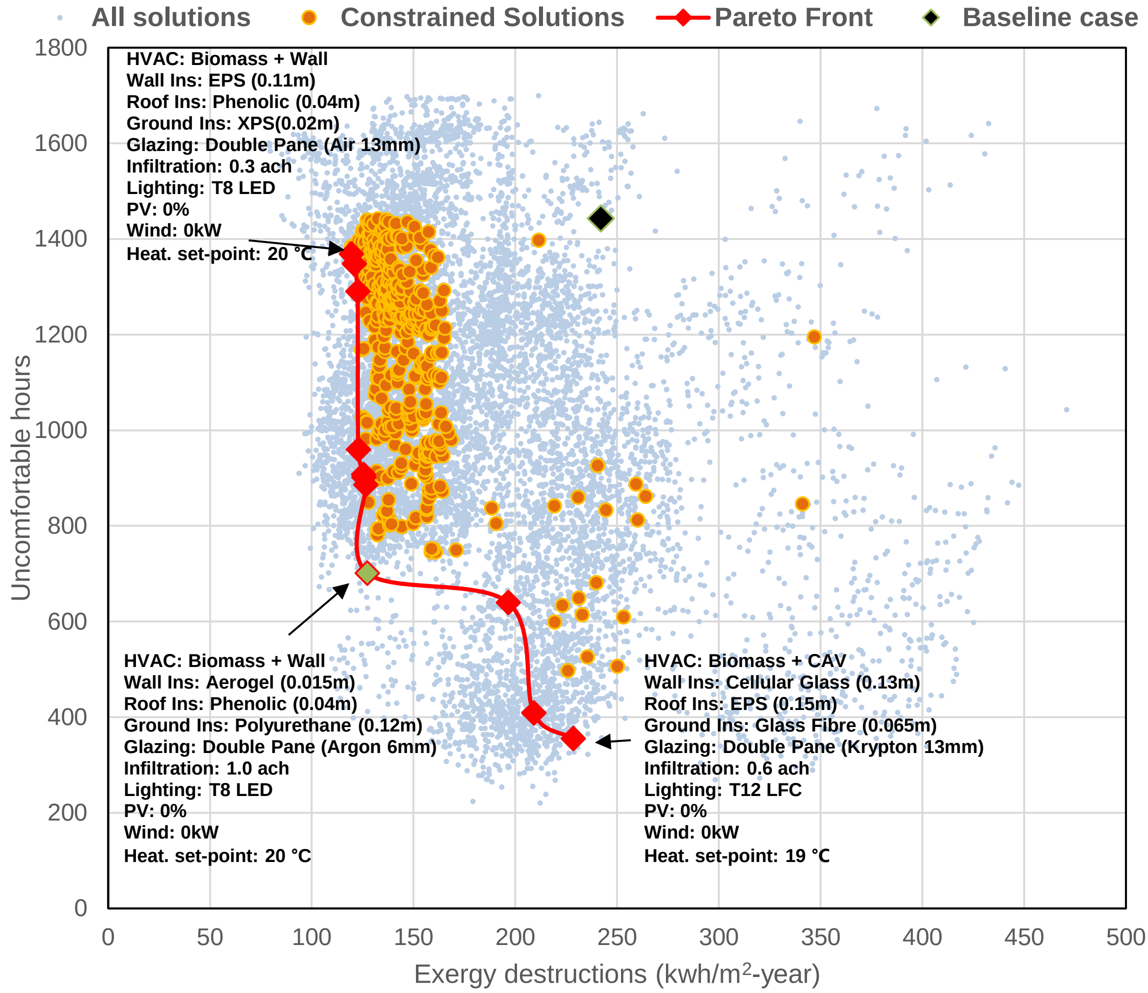


Figure 7-3 Optimisation results and Pareto front (Exergy destructions - Comfort) for the Primary School

Figure 7-4 illustrates the simultaneous minimisation of exergy destructions and maximisation of NPV. In this case, the Pareto front is formed by nine designs. The most frequent HVAC design is H31: microCHP with a CAV system, presented in eight of the nine cases. The only other system is H28: Biomass boiler and wall heating. For the wall insulation, the most frequent technologies are EPS and glass fibre, while for both roof and ground is EPS. The most common infiltration rate is 0.4 *ach*, with a frequency of 44.4%, while the most frequent glazing system is double glazing with 6 mm gap of Krypton (freq:33.3%). For the lighting system it is T5 LFC the more frequent technology. For renewable systems, just one of the models in the Pareto front includes a 20 kW wind turbine. The next graph shows BER description of extreme Pareto solutions as well as the BER design closest to the utopia point.

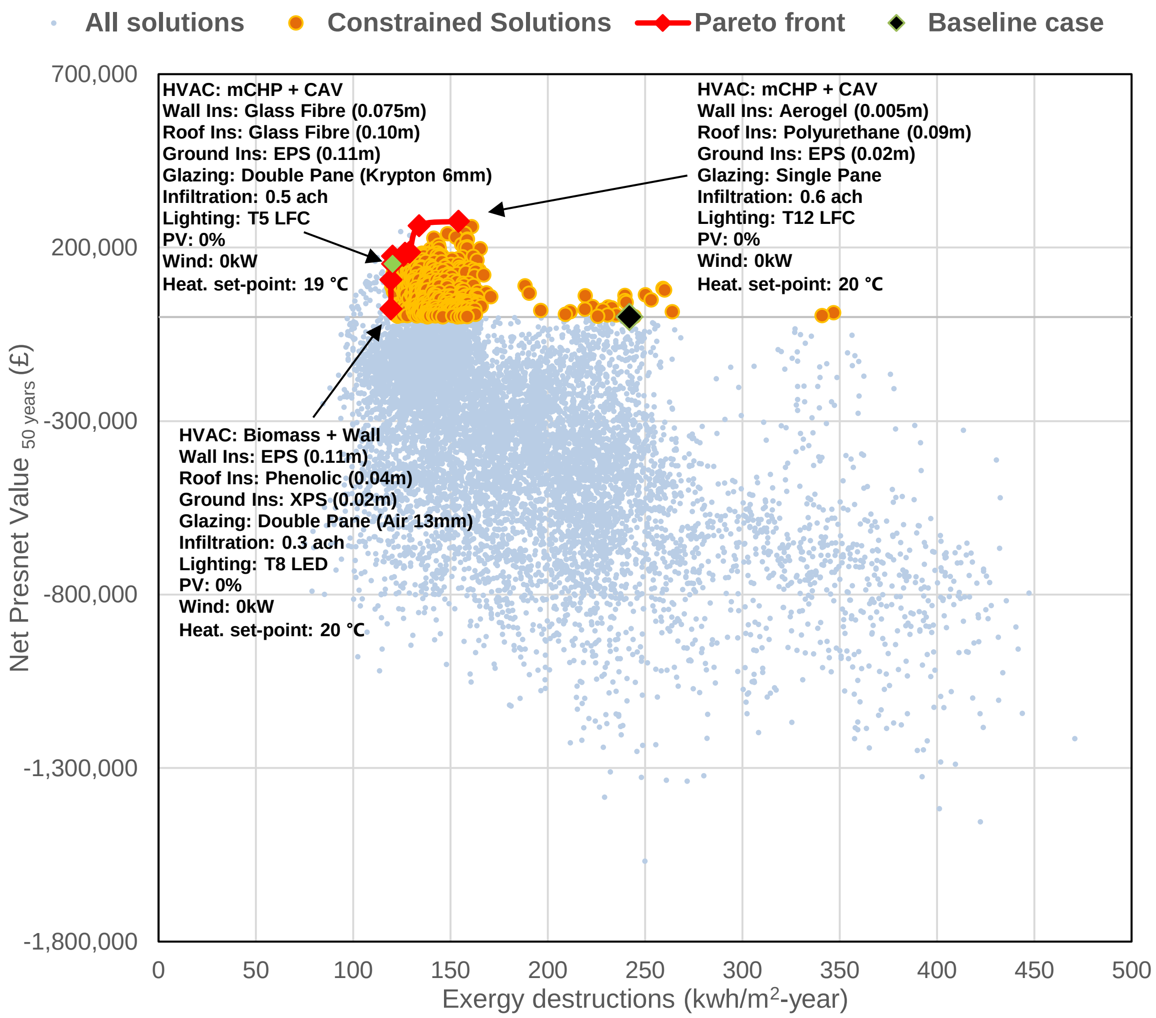


Figure 7-4 Optimisation results and Pareto front (Exergy destructions - NPV) for the Primary School

The results for the dual optimisation of thermal comfort and NPV are illustrated in Figure 7-5. The Pareto front is formed by thirteen solutions. The most common HVAC system is H28: Biomass boiler and wall heating with a recurrence of 46.2%. The most common insulation measures are cellular glass and cork board for the walls, EPS for the roof, and polyurethane for the floor. The infiltration rate that dominates the optimal solutions is 0.8 *ach*, with no retrofit in the glazing system. Regarding active systems, the baseline's T12 LFC is the most common solution with no installation of PV panels and wind turbines. The next graph shows BER description of extreme Pareto solutions as well as the closest BER design to the utopia point.

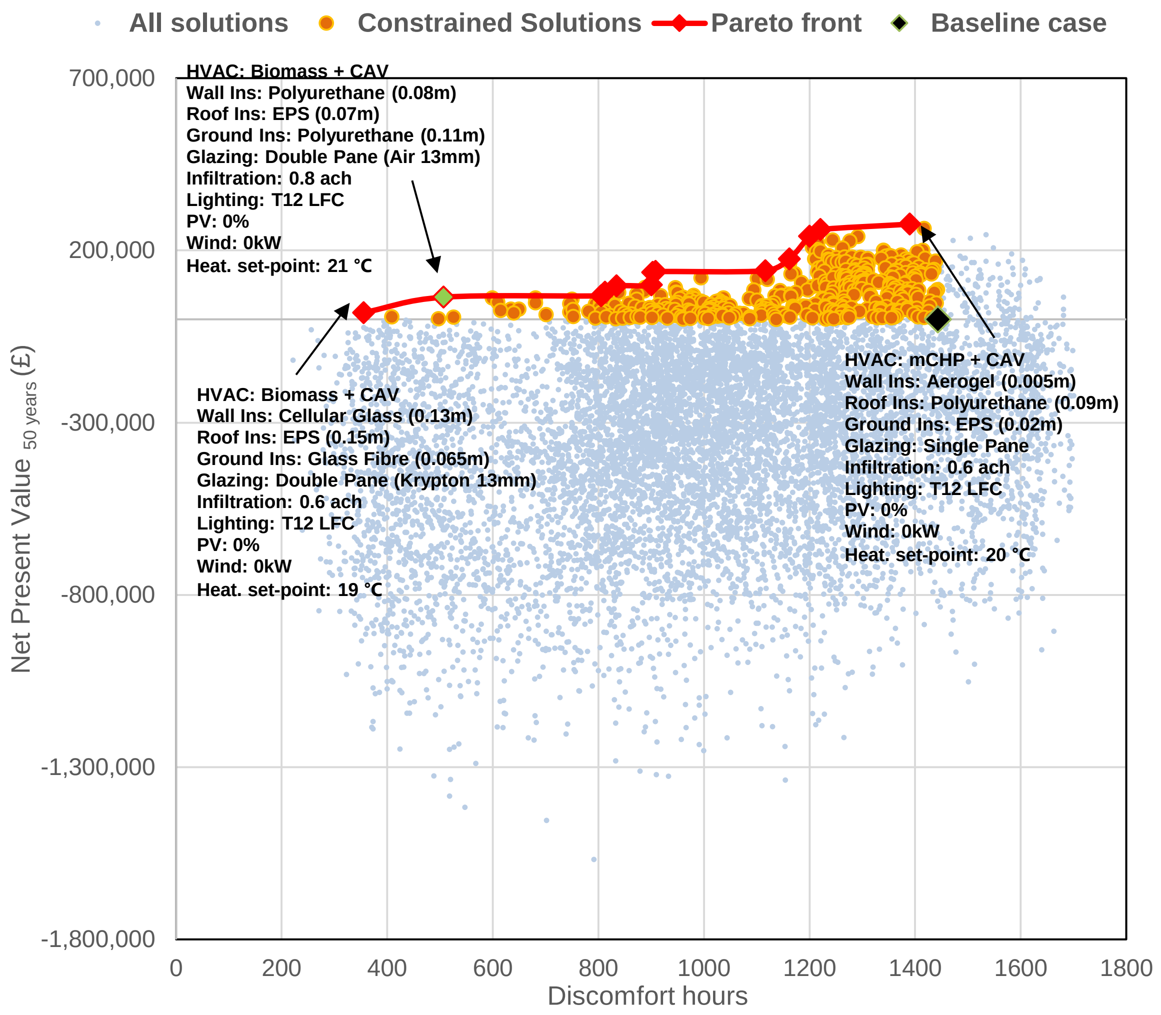


Figure 7-5 Optimisation results and Pareto front (Comfort - NPV) for the Primary School

7.2.2.2 A/C Office

The same dual-objective analysis is done for the office case. First, Figure 7-6 illustrates the simultaneous minimisation of exergy destructions and discomfort hours. The Pareto front is formed by thirty-six solutions. The most frequent HVAC systems are H32: condensing gas boiler with CAV and MVHR system with a concurrence of 30.6%, followed by H16: District System with underfloor heating/cooling, and by H31: microCHP with a CAV system, both with a frequency of 19.4%. In this case, thanks to a larger Pareto front, it is possible to identify specific insulation solutions (technology and thickness) that repeat. For the wall, the most common insulation measure is 0.10m of EPS, followed by 0.07m of XPS and 0.14m of cellular glass. For the roof it is 0.14m of XPS followed by 0.09m of phenolic board. For the ground, the most common measure is 0.02m of cork board. In respect to the infiltration rate, 1.0 *ach* is the most common value. For the active system, all the solutions present T8 LED lighting system

(100% frequency), and as in the case of the school, no implementation of PV panels and wind turbines dominate the designs. The next graph shows BER description of extreme Pareto solutions as well as the closest BER design to the utopia point.

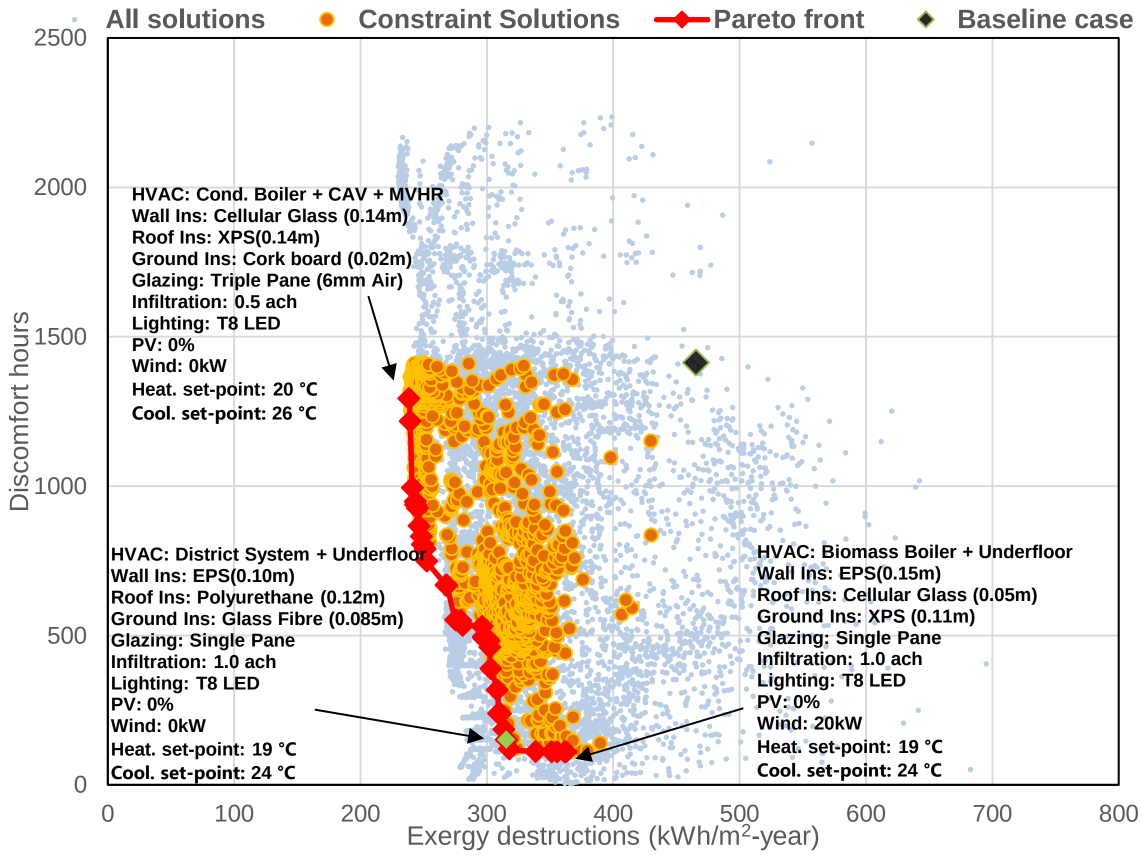


Figure 7-6 Optimisation results and Pareto front (Exergy destructions - Comfort) for the A/C Office

Figure 7-7 illustrates the simultaneous minimisation of exergy destructions and maximisation of NPV. In this case, the Pareto front is formed by fifteen designs. H32: Condensing gas boiler with CAV and MVHR system has a frequency of 100%, presented in all of the Pareto solutions. For the wall insulation, the most frequent measure is 0.09m of EPS, while for the roof is 0.14m of EPS and for the ground is .04m of XPS. The most common infiltration rate is 0.5 *ach*, with the frequency of 40.0%, while the most frequent glazing system (60%) is the baseline's single pane. For the lighting system, again, T8 LED is presented in all the solutions, with low frequency of renewable systems. The graph also shows the BER description of extreme Pareto solutions as well as the closest BER design to the utopia point. As can be noticed, the Pareto front is clustered in one region due to the implemented constraints, and as a result similar BER designs are obtained in this optimisation analysis.

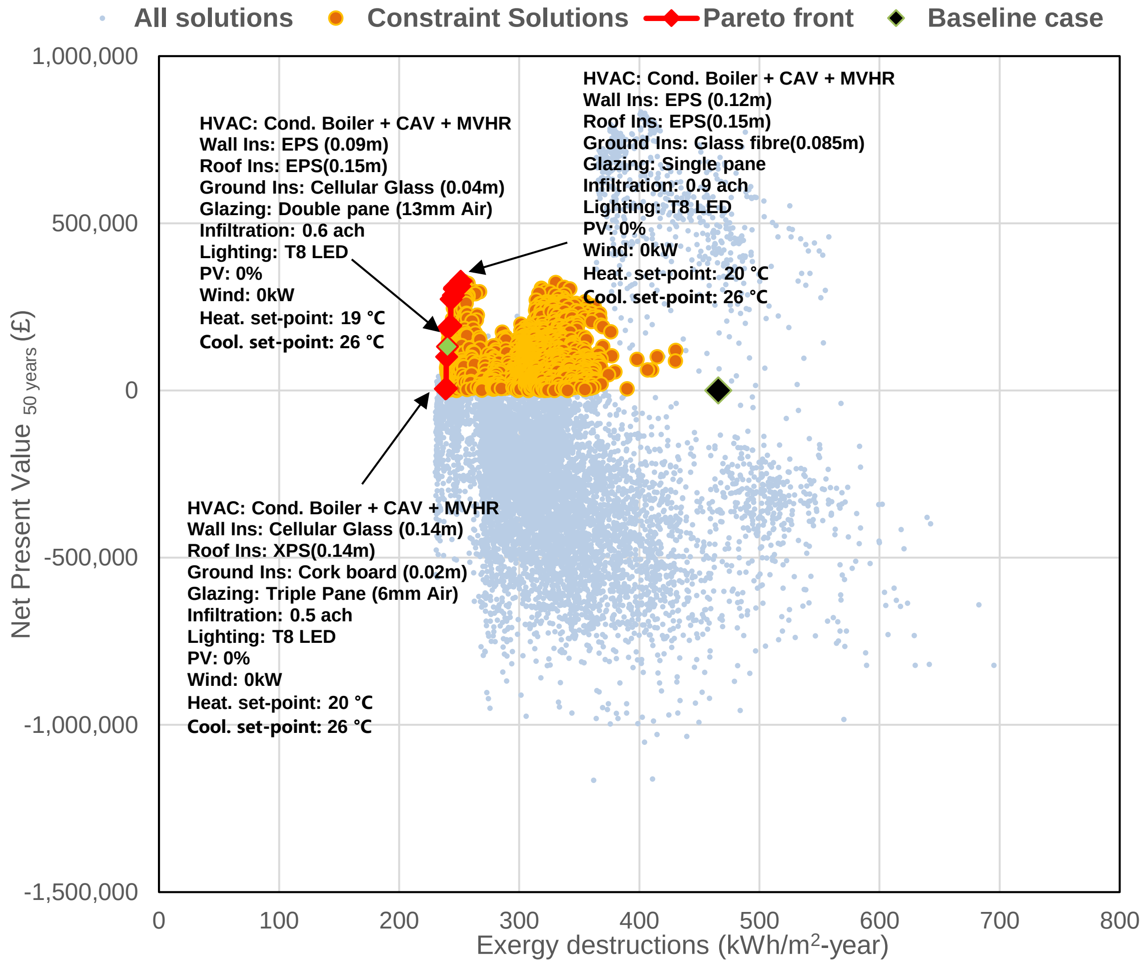


Figure 7-7 Optimisation results and Pareto front (Exergy destructions - NPV) for the A/C Office

Finally, the results for the dual optimisation of thermal comfort and NPV can be seen in Figure 7-8. The Pareto front is formed by eighteen solutions. An interesting outcome is that there is a large group of solutions (left-upper corner) that appear to have better performance than the Pareto front itself. However, all these solutions, although presenting a better NPV, have larger capital investments than specified in the constraint set. Nevertheless, good performance is achieved for both objective functions. In this case, the most common HVAC system is H31: microCHP with a CAV system with a recurrence of 61.1%. The most common insulation measures are 0.10m of EPS for the walls, 0.11m of EPS for the roof, and 0.14m of EPS for the floor. Again, no improvement in the envelope air-tightness and glazing system is preferred by the model. Regarding active systems, T8 LED dominates all the solutions, with no installation of PV panels; however, a 20 kW wind turbine is presented in 44.4% of the optimal cases. The next graph shows BER description of extreme Pareto solutions as well as the closest BER design to the utopia point.

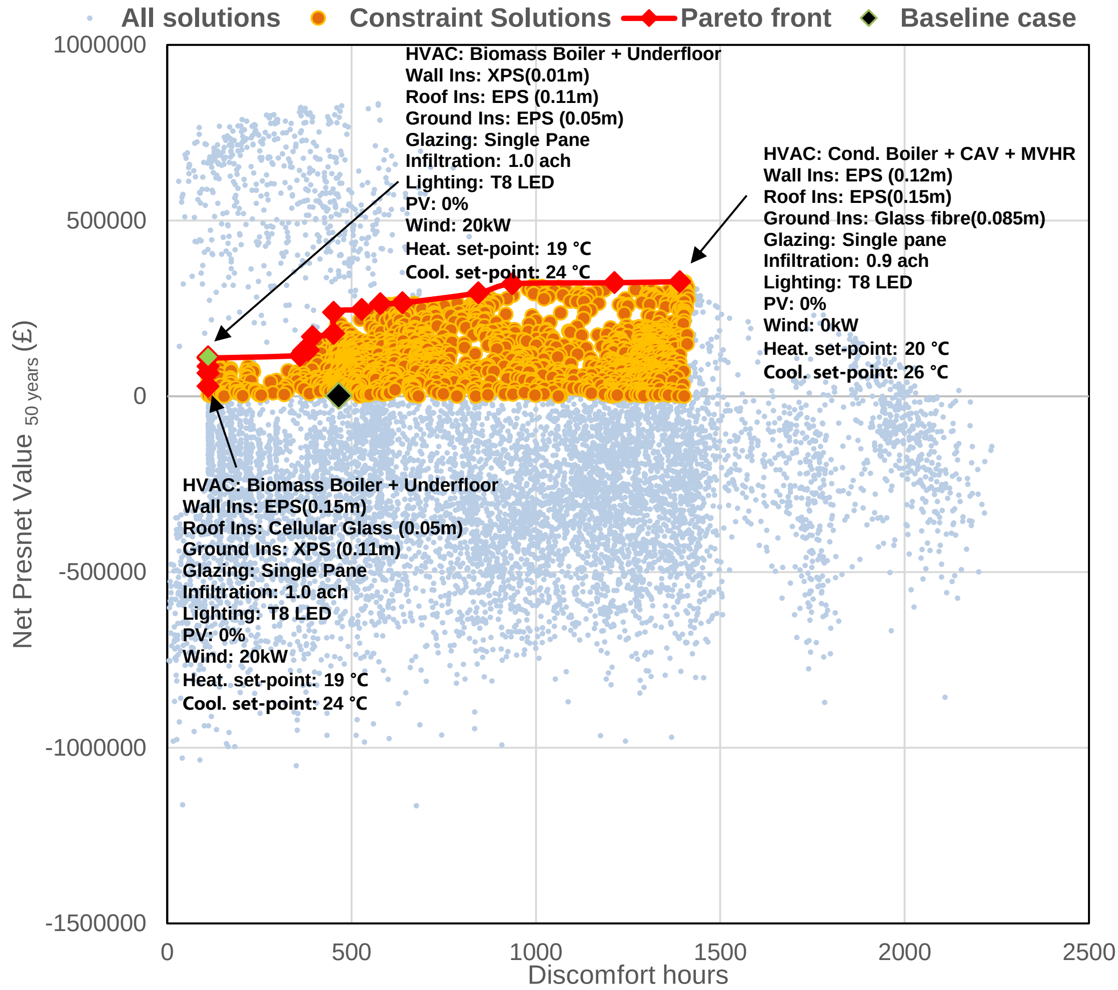


Figure 7-8 Optimisation results and Pareto front (Comfort - NPV) for the A/C Office

This dual-objective analysis has helped to show the design characteristics for different BER solutions, where although similar criteria were considered for the two buildings' cases, different results were obtained due the different operational nature of each building type. This analysis provides the first understanding of the difficulties in optimising conflicting objectives and the influence of these on a desired output. The number of non-dominated solutions (or Pareto front solutions) for objectives whose criteria are not conflictive are presented by a lower number of solutions and a lesser design variation, compared to objectives that are entirely conflicting (exergy destructions and NPV).

7.2.3 Triple-objective analysis

Triple objetive analysis considers the simulatenous optimisation of all the treated objective functions. In this case a 'Pareto surface' is obtained, represented in a 3D space. As the optimisation study is heavily constrained, the number of Pareto solutions is small considering the large search space of around 10,000 cases for each case study.

7.2.3.1 Primary School

For the school's study, the constrained solutions' space consists of 417 models, of which the Pareto front is composed of only 70 possible solutions (Appendix E.1.). Figure 7-9 shows a comparison of all the constrained solutions and the non-dominated Pareto solutions found by the model. Infiltration (ach) was taken as the colour range to illustrate the combined impact of this parameter in the three objectives. As can be seen, all the Pareto points present a better performance compared to the baseline model. Given the constraints, the Pareto front results suggest that the optimisation study found more models oriented to minimise exergy destructions and maximise Net Present Value, while struggling to optimise the thermal comfort objective. This is also complemented by the fact that the majority of optimal solutions present high values of infiltration levels (0.5 < x <1.0 ach). This might be the case for obtaining average improvement in occupant thermal comfort. Nevertheless, the Pareto front also obtained models with good thermal comfort performance, with discomfort values of 400 hours or less annually.

In a more detailed analysis, Figure 7-10 presents frequency graphs of the most important design variables. This graph illustrates that 0.8 *ach* of infiltration rate dominates the Pareto front, followed by 0.9 and 0.7 *ach*. Regarding the HVAC system, H31: microCHP with fuel cell and electric boiler with CAV system is presented in the majority of optimal solutions. On the other hand, the optimisation suggests not to retrofit the glazing systems. In respect to insulation, Polyurethane is found to be the most frequent technology among all three parts of the envelope, suggesting its good performance for the size and operation as the one analysed. The most common insulation thicknesses are found to be 5 cm, 1cm, and 2 cm for wall, roof, and ground respectively.

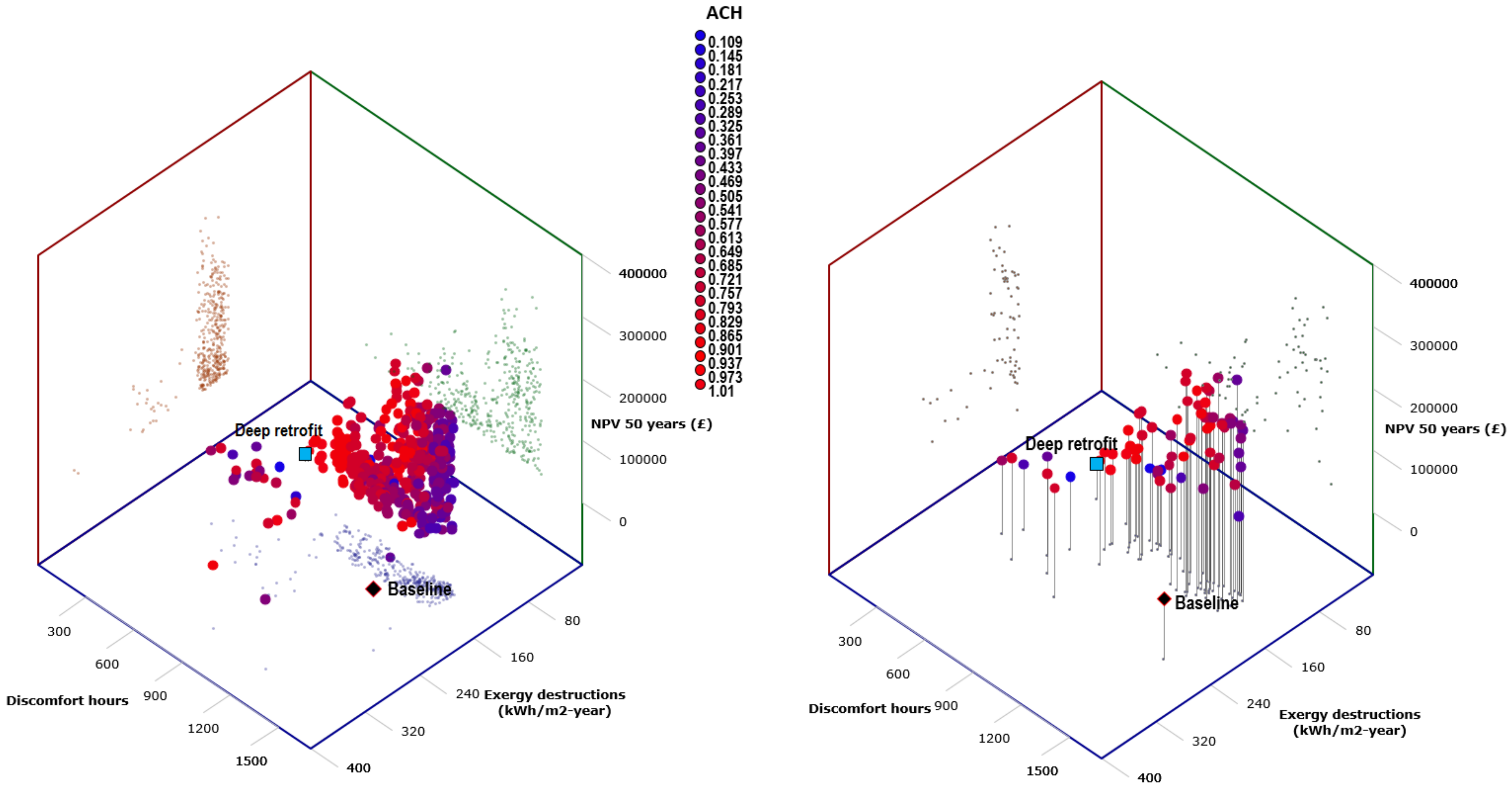


Figure 7-9 Constrained results from the multi-objective optimisation (left) and the Pareto optimal solutions (right). Primary School

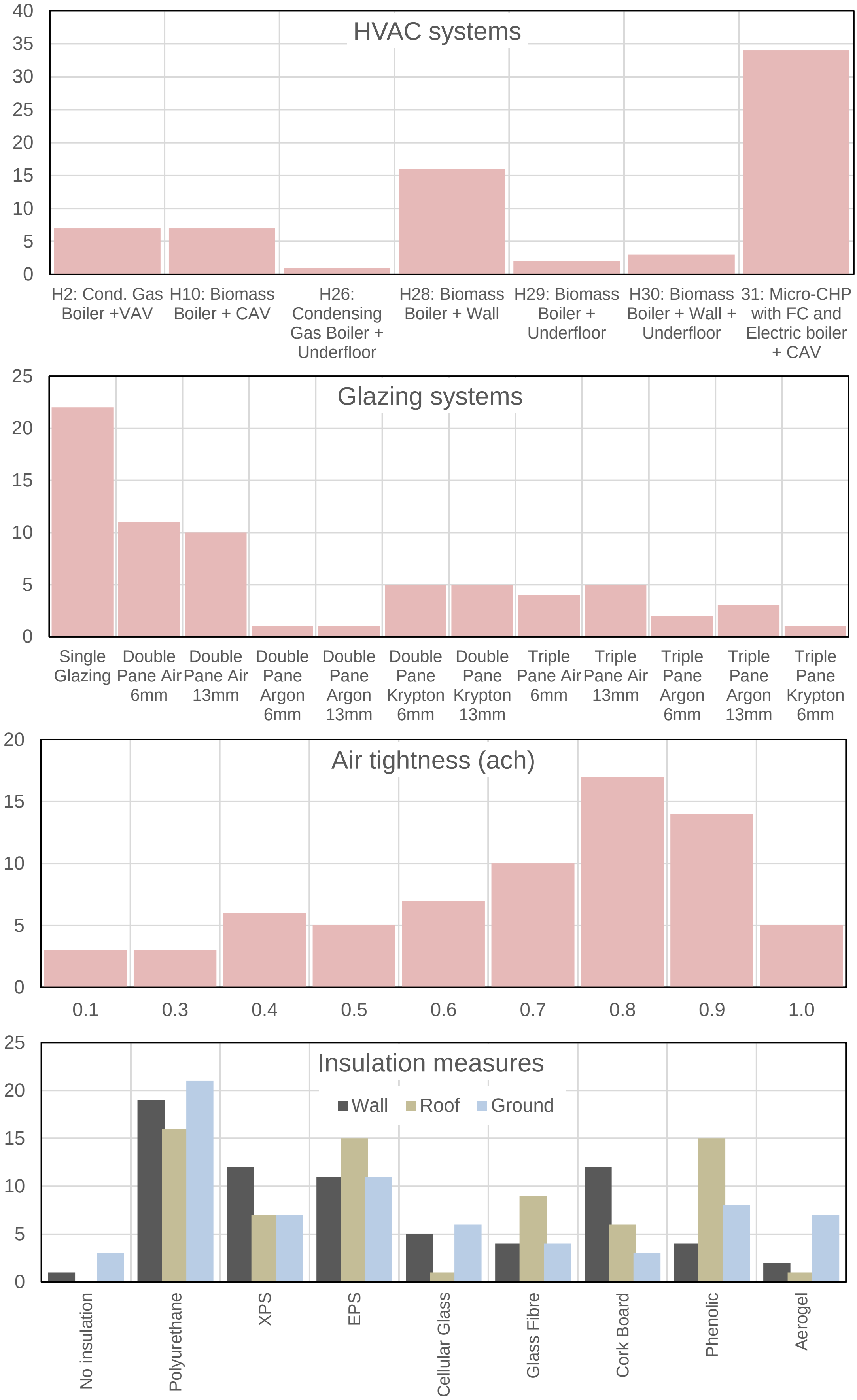


Figure 7-10 Frequency distribution graphs of main retrofit variables from the Pareto front of the Primary School case

Other design variables that are not illustrated and dominate the Pareto front are T12 LFC for the lighting system, the implementation of a 20 kW wind turbine, no installation of PV roof panels, and a heating set-point of 18 °C. However, this low set-point variable negatively impacts the improvement in thermal comfort.

Table 7-5 shows a basic statistic description of the Pareto front objective functions. By analysing the mean and the median, the algorithms' performance and the skewness on each objective can be noticed. Also a comparison is made between the design values of the baseline building and the deep-BER developed in the last chapter.

Table 7-5 Descriptive statistics of Primary School Pareto front objective functions and comparison with baseline and deep retrofit design values

Values	Exergy destructions (kWh/m²-year)	Thermal discomfort hours	Net Present Value $_{50\ years}$ (£)
Mean	147.8	1,062	114,683
Standard Deviation	31.4	272	76,651
Standard Error	3.75	33	9,162
Median	138.7	1,165	107,500
Minimum	119.5	355	2,069
Maximum	260.1	1,419	276,182
Baseline	241.9	1443	n/a
Deep-retrofit	121.7	490	-42,954

On the other hand, Table 7-6 and Table 7-7 show the main energy and economic, and exergy and exergoeconomic indicators respectively. Also, a comparison is made against the baseline values and the deep retrofit design to compare the model's capabilities to deliver better solutions under specific objective functions.

Table 7-6 Descriptive statistics of Primary School Pareto front energy and economic indicators and comparison with baseline and deep retrofit design values

Values	EUI (kWh/m²-year)	Carbon emissions (tCO_2)	Total Cost Retrofit (£)	Discounted Payback (years)
Mean	101.0	99.5	295,859	34.7
Standard Deviation	20.6	22.6	93,816	9.4
Standard Error	1.0	1.1	4,600	0.5
Median	102.5	107.9	290,093	35.3
Minimum	51.2	45.1	63,424	9.4
Maximum	181.3	145.3	610,332	50.6
Baseline	187.9	214.8	n/a	n/a
Deep-retrofit	74.9	20.9	734,968	84.3

Table 7-7 Descriptive statistics of Primary School Pareto front exergy and exergoeconomic indicators and comparison with baseline and deep retrofit design values

Values	Primary exergy input (kWh/m^2-year)	Exergy efficiency (-)	Exergy destruction cost rate (£/h)	$Exec_{CB}$ (£/h)
Mean	162.0	0.086	4.1	3.8
Standard Deviation	28.0	0.014	2.3	2.1
Standard Error	1.4	0.001	0.1	0.1
Median	156.3	0.084	4.5	4.3
Minimum	130.3	0.037	1.0	0.6
Maximum	360.5	0.133	15.4	15.3
Baseline	267.4	0.095	2.72	2.7
Deep-retrofit	139.1	0.125	1.22	1.9

7.2.3.2 A/C Office

For the office case, a much larger constrained solution of 1,640 is obtained, resulting in a Pareto front consisting of 230 solutions (Appendix E.2). Figure 7-11 shows the constrained and the Pareto front models. Unlike the school's case, a much larger variation of infiltration rate can be noticed. Given that the nature of operation is an office building, it has to be considered that a larger infiltration rate might help reduce cooling energy demand and improve thermal comfort during summer months. Thus, a better distribution among the thermal comfort graph can be perceived in the Pareto front. This shows the impact on an increasingly air-tight building in a temperate climate such as London (UK), where overheating risk in summer months is a factor that should be taken into consideration in any BER design analysis.

Figure 7-12 presents the frequency graphs, illustrating that aforementioned variability in the infiltration rate, where values between 0.4 and 0.7 *ach* present similar variabilities among Pareto solutions. In the case of HVAC systems two designs clearly dominate, H32: Condensing gas boiler and water-based chiller plus a CAV and MVHR system, followed by H31: microCHP with fuel cell and electric boiler with CAV system. Again, single-glazing dominates the solution space, mainly due to its high cost and poor performance of double and triple-glazing systems on the searched objectives. In respect to insulation, EPS clearly dominates every part of the envelope, where the most common insulation thicknesses are found to be .01m, .09m, and .02m for the wall, roof, and ground respectively.

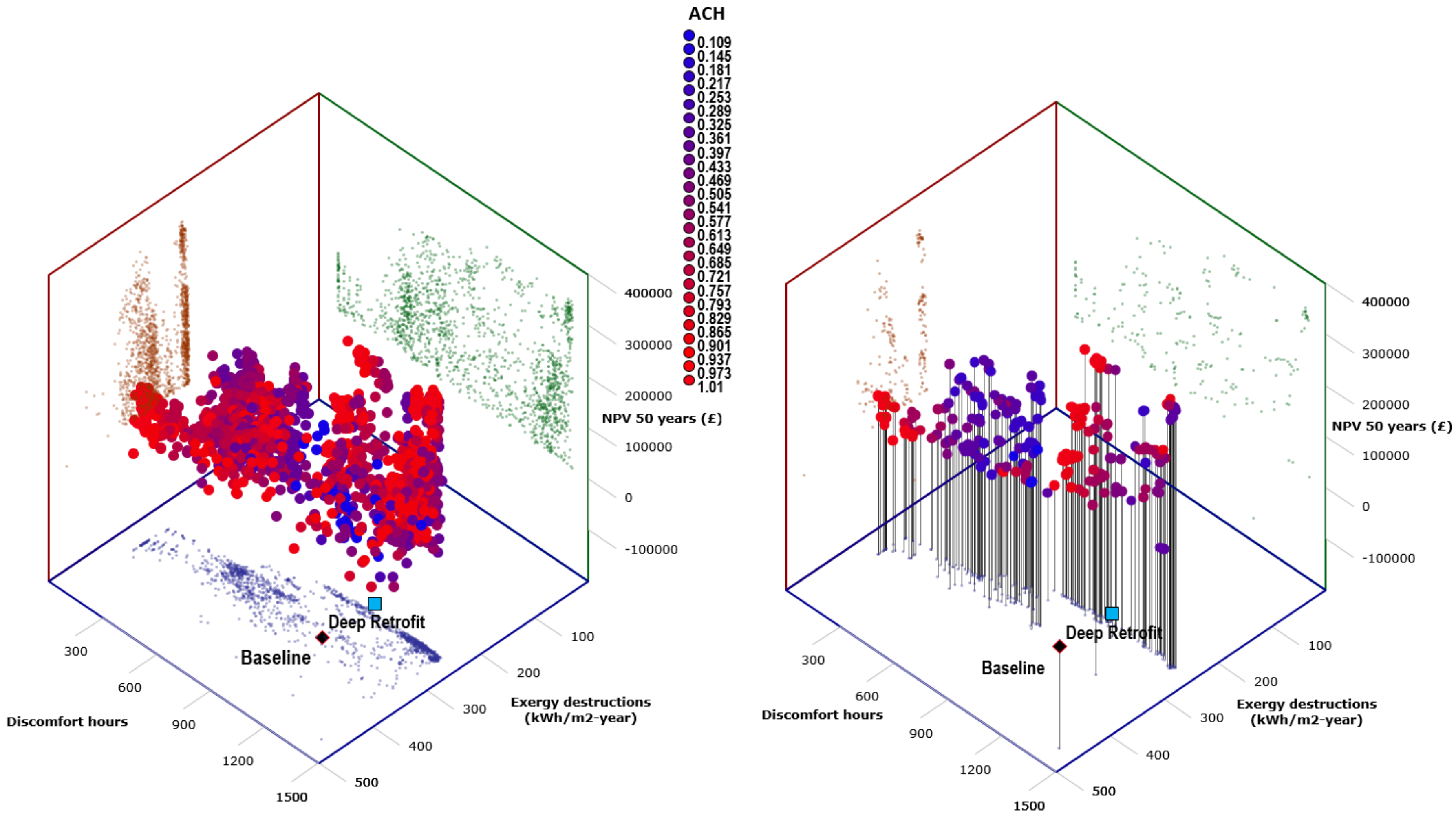


Figure 7-11 Constrained results from the multi-objective optimisation (left) and the Pareto optimal solutions (right). Office building

Figure 7-12 Frequency distribution graphs of main retrofit variables from the Pareto front of the A/C Office case

Other design variables that dominate the Pareto front are T8 LED for the lighting system, the implementation of a 20 kW wind turbine, no installation of PV roof panels, a heating set-point of 22 °C, and a cooling set-point of 24 °C.

Table 7-8 shows the statistical description of the Pareto front and a comparison with the baseline case and the deep-BER design. By analysing the mean and the median, compared to the school's case, less skewness on the outputs can be noticed, giving close to a normal distribution. This means that the algorithm formed populations are able to optimise solutions without compromising too much on any objective.

Table 7-8 Descriptive statistics of A/C Office Pareto front objective functions and comparison with baseline and deep retrofit design values

Values	Exergy destructions (kWh/m^2-year)	Thermal discomfort	Net Present Value $_{50\ years}$ (£)
Mean	284.3	744	133,586
Standard Deviation	36.4	370	94,384
Standard Error	2.4	24	6,224
Median	280.1	720	115,835
Minimum	238.4	111	2,989
Maximum	366.1	1405	326,305
Baseline	465.5	1,413	n/a
Deep-retrofit	262.7	1,101	-154,818

Table 7-9 and Table 7-10 show the energy-based and exergy-based indicators obtained from the statistical analysis of the Pareto front values, and a comparison with baseline and deep retrofit values is also shown.

Table 7-9 Descriptive statistics of A/C Office Pareto front energy and economic indicators and comparison with baseline and deep retrofit design values

Values	EUI (kWh/m^2-year)	Carbon emissions (tCO_2)	Total Cost Retrofit (£)	Discounted Payback (years)
Mean	154.0	170.8	532,506	35.1
Standard Deviation	24.9	16.6	139,574	9.0
Standard Error	0.6	0.4	3,447	0.2
Median	149.5	168.5	526,640	35.8
Minimum	98.7	124.3	198,131	14.6
Maximum	227.8	241.5	973,575	50.7
Baseline	288.5	285.6	n/a	n/a
Deep-retrofit	120.6	133.9	980,401	61.4

Table 7-10 Descriptive statistics of A/C Office Pareto front exergy and exergoeconomic indicators and comparison with baseline and deep retrofit design values

Values	Primary exergy input (kWh/m^2-year)	Exergy efficiency (-)	Exergy destruction cost rate (£/h)	$Exec_{CB}$ (£/h)
Mean	365.7	0.208	5.7	5.2
Standard Deviation	46.5	0.012	2.8	2.9
Standard Error	1.2	0.0003	0.1	0.1
Median	373.1	0.204	5.2	4.9
Minimum	305.7	0.168	2.6	1.4
Maximum	526.5	0.269	11.8	11.5
Baseline	457.2	0.154	6.3	6.3
Deep-retrofit	333.9	0.204	4.2	4.9

7.2.4 Algorithm behaviour - Convergence study

However, to demonstrate the MOO model behaviour, a convergence study is necessary to check the evolution of the population around the objective functions. A convergence study shows the best solution for each generation, and indicates a convergence rate for the specific algorithm used in this study (NSGA-II). In addition, the convergence study is required to identify whether true optimum values are reached and the algorithm did not converge into local singularity. Finally, it also provides fundamental information for the future planning of MOO studies' designs under the same analysed conditions.

For both cases, the convergence metrics were computed for every generation. For the Primary school, Figure 7-13 illustrates the evolution of the three objective functions corresponding to each generation and its convergence with an allowance of one hundred generations. The results demonstrate that exergy destructions converged after the nineteenth generation (119.4 kWh/m^2-year), discomfort hours converged after the fiftieth generation (355 hours), and NPV after the twenty-fifth generation (£276,182). As it can be seen, the minimum value for exergy destructions found in the first generation (129.8 kWh/m^2-year) is similar to the one found in the last generations, meaning that the algorithm selected a 'strong' and 'healthy individual' (building model) from the first generation. However, due to the model's strict constraints, larger number of generations were required for the discomfort hours to converge within an acceptable value.

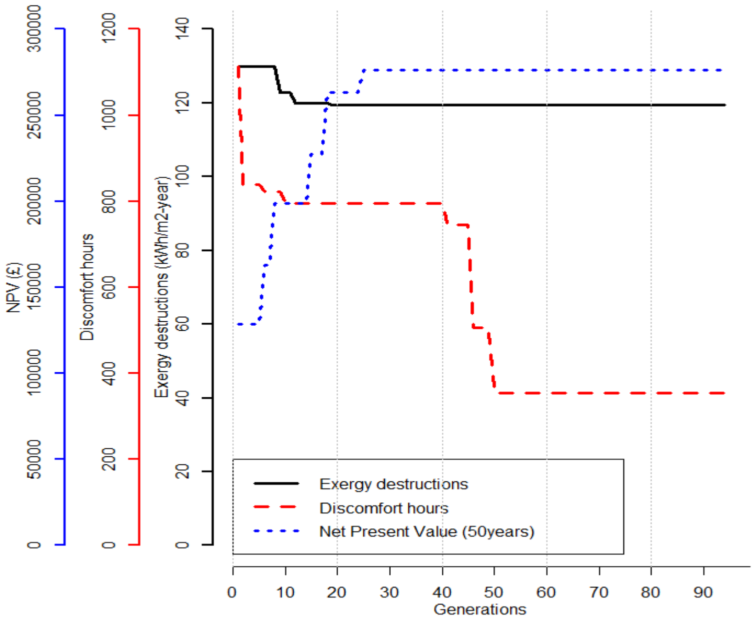


Figure 7-13 Convergence of Primary School optimisation procedure for the three objective functions

For the A/C Office case, Figure 7-14 presents different convergence rates for the three objectives where an opposite effect can be seen. Although barely noticeable, exergy destructions converge after the sixty-second generation (238.4 kWh/m^2-year); however, after the eighth generation the model already achieved a similar optimal output (241.8 kWh/m^2-year). For the discomfort hours the algorithm convergences at the thirty-third generation (110.5 hours); however, as in the exergy destruction case, similar values are obtained just after the second generation (113 hours). Finally, NPV shows a late convergence behaviour achieving minimum value late in the process. It is after the eighty-fifth generation when NPV reaches the minimum value of £326,306.

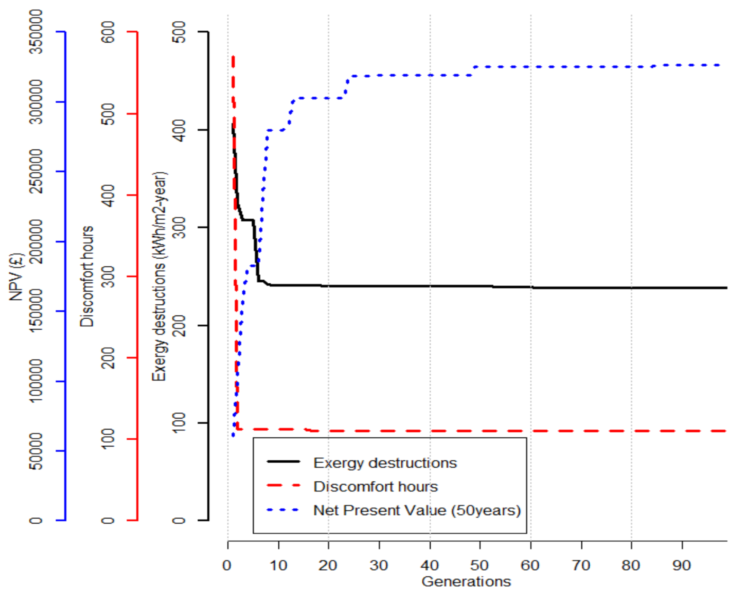


Figure 7-14 Convergence of A/C Office optimisation procedure for the three objective functions

7.3 Multiple-criteria decision analysis (compromise programming)

Once the optimisation is completed and the Pareto-solutions are obtained, a decision-making support process is necessary in order to determine a single solution that should be finally implemented. However, as all the Pareto solutions can be considered as 'equally good', this decision-making process, considering all the analysed objectives, is necessary. Multi-criteria decision making (MCDM) methods support the process of making a decision when multiple objectives exist. Therefore, the final solution will depend on the preference given by the decision maker to each of the objective functions, determining different weighting value for each one. As the three objectives analysed in this study are conflicting among them, compromises in the solution are expected. Nevertheless, the biggest advantage of such screening process is the ability for the decision maker to analyse the available data and if needed actively change the final decision.

As mentioned in Chapter 5 (Section 5.2.5.1), in order to tackle the multi-objective optimisation procedure within ExRET-Opt, a 'Compromise Programming' based on the Tchebyshev distance (α_{cheb}) parameter was selected as the MCDM method capable to analyse the Pareto fronts. In compromise programming, firstly, the non-dominated set is defined with respect to the ideal (Utopian - Z^*) and anti-ideal (Nadir - Z_*) points, which represent the optimisation and anti-optimisation of each objective individually. For this study, the process can be written as follows:

$$\alpha_{exergy\_dest} \geq \left(\frac{\left| Z_{exergy\_dest}(x) - Z^*_{exergy\_dest} \right|}{\left| Z^*_{exergy\_dest} - Z_{*exergy\_dest} \right|} \right) * \left(p_{exergy\_dest} \right) \tag{7.5}$$

$$\alpha_{discomfort} \geq \left(\frac{\left| Z_{discomfort}(x) - Z^*_{discomfort} \right|}{\left| Z^*_{discomfort} - Z_{*discomfort} \right|} \right) * \left(p_{discomfort} \right) \tag{7.6}$$

$$\alpha_{NPV} \geq \left(\frac{\left| Z^*_{NPV} - Z_{NPV}(x) \right|}{\left| Z^*_{NPV} - Z_{*NPV} \right|} \right) * \left(p_{NPV} \right) \tag{7.7}$$

For the application of compromise programming, the weighting procedure by scanning different combinations for the three objectives is subject to the following constraint:

$$\sum_{j=1}^{n} p_j = p_{exergy\_dest} + p_{discomfort} + p_{NPV} = 1 \tag{7.8}$$

Finally, as an individual distance (α_j) is obtained for each objective, these are added up for every solution:

$$\alpha_{cheb} = \sum_{j=1}^{n} \alpha_j = \alpha_{exergy\_dest} + \alpha_{discomfort} + \alpha_{NPV} \geq 0 \tag{7.9}$$

The method then scans all the feasible sets and minimises the deviation from the ideal point, obtaining the minimum Chebyshev distance ([min]α_{cheb}):

$$[min]\alpha_{cheb} = min \sum_{j=1}^{n} \alpha_j \tag{7.10}$$

7.3.1 Primary School MCDM

For the school's case, the entire range of defined criteria and different weights of coefficient values is summarised in Table 7-11. The table highlights the minimum Chebyshev distance obtained for each weighting design along the BER retrofit parameters code (Appendix B.5) and the obtained results for each objective function.

Table 7-11 Sample of 'optimal solutions' obtained from Primary School Pareto front using Compromise Programming

p_{ex}	p_{com}	p_{NPV}	[min] α_{cheb}	$Ex_{dest,bui}$ (kWh/m^2-year)	*Discomfort* (hours)	$NPV_{50years}$ (£)	X^{HVAC} (Type)	X^{wall} (m)	X^{roof} (m)	X^{ground} (m)	X^{seal} (ach)	X^{glaz} (type)	X^{light} Light techn.	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)	X^{cool} (°C)
1	**0**	**0**	0.00	119.4	1,369	23,493	28	3.11	7.04	2.02	0.3	2	3	0	0	20	---
0.9	**0.1**	**0**	0.08	122.8	960	2,069	28	3.02	4.05	4.12	0.7	1	3	0	20	19	---
0.9	**0**	**0.1**	0.04	120.3	1,382	175,127	31	5.075	5.1	3.11	0.5	5	2	0	0	19	---
0.8	**0.2**	**0**	0.11	127.4	701	13,964	28	8.015	7.04	1.12	1	3	3	0	0	20	---
0.8	**0.1**	**0.1**	0.14	120.3	1,382	175,127	31	5.075	5.1	3.11	0.5	5	2	0	0	19	---
0.8	**0**	**0.2**	0.08	120.3	1,382	175,127	31	5.075	5.1	3.11	0.5	5	2	0	0	19	---
0.7	**0.3**	**0**	0.14	127.4	701	13,964	28	8.015	7.04	1.12	1	3	3	0	0	20	---
0.7	**0.2**	**0.1**	0.20	127.4	701	13,964	28	8.015	7.04	1.12	1	3	3	0	0	20	---
0.7	**0.1**	**0.2**	0.17	120.3	1,382	175,127	31	5.075	5.1	3.11	0.5	5	2	0	0	19	---
0.7	**0**	**0.3**	0.09	134.0	1,417	263,272	31	3.14	3.15	1.11	0.4	0	0	0	0	20	---
0.6	**0.4**	**0**	0.16	127.4	701	13,964	28	8.015	7.04	1.12	1	3	3	0	0	20	---
0.6	**0.3**	**0.1**	0.23	127.4	701	13,964	28	8.015	7.04	1.12	1	3	3	0	0	20	---
0.6	**0.2**	**0.2**	0.27	120.3	1,382	175,127	31	5.075	5.1	3.11	0.5	5	2	0	0	19	---
0.6	**0.1**	**0.3**	0.18	134.0	1,417	263,272	31	3.14	3.15	1.11	0.4	0	0	0	0	20	---
0.6	**0**	**0.4**	0.08	134.0	1,417	263,272	31	3.14	3.15	1.11	0.4	0	0	0	0	20	---
0.5	**0.5**	**0**	0.19	127.4	701	13,964	28	8.015	7.04	1.12	1	3	3	0	0	20	---
0.5	**0.4**	**0.1**	0.25	127.4	701	13,964	28	8.015	7.04	1.12	1	3	3	0	0	20	---
0.5	**0.3**	**0.2**	0.32	127.4	701	13,964	28	8.015	7.04	1.12	1	3	3	0	0	20	---
0.5	**0.2**	**0.3**	0.27	134.0	1,417	263,272	31	3.14	3.15	1.11	0.4	0	0	0	0	20	---
0.5	**0.1**	**0.4**	0.17	134.0	1,417	263,272	31	3.14	3.15	1.11	0.4	0	0	0	0	20	---
0.5	**0**	**0.5**	0.08	134.0	1,417	263,272	31	3.14	3.15	1.11	0.4	0	0	0	0	20	---
0.4	**0.6**	**0**	0.22	127.4	701	13,964	28	8.015	7.04	1.12	1	3	3	0	0	20	---

Table 7-11 cont. Sample of 'optimal solutions' obtained from Primary School Pareto front using Compromise Programming

p_{ex}	p_{com}	p_{NPV}	[min] α_{cheb}	$Ex_{dest,bui}$ (kWh/m^2-year)	*Discomfort* (hours)	$NPV_{50years}$ (£)	X^{HVAC} (Type)	X^{wall} (m)	X^{roof} (m)	X^{ground} (m)	X^{seal} (ach)	X^{glaz} (type)	X^{light} Light techn.	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)	X^{cool} (°C)
0.4	**0.5**	**0.1**	0.28	127.4	701	13,964	28	8.015	7.04	1.12	1	3	3	0	0	20	---
0.4	**0.4**	**0.2**	0.34	127.4	701	13,964	28	8.015	7.04	1.12	1	3	3	0	0	20	---
0.4	**0.3**	**0.3**	0.35	134.0	1,417	263,272	31	3.14	3.15	1.11	0.4	0	0	0	0	20	---
0.4	**0.2**	**0.4**	0.26	134.0	1,417	263,272	31	3.14	3.15	1.11	0.4	0	0	0	0	20	---
0.4	**0.1**	**0.5**	0.16	134.0	1,417	263,272	31	3.14	3.15	1.11	0.4	0	0	0	0	20	---
0.4	**0**	**0.6**	0.07	134.0	1,417	263,272	31	3.14	3.15	1.11	0.4	0	0	0	0	20	---
0.3	**0.7**	**0**	0.23	209.1	409	7,548	10	3.08	3.11	6.05	0.3	5	0	0	0	18	---
0.3	**0.6**	**0.1**	0.31	127.4	701	13,964	28	8.015	7.04	1.12	1	3	3	0	0	20	---
0.3	**0.5**	**0.2**	0.37	127.4	701	13,964	28	8.015	7.04	1.12	1	3	3	0	0	20	---
0.3	**0.4**	**0.3**	0.43	160.8	1,220	260,385	31	6.05	3.1	0	0.8	1	0	0	0	21	---
0.3	**0.3**	**0.4**	0.35	134.0	1,417	263,272	31	3.14	3.15	1.11	0.4	0	0	0	0	20	---
0.3	**0.2**	**0.5**	0.25	134.0	1,417	263,272	31	3.14	3.15	1.11	0.4	0	0	0	0	20	---
0.3	**0.1**	**0.6**	0.16	134.0	1,417	263,272	31	3.14	3.15	1.11	0.4	0	0	0	0	20	---
0.3	**0**	**0.7**	0.06	134.0	1,417	263,272	31	3.14	3.15	1.11	0.4	0	0	0	0	20	---
0.2	**0.8**	**0**	0.15	228.4	355	19,333	10	4.13	3.15	5.065	0.6	6	0	0	0	19	---
0.2	**0.7**	**0.1**	0.25	228.4	355	19,333	10	4.13	3.15	5.065	0.6	6	0	0	0	19	---
0.2	**0.6**	**0.2**	0.34	228.4	355	19,333	10	4.13	3.15	5.065	0.6	6	0	0	0	19	---
0.2	**0.5**	**0.3**	0.44	228.4	355	19,333	10	4.13	3.15	5.065	0.6	6	0	0	0	19	---
0.2	**0.4**	**0.4**	0.41	160.8	1,220	260,385	31	6.05	3.1	0	0.8	1	0	0	0	21	---
0.2	**0.3**	**0.5**	0.33	160.8	1,220	260,385	31	6.05	3.1	0	0.8	1	0	0	0	21	---
0.2	**0.2**	**0.6**	0.24	154.1	1,389	276,182	31	8.005	1.09	3.02	0.6	0	0	0	0	20	---
0.2	**0.1**	**0.7**	0.15	154.1	1,389	276,182	31	8.005	1.09	3.02	0.6	0	0	0	0	20	---
0.2	**0**	**0.8**	0.05	154.1	1,389	276,182	31	8.005	1.09	3.02	0.6	0	0	0	0	20	---

Table 7-11 cont. Sample of 'optimal solutions' obtained from Primary School Pareto front using Compromise Programming

p_{ex}	p_{com}	p_{NPV}	[min] α_{cheb}	$Ex_{dest,bui}$ (kWh/m^2-year)	*Discomfort* (hours)	$NPV_{50years}$ (£)	X^{HVAC} (Type)	X^{wall} (m)	X^{roof} (m)	X^{ground} (m)	X^{seal} (ach)	X^{glaz} (type)	X^{light} Light techn.	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)	X^{cool} (°C)
0.1	**0.9**	**0**	0.08	228.4	355	19,333	10	4.13	3.15	5.065	0.6	6	0	0	0	19	---
0.1	**0.8**	**0.1**	0.17	228.4	355	19,333	10	4.13	3.15	5.065	0.6	6	0	0	0	19	---
0.1	**0.7**	**0.2**	0.26	228.4	355	19,333	10	4.13	3.15	5.065	0.6	6	0	0	0	19	---
0.1	**0.6**	**0.3**	0.36	228.4	355	19,333	10	4.13	3.15	5.065	0.6	6	0	0	0	19	---
0.1	**0.5**	**0.4**	0.45	228.4	355	19,333	10	4.13	3.15	5.065	0.6	6	0	0	0	19	---
0.1	**0.4**	**0.5**	0.38	160.8	1,220	260,385	31	6.05	3.1	0	0.8	1	0	0	0	21	---
0.1	**0.3**	**0.6**	0.31	160.8	1,220	260,385	31	6.05	3.1	0	0.8	1	0	0	0	21	---
0.1	**0.2**	**0.7**	0.22	154.1	1,389	276,182	31	8.005	1.09	3.02	0.6	0	0	0	0	20	---
0.1	**0.1**	**0.8**	0.12	154.1	1,389	276,182	31	8.005	1.09	3.02	0.6	0	0	0	0	20	---
0.1	**0**	**0.9**	0.02	154.1	1,389	276,182	31	8.005	1.09	3.02	0.6	0	0	0	0	20	---
0	**1**	**0**	0.00	228.4	355	19,333	10	4.13	3.15	5.065	0.6	6	0	0	0	19	---
0	**0.9**	**0.1**	0.09	228.4	355	19,333	10	4.13	3.15	5.065	0.6	6	0	0	0	19	---
0	**0.8**	**0.2**	0.19	228.4	355	19,333	10	4.13	3.15	5.065	0.6	6	0	0	0	19	---
0	**0.7**	**0.3**	0.28	228.4	355	19,333	10	4.13	3.15	5.065	0.6	6	0	0	0	19	---
0	**0.6**	**0.4**	0.37	228.4	355	19,333	10	4.13	3.15	5.065	0.6	6	0	0	0	19	---
0	**0.5**	**0.5**	0.44	160.8	1,220	260,385	31	6.05	3.1	0	0.8	1	0	0	0	21	---
0	**0.4**	**0.6**	0.36	160.8	1,220	260,385	31	6.05	3.1	0	0.8	1	0	0	0	21	---
0	**0.3**	**0.7**	0.28	160.8	1,220	260,385	31	6.05	3.1	0	0.8	1	0	0	0	21	---
0	**0.2**	**0.8**	0.19	154.1	1,389	276,182	31	8.005	1.09	3.02	0.6	0	0	0	0	20	---
0	**0.1**	**0.9**	0.10	154.1	1,389	276,182	31	8.005	1.09	3.02	0.6	0	0	0	0	20	---
0	**0**	**1**	0.00	154.1	1,389	276,182	31	8.005	1.09	3.02	0.6	0	0	0	0	20	---

Having this type of information gives the decision maker the flexibility and possibility of a straightforward BER design change, if new insights arise as a result of the objectives' priorities adjustment. From a detailed analysis of the last table, it is found that only nine solutions are considered by the MCDM process, as similar BER design repeats in different weighting coefficients. To make a comparison with the previous analysed solutions, Figure 7-15 illustrates these specific solutions.

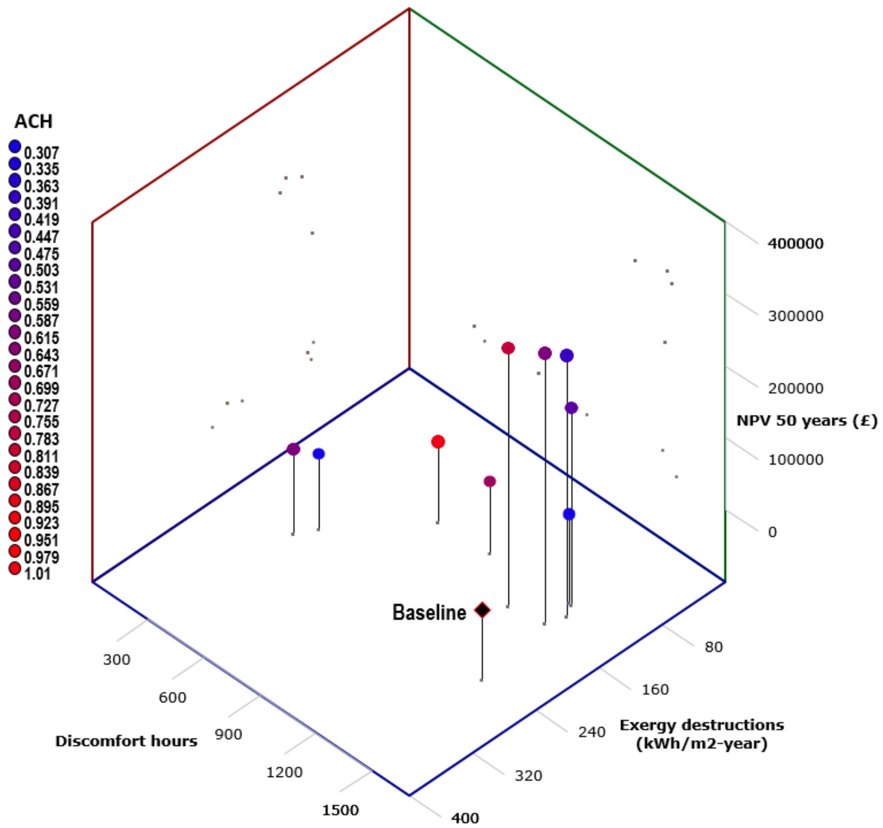


Figure 7-15 Primary School optimal solutions found by Compromise Programming MCDM method

Figure 7-16 shows the compromise solutions for different weights for all pairs of objective functions combinations, demonstrating how the objective functions' outputs change with respect to the coefficient weight. These graphs show the competitive nature of all three objectives. For example, as a result of demanding more exergy to cover internal thermal conditions, an increase in exergy destructions leads to a decrease in occupant thermal discomfort. However, meeting at p_{exergy}=0.4 and $p_{discomfort}$=0.6 good solutions for both objectives can be obtained. When comparing NPV and exergy destructions, it demonstrates that projects with higher NPV merely increase exergy destructions, meaning that a compromise in building exergy efficiency could lead to a more profitable project. Finally, a less profitable project (low NPV) is required to obtain good internal conditions as a result of two reasons: the necessity of more energy leading to a larger expenditure and/or the need to have a higher capital investment for technology that leads to better internal conditions.

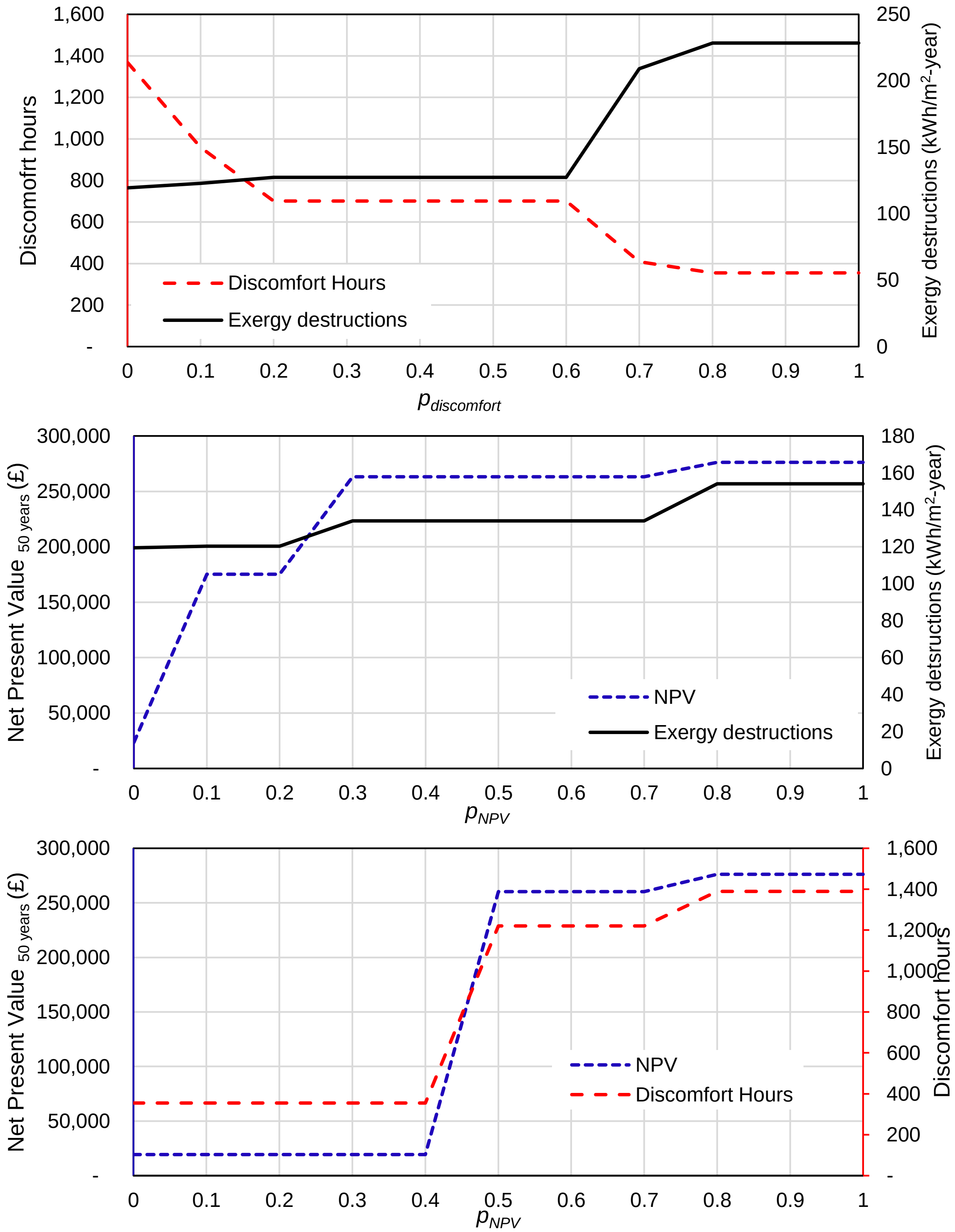


Figure 7-16 Changes in the Primary School objective function values with respect to the weighting coefficient

7.3.2 A/C Office MCDM

For the A/C Office case, the entire range of defined criteria and different weight of coefficient values is summarised in Table 7-12.

Table 7-12 Sample of 'optimal solutions' obtained from A/C Office Pareto front using Compromise Programming

p_{ex}	p_{dis}	p_{NPV}	[min] α_{cheb}	$Ex_{dest,bui}$ (kWh/m^2-year)	***Discomfort*** (hours)	$NPV_{50years}$ (£)	X^{HVAC} (Type)	X^{wall} (m)	X^{roof} (m)	X^{ground} (m)	X^{seal} (ach)	X^{glaz} (type)	X^{light} Light techn.	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)	X^{cool} (°C)
1	**0**	**0**	0.00	238.4	1,294	4,671	32	4.14	2.14	6.02	0.5	7	3	0	0	20	26
0.9	**0.1**	**0**	0.09	240.9	994	42,270	32	1.14	2.14	8.005	0.7	8	3	0	0	22	26
0.9	**0**	**0.1**	0.05	243.2	1,365	272,846	32	3.1	3.11	0	0.5	0	3	25	0	20	26
0.8	**0.2**	**0**	0.15	240.9	994	42,270	32	1.14	2.14	8.005	0.7	8	3	0	0	22	26
0.8	**0.1**	**0.1**	0.14	243.2	1,365	272,846	32	3.1	3.11	0	0.5	0	3	25	0	20	26
0.8	**0**	**0.2**	0.06	246.0	1,400	307,130	32	3.09	3.15	3.05	0.5	0	3	0	0	20	26
0.7	**0.3**	**0**	0.22	246.3	867	22,615	32	4.14	7.09	3.02	0.8	7	3	0	0	22	24
0.7	**0.2**	**0.1**	0.21	249.2	1,079	307,082	32	3.1	3.14	2.01	0.6	0	3	0	0	22	24
0.7	**0.1**	**0.2**	0.15	249.2	1,079	307,082	32	3.1	3.14	2.01	0.6	0	3	0	0	22	24
0.7	**0**	**0.3**	0.06	246.0	1,400	307,130	32	3.09	3.15	3.05	0.5	0	3	0	0	20	26
0.6	**0.4**	**0**	0.26	252.4	750	6,478	32	4.14	2.14	6.02	1	7	3	0	20	22	24
0.6	**0.3**	**0.1**	0.28	249.2	1,079	307,082	32	3.1	3.14	2.01	0.6	0	3	0	0	22	24
0.6	**0.2**	**0.2**	0.21	249.2	1,079	307,082	32	3.1	3.14	2.01	0.6	0	3	0	0	22	24
0.6	**0.1**	**0.3**	0.14	249.2	1,079	307,082	32	3.1	3.14	2.01	0.6	0	3	0	0	22	24
0.6	**0**	**0.4**	0.07	249.2	1,079	307,082	32	3.1	3.14	2.01	0.6	0	3	0	0	22	24
0.5	**0.5**	**0**	0.30	252.4	750	6,478	32	4.14	2.14	6.02	1	7	3	0	20	22	24
0.5	**0.4**	**0.1**	0.33	257.4	936	319,917	32	3.1	3.11	0	1	0	3	0	20	22	24
0.5	**0.3**	**0.2**	0.27	257.4	936	319,917	32	3.1	3.11	0	1	0	3	0	20	22	24
0.5	**0.2**	**0.3**	0.21	257.4	936	319,917	32	3.1	3.11	0	1	0	3	0	20	22	24
0.5	**0.1**	**0.4**	0.14	249.2	1,079	307,082	32	3.1	3.14	2.01	0.6	0	3	0	0	22	24
0.5	**0**	**0.5**	0.05	251.1	1,391	326,306	32	3.12	3.15	5.085	0.9	0	3	0	0	20	26
0.4	**0.6**	**0**	0.25	317.9	120	5,149	16	3.1	1.12	5.085	1	0	3	0	0	19	24

Table 7-12 cont. Sample of 'optimal solutions' obtained from A/C Office Pareto front using Compromise Programming

p_{ex}	p_{dis}	p_{NPV}	[min] α_{cheb}	$Ex_{dest,bui}$ (kWh/m^2-year)	*Discomfort* (hours)	$NPV_{50years}$ (£)	X^{HVAC} (Type)	X^{wall} (m)	X^{roof} (m)	X^{ground} (m)	X^{seal} (ach)	X^{glaz} (type)	X^{light} Light techn.	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)	X^{cool} (°C)
0.4	**0.5**	**0.1**	0.35	318.7	121	13,340	16	3.12	3.13	3.03	1	0	3	0	0	19	24
0.4	**0.4**	**0.2**	0.32	257.4	936	319,917	32	3.1	3.11	0	1	0	3	0	20	22	24
0.4	**0.3**	**0.3**	0.26	257.4	936	319,917	32	3.1	3.11	0	1	0	3	0	20	22	24
0.4	**0.2**	**0.4**	0.20	257.4	936	319,917	32	3.1	3.11	0	1	0	3	0	20	22	24
0.4	**0.1**	**0.5**	0.13	257.4	936	319,917	32	3.1	3.11	0	1	0	3	0	20	22	24
0.4	**0**	**0.6**	0.04	251.1	1,391	326,306	32	3.12	3.15	5.085	0.9	0	3	0	0	20	26
0.3	**0.7**	**0**	0.19	317.9	120	5,149	16	3.1	1.12	5.085	1	0	3	0	0	19	24
0.3	**0.6**	**0.1**	0.29	318.7	121	13,340	16	3.12	3.13	3.03	1	0	3	0	0	19	24
0.3	**0.5**	**0.2**	0.37	257.4	936	319,917	32	3.1	3.11	0	1	0	3	0	20	22	24
0.3	**0.4**	**0.3**	0.31	257.4	936	319,917	32	3.1	3.11	0	1	0	3	0	20	22	24
0.3	**0.3**	**0.4**	0.24	257.4	936	319,917	32	3.1	3.11	0	1	0	3	0	20	22	24
0.3	**0.2**	**0.5**	0.18	257.4	936	319,917	32	3.1	3.11	0	1	0	3	0	20	22	24
0.3	**0.1**	**0.6**	0.12	257.4	936	319,917	32	3.1	3.11	0	1	0	3	0	20	22	24
0.3	**0**	**0.7**	0.03	251.1	1,391	326,306	32	3.12	3.15	5.085	0.9	0	3	0	0	20	26
0.2	**0.8**	**0**	0.13	317.9	120	5,149	16	3.1	1.12	5.085	1	0	3	0	0	19	24
0.2	**0.7**	**0.1**	0.23	318.7	121	13,340	16	3.12	3.13	3.03	1	0	3	0	0	19	24
0.2	**0.6**	**0.2**	0.32	352.4	111	99,521	29	1.04	3.14	3.05	1	0	3	0	20	22	24
0.2	**0.5**	**0.3**	0.35	257.4	936	319,917	32	3.1	3.11	0	1	0	3	0	20	22	24
0.2	**0.4**	**0.4**	0.29	257.4	936	319,917	32	3.1	3.11	0	1	0	3	0	20	22	24
0.2	**0.3**	**0.5**	0.23	257.4	936	319,917	32	3.1	3.11	0	1	0	3	0	20	22	24
0.2	**0.2**	**0.6**	0.17	257.4	936	319,917	32	3.1	3.11	0	1	0	3	0	20	22	24
0.2	**0.1**	**0.7**	0.11	257.4	936	319,917	32	3.1	3.11	0	1	0	3	0	20	22	24
0.2	**0**	**0.8**	0.02	251.1	1,391	326,306	32	3.12	3.15	5.085	0.9	0	3	0	0	20	26

Table 7-12 cont. Sample of 'optimal solutions' obtained from A/C Office Pareto front using Compromise Programming

p_{ex}	p_{dis}	p_{NPV}	[min] α_{cheb}	$Ex_{dest,bui}$ (kWh/m^2-year)	*Discomfort* (hours)	$NPV_{50years}$ (£)	X^{HVAC} (Type)	X^{wall} (m)	X^{roof} (m)	X^{ground} (m)	X^{seal} (ach)	X^{glaz} (type)	X^{light} Light techn.	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)	X^{cool} (°C)
0.1	**0.9**	**0**	0.07	317.9	120	5,149	16	3.1	1.12	5.085	1	0	3	0	0	19	24
0.1	**0.8**	**0.1**	0.16	352.4	111	99,521	29	1.04	3.14	3.05	1	0	3	0	20	22	24
0.1	**0.7**	**0.2**	0.23	352.4	111	99,521	29	1.04	3.14	3.05	1	0	3	0	20	22	24
0.1	**0.6**	**0.3**	0.30	365.6	111	111,630	29	2.01	3.11	3.05	1	0	3	0	20	19	24
0.1	**0.5**	**0.4**	0.33	347.0	451	238,771	31	3.1	2.1	3.02	0.6	0	3	0	0	22	24
0.1	**0.4**	**0.5**	0.28	257.4	936	319,917	32	3.1	3.11	0	1	0	3	0	20	22	24
0.1	**0.3**	**0.6**	0.22	257.4	936	319,917	32	3.1	3.11	0	1	0	3	0	20	22	24
0.1	**0.2**	**0.7**	0.16	257.4	936	319,917	32	3.1	3.11	0	1	0	3	0	20	22	24
0.1	**0.1**	**0.8**	0.09	257.4	936	319,917	32	3.1	3.11	0	1	0	3	0	20	22	24
0.1	**0**	**0.9**	0.01	251.1	1,391	326,306	32	3.12	3.15	5.085	0.9	0	3	0	0	20	26
0	**1**	**0**	0.00	361.6	111	28,663	29	2.14	4.06	4.1	1	0	3	0	20	19	24
0	**0.9**	**0.1**	0.07	365.6	111	111,630	29	2.01	3.11	3.05	1	0	3	0	20	19	24
0	**0.8**	**0.2**	0.13	365.6	111	111,630	29	2.01	3.11	3.05	1	0	3	0	20	19	24
0	**0.7**	**0.3**	0.20	365.6	111	111,630	29	2.01	3.11	3.05	1	0	3	0	20	19	24
0	**0.6**	**0.4**	0.27	365.6	111	111,630	29	2.01	3.11	3.05	1	0	3	0	20	19	24
0	**0.5**	**0.5**	0.27	347.0	451	238,771	31	3.1	2.1	3.02	0.6	0	3	0	0	22	24
0	**0.4**	**0.6**	0.26	325.8	579	263,126	31	3.12	7.09	6.03	0.5	0	3	0	0	19	24
0	**0.3**	**0.7**	0.21	257.4	936	319,917	32	3.1	3.11	0	1	0	3	0	20	22	24
0	**0.2**	**0.8**	0.14	257.4	936	319,917	32	3.1	3.11	0	1	0	3	0	20	22	24
0	**0.1**	**0.9**	0.08	257.4	936	319,917	32	3.1	3.11	0	1	0	3	0	20	22	24
0	**0**	**1**	0.00	251.1	1,391	326,306	32	3.12	3.15	5.085	0.9	0	3	0	0	20	26

Analysing the last table, compared with the school's case, a larger number of different solutions are found, as the MCDM scanning delivers sixteen different BER designs (Figure 7-17)

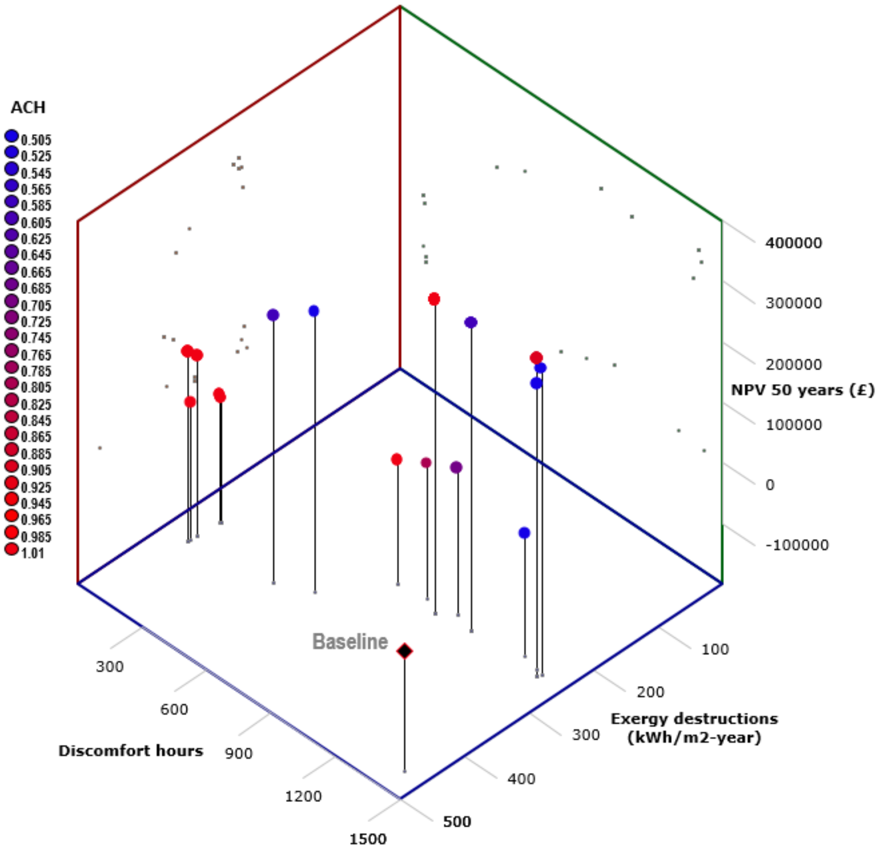


Figure 7-17 A/C Office optimal solutions found by Compromise Programming MCDM method

Figure 7-18 shows the compromise solutions for different weights for all pairs of objective functions' combinations. For the office case, the competitiveness of the objectives is similar to those found for the school. When moving from a $\boldsymbol{p}_{discomfort}$ = 0 to $\boldsymbol{p}_{discomfort}$ = 1, an increase in exergy destructions and a decrease in occupant thermal discomfort can be seen. By compromising a little more in exergy destructions, a big improvement in thermal comfort can be seen ($\boldsymbol{p}_{discomfort}$ = 0 .6). When comparing NPV and exergy destructions, a small compromise in exergy destructions can be made to obtain a large increase in NPV, as it can be noted for $\boldsymbol{p}_{NPV}$ = 0.1. After such compromise in exergy destructions, the graph illustrates that larger destructions will barely lead to a more profitable project. Finally, if comparing NPV and discomfort, by compromising the two objectives halfway (**p**=0.5), reasonable outputs can be obtained.

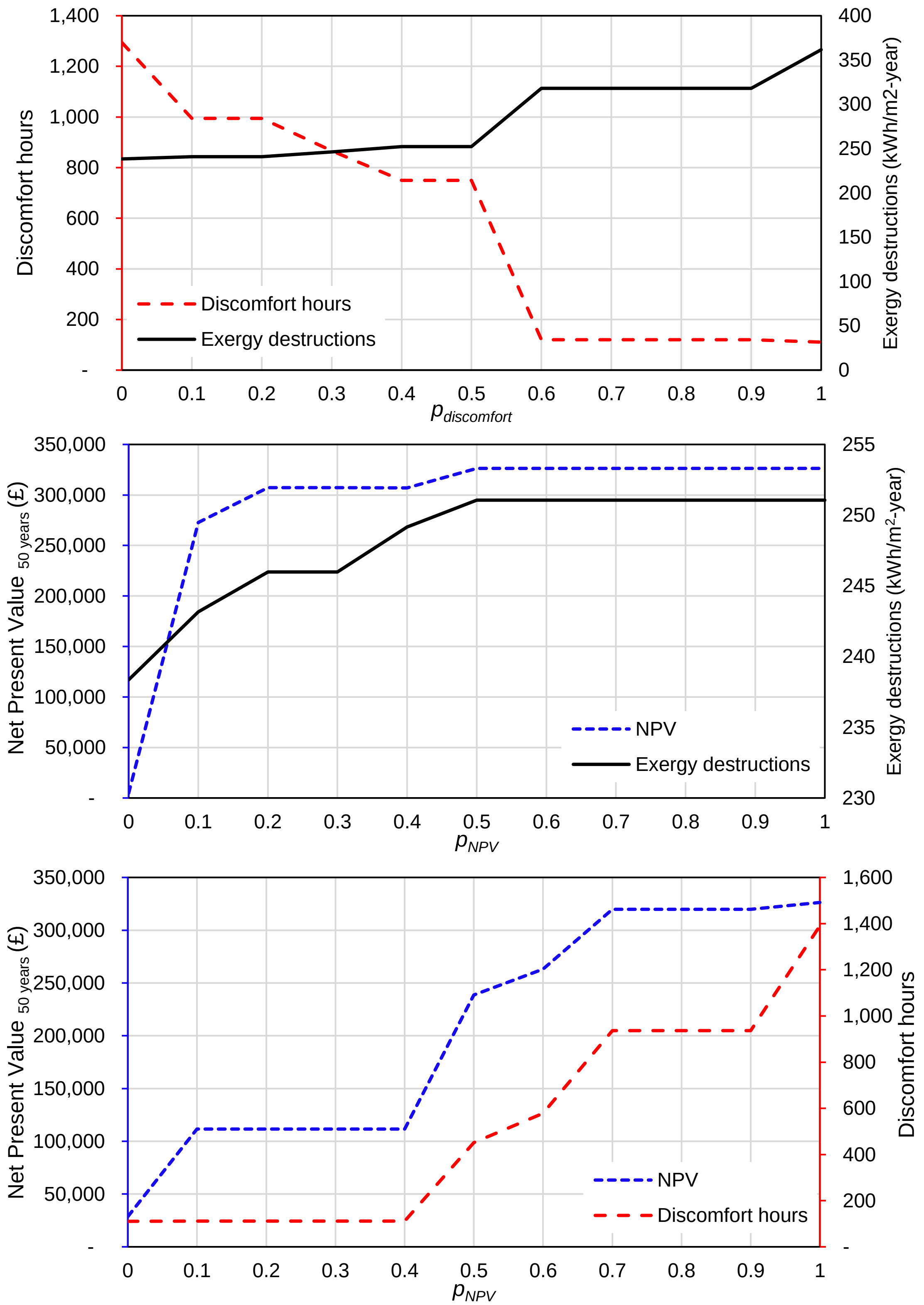


Figure 7-18 Changes in the A/C Office objective function values with respect to the weighting coefficient

As shown, the real benefit of multi-objective optimisation can only be realised with the application of multi-criteria methods, where sometimes, in order to achieve desired solutions, a compromise in one of the objectives is necessary. However, for the model comparison between a Pareto solution and the baseline case, a single solution is necessary. Therefore, in this study, the model closest to the utopia point will be considered. The utopia point is a theoretical model which contains the minimum value for each of the three objectives optimised individually. To find this particular model, a weight coefficient with similar values has to be considered. This means a weight of p_{exergy_dest} =0.33, $p_{discomfort}$ =0.33, and p_{NPV} =0.33.

For the primary school, the model close to the utopia consists of HVAC system H28: a 125 kW biomass-based condensing boiler connected to a wall heating system working with a heating set-point at 20 °C. The insulation for the wall is composed of Aerogel with a thickness of 0.015m, while the roof insulation is composed of 0.04m of phenolic board, and the ground of 0.12m of polyurethane. The infiltration rate keeps the baseline levels of 1.0 *ach*, while the glazing system is retrofitted with double-glazed, with a 6mm gap of Argon gas. For active systems, the lighting system is retrofitted to install T8 LEDs. Furthermore, the BER design does not consider any implementation of renewable electricity generation (PV or wind turbines). The BER solution information and objective outputs can be seen in Table 7-13 and a schematic diagram of the building energy system in Figure 7-19.

The A/C Office BER design, closest to the utopia point, is configured by H32: a 119 kW condensing gas boiler and an 11.5 kW water-based chiller connected to a CAV system plus a MVHR system. The design considers the heating and cooling set-points at 22 and 24 °C respectively. The envelope insulation technologies are composed of 0.10m of EPS and 0.11m of EPS for the wall and roof respectively, with no insulation in the ground floor. The model also does not consider any measures to improve air-tightness and the glazing system, leaving the building with the same baseline variables of 1.0 *ach* and single-glazing system respectively. However, it considers an improvement in the lighting system by installing T8 LED system and the installation of a 20kW wind turbine for the generation of in-site renewable electricity. The solution information and objective outputs can be seen in Table 7-14 and a schematic diagram of the building system in Figure 7-20.

A note on some practical limitations: At this stage of the modelling process it is important to highlight the practical limitations of the optimisation module. Given the model's complexity and interaction among different simulation tools, the whole framework may not capture all the issues of comfort, maintenance and actual building energy and economic performance. For example, single pane glazing can lead to higher discomfort levels due to asymmetric radiation and condensation. The latter also could lead to maintenance issues, which in turn leads to higher life cycle costs which are not accounted by the model. Other issue presented with high frequency in 'optimal solutions' is the high ventilation rates (>0.9 ach) which might result in drafts. Among active systems, wind turbines might not perform well in turbulent (urban) environments while structural limitations and orientations are major barriers for PV panels.

Table 7-13 Closest to 'utopia' solution discovered in the Primary school Pareto front

p_{ex}	p_{dis}	p_{NPV}	[min] α_{cheb}	$Ex_{dest,bui}$ (kWh/m^2-year)	*Discomfort* (hours)	$NPV_{50years}$ (£)	X^{HVAC} (Type)	X^{wall} (m)	X^{roof} (m)	X^{ground} (m)	X^{seal} (ach)	X^{glaz} (type)	X^{light} Light techn.	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)	X^{cool} (°C)
0.33	**0.33**	**0.33**	0.38	127.4	701	13,964	28	8.015 U$_{val}$: 0.57	7.04 U$_{val}$: 0.45	1.12 U$_{val}$: 0.18	1.0	3	3	0	0	20	---

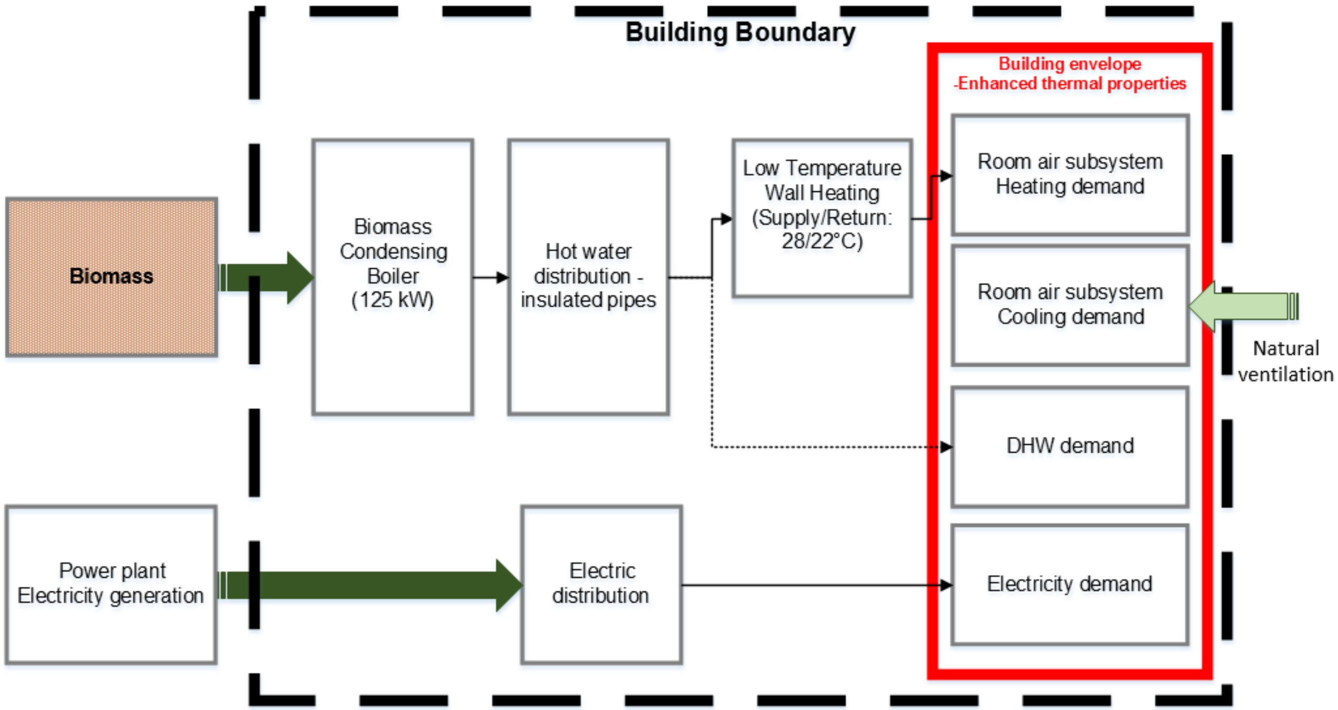


Figure 7-19 Schematic layout of the energy system for the Primary School 'close to Utopia' BER model

Table 7-14 Closest to 'utopia' solution discovered in the A/C Office Pareto front

p_{ex}	p_{dis}	p_{NPV}	[min] α_{cheb}	$Ex_{dest,bui}$ (kWh/m^2-year)	***Discomfort*** (hours)	$NPV_{50years}$ (£)	X^{HVAC} (Type)	X^{wall} (m)	X^{roof} (m)	X^{ground} (m)	X^{seal} (ach)	X^{glaz} (type)	X^{light} Light techn.	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)	X^{cool} (°C)
0.33	**0.33**	**0.33**	0.27	257.4	936	319,917	32	3.10 U_{val}: 0.29	3.11 U_{val}: 0.29	0 U_{val}: 0.54	1.0	0	3	0	20	22	24

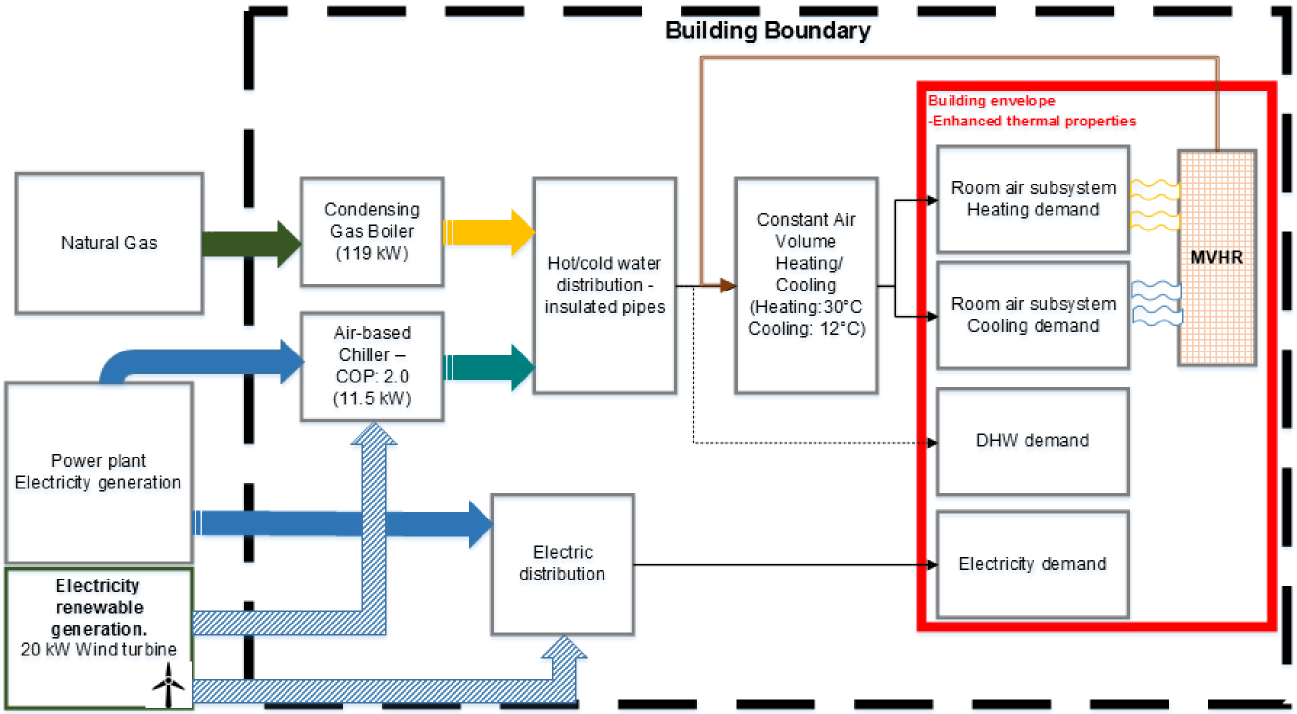


Figure 7-20 Schematic layout of the energy system for the A/C Office 'close to Utopia' BER model

7.4 Comparison between baseline, 'deep retrofit', and 'equal weight' optimisation designs

To investigate the strength of the whole optimisation framework and tool implementation, in this section a series of main outputs obtained from the 'closest to utopia' or 'equal weight' models will be compared to those from the baseline cases (section 6.2) and the scenario-by-scenario deep energy retrofit building models (section 6.4) presented in the previous chapter.

7.4.1 Primary School

For the school's case, from the baseline value of 187.9 kWh/m^2-year for energy use, the deep BER was able to reduce it to 46.3 kWh/m^2-year; while using the optimisation mode with set constraints, the utopian model reduces it to 118.1 kWh/m^2-year. The utopian model compromises on a greater energy use, as the optimisation process has a constraint to achieve a DPB of 50 years or less. For this reason, the utopian model presents a better cost feasibility as it achieves a DPB of 49 years compared to the 84 years of the deep BER. This was possible by reducing the retrofit capital cost from £734,968 to £329,856. However, the utopian model had to compromise on thermal comfort levels going from 490 uncomfortable hours obtained in the deep BER to 701 hours. Nevertheless, it is still a major improvement from the 1,443 hours from the base case. An indicator that the optimised design did not suffer much was the carbon emission reductions, as it was able to reduce the baseline values up to 72.8%, compared to 90.2% from the deep BER.

Notwithstanding, interesting outputs come from the exergy and exergoeconomic analyses. Figure 7-21 presents a comparison of the models' annual exergy demand and exergy destruction rates. As it can be noted in the demand side (in red), thanks to using exergy as one of the objective functions, it was possible to minimise exergy demand within the utopian BER strategy. However, as it can be seen in the right-hand side of the graph, exergy destructions or irreversibilities are still high (similar in both retrofit cases) especially for the HVAC system. This is because the utopian case delivered a less exergetically efficient design due to the investment constraints, unable to install any energy renewable measure or improvements in the building infiltration rates. In fact, utopian case presents the lowest building exergy efficiency among all cases with the value of 0.081, lower than the baseline (0.095) and the deep BER (0.125).

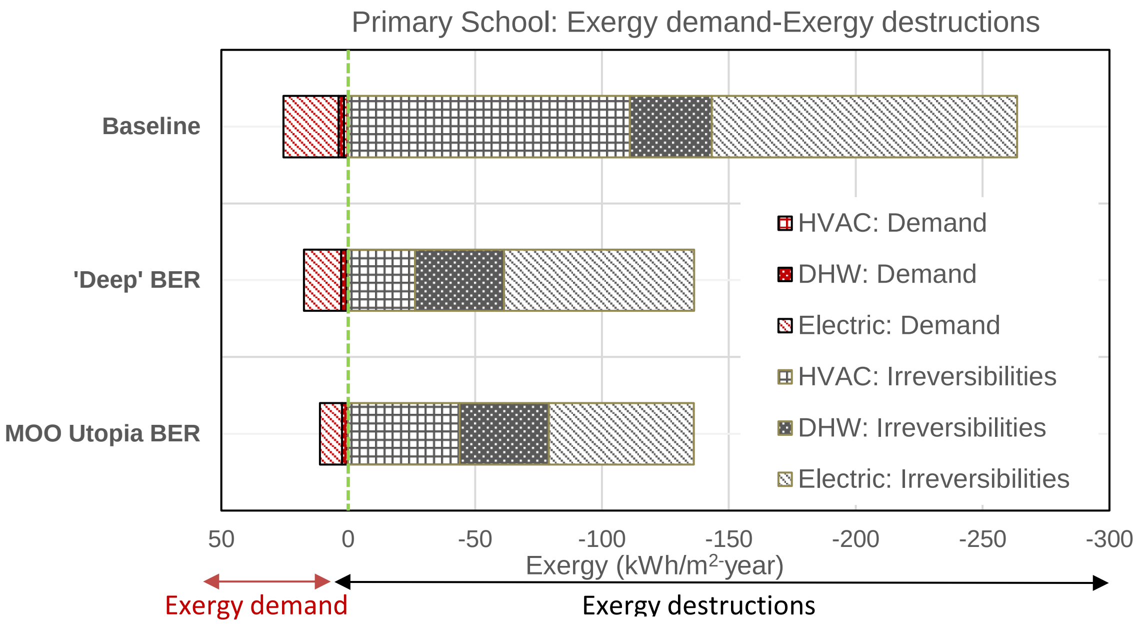


Figure 7-21 A comparison of exergy demand and exergy destructions for the Primary School baseline, deep BER, and Utopia BER cases

Exergoeconomic analysis, especially the heating product cost formation, delivers an interesting outcome. Figure 7-22 compares the cost formation for the three cases. For the utopian model, the results show a good economic behaviour before the energy stream arrives to the emission system. However, after the stream passes this level, the product cost suddenly increases. This could be due to two reasons: a) high investment cost for the wall heating panels and envelope insulation b) high destruction rates at the room-air subsystem.

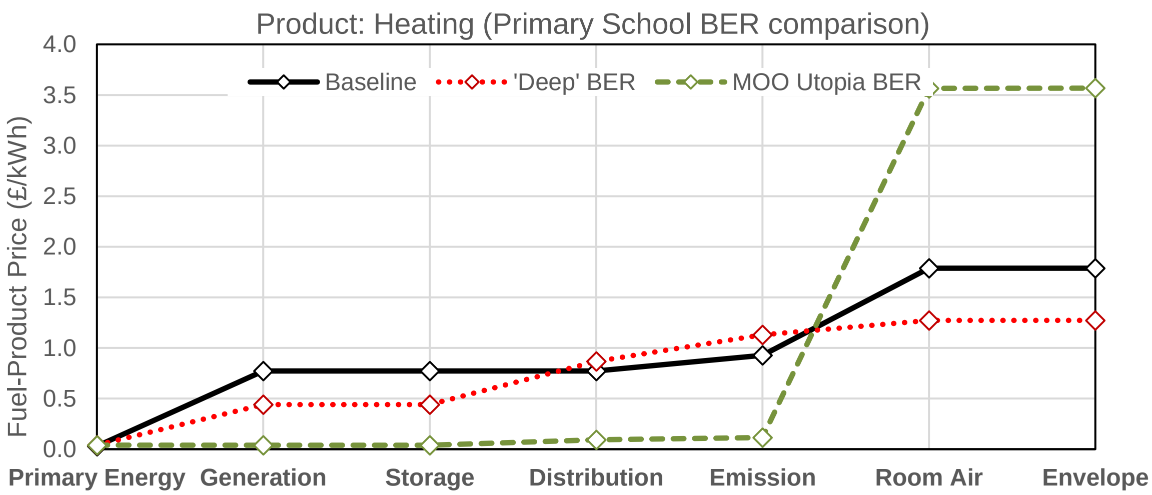


Figure 7-22 Cost formation comparison for heating of the Primary School baseline, deep BER, and Utopia BER cases

The effect of a higher heating product exergy cost rate at the last levels of the energy supply chain, combined with the high HVAC system irreversibilities, makes the utopian model suffer from higher destruction cost rates compared to the deep BER design. This is illustrated in

Figure 7-23, showing that total exergy destruction rates are £1.22/h for the deep BER and £1.38/h for the utopian model; however, both designs represent an improvement from the baseline case (£2.7/h). Moreover, BER capital cost rate - ***Z*** (in light red) and annual revenue rate - ***R*** (in light green) are illustrated for both projects. Here is where the economic difference can be seen between both BER projects. While the deep BER has a ***Z*** of £3.15/h and an ***R*** of £2.46/h, the utopian model has a ***Z*** of £1.41/h and an ***R*** of £1.47/h. The higher rates of the former are due to the higher capital cost investment in more efficient technology that eventually generates more annual income; however, even then it fails to provide a cost-effective solution. When analysing the $Exec_{CB}$ indicator with the aim to find the best possible exergoeconomic design, this results in values of £1.91/h and £1.31/h for the deep BER and utopian BER respectively, meaning that the latter provides better overall exergoeconomic performance.

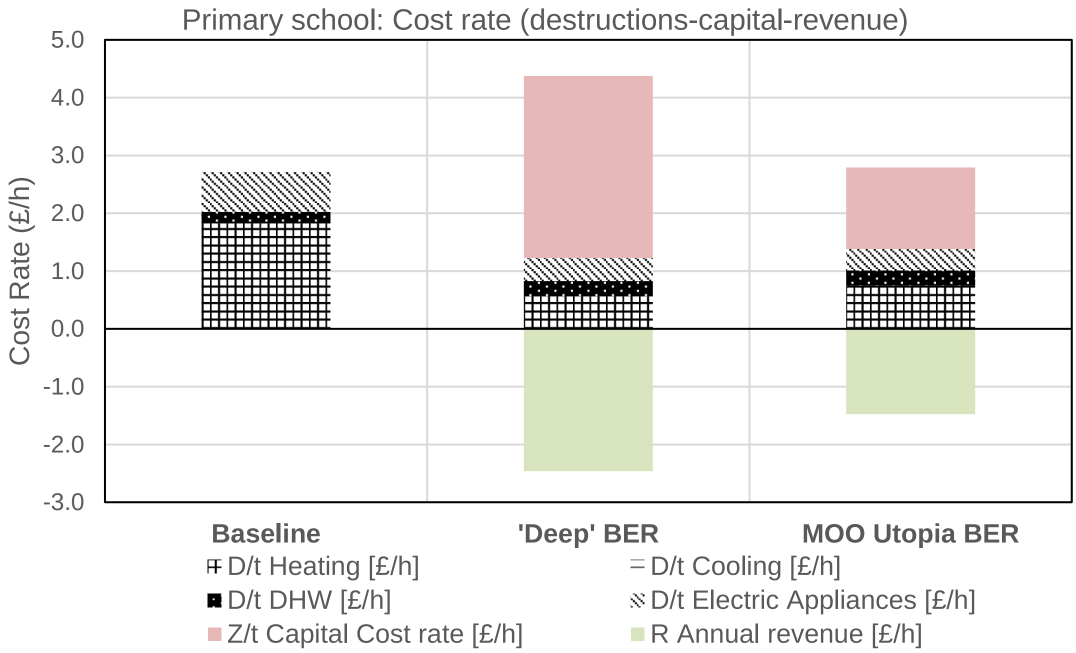


Figure 7-23 Primary school exergy destruction, BER capital cost and annual revenue cost rate

The school's utopian model may have suffered exergetically by the imposition of budget constraints in the MOO problem definition. However, ExRET-Opt tool, focusing on both exergy destructions and NPV values was able to find a trade-off between both objectives. Nevertheless, to achieve this result, a compromise in the occupant thermal comfort is observed. This shows that the model finds it difficult to deliver high exergetic efficient solutions with positive NPV values for the specific model of the Primary school presented in this study.

7.4.2 A/C Office

For the office case, from the baseline value of 288.5 kWh/m^2-year for energy use, the unconstrained deep BER was able to reduce it to 94.6 kWh/m^2-year. By using the optimisation tool and the set constraints, the utopian model obtained a value of 147.5 kWh/m^2-year. As in the case of the school, the lower EUIs found in the deep BER are mainly due to the installation of PV panels and wind turbines for the generation and in-site use of renewable electricity. However, the utopian model has a lower capital investment cost, with a reduction of deep BER capital cost from £980,401 to £341,054. With this investment, the project was able to deliver a positive NPV and a DPB of 17.6 years. In addition, the utopian model was able to provide a better occupant thermal comfort than the deep retrofit (936 vs 1,001 hours). Finally, the utopian model was able to achieve similar carbon emission reductions of 43.5%, while the deep retrofit did it by 53.1%.

When analysing the outputs exergetically and exergoeconomically, Figure 7-24 presents a comparison of the models' annual exergy demand and building's exergy destruction rates. In this case, the constrained exergy-based optimisation could not lower the exergy demand compared to the deep BER; however, a slight minimisation in total exergy destructions can be perceived. This result is significant considering that the investment of the utopian project compared to the deep BER is almost two thirds less. In this sense, even with the investment and thermal comfort constraints set in the optimisation problem, the utopian case delivered a better exergy efficiency performance by achieving a value of 0.221, compared to the 0.154 of the base case and the 0.204 of the deep BER. In addition, the utopian model presents the highest exergy destructions minimisation rate, reducing it by 44.7% compared to the 42.4% of the deep BER. The installation of the MVHR system is the main cause of this decrease by recycling low-grade energy into the space conditioning system.

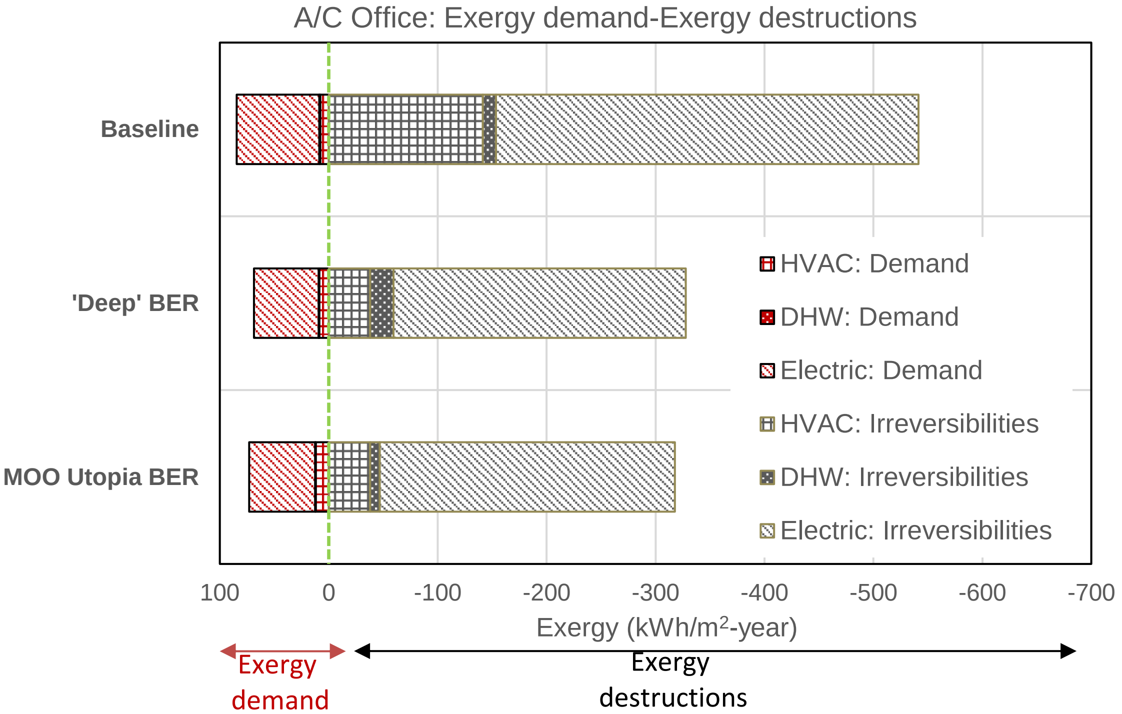


Figure 7-24 A comparison of exergy demand and exergy destructions for the A/C Office baseline, deep BER, and Utopia BER cases

The next two graphs (Figure 7-25 and Figure 7-26) illustrate and compare the cost formation for both heating and cooling products. Unlike the school's case, the utopian model shows a good exergoeconomic behaviour in both streams along the HVAC energy supply chain. Again, the utilisation of a MVHR at the room-air subsystem makes the product cost rate not to significantly increase anymore after the generation stage, delivering lower final product cost values, than those compared to the baseline and the deep BER cases.

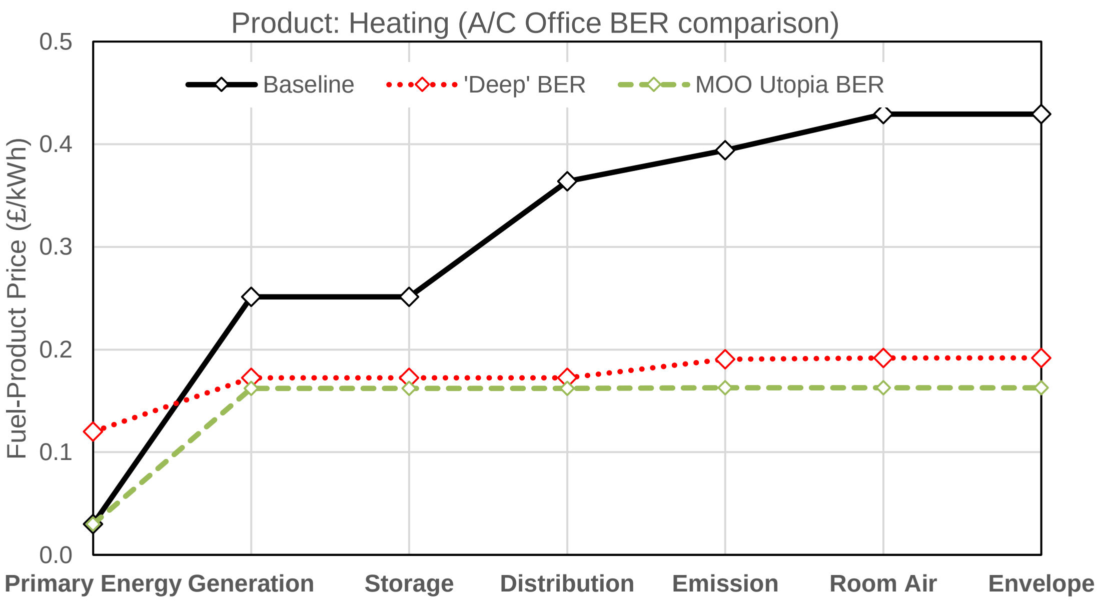


Figure 7-25 Cost formation comparison for heating of the A/C Office baseline, deep BER, and Utopia BER cases

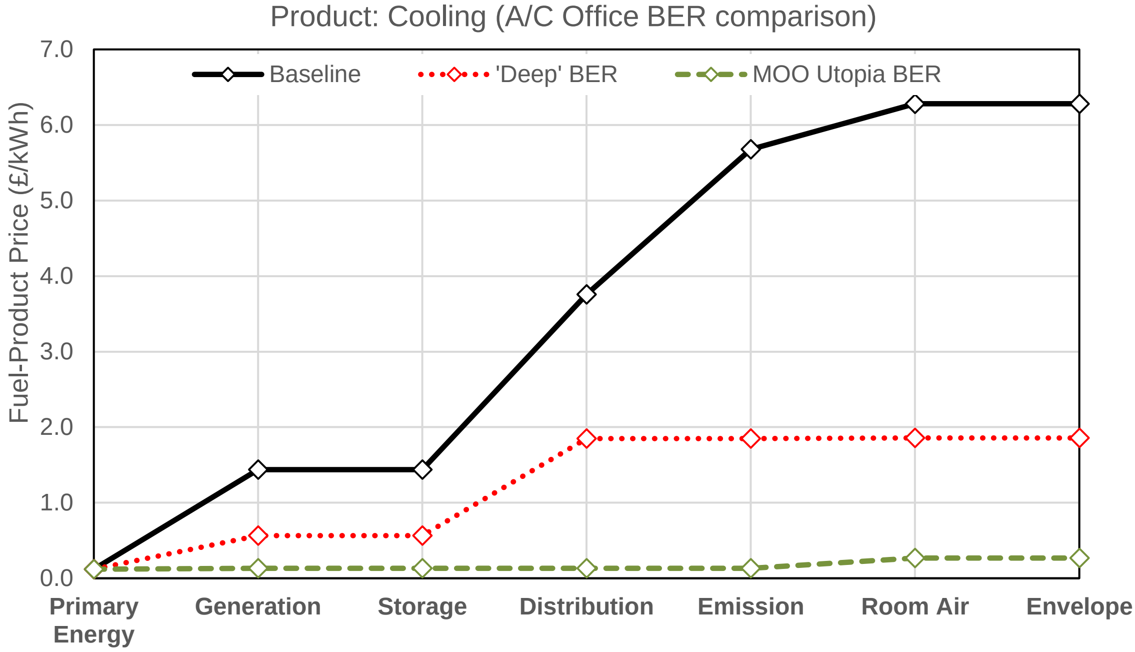


Figure 7-26 Cost formation comparison for cooling of the A/C Office baseline, deep BER, and Utopia BER cases

By having a lower exergetic product cost rate combined with higher system exergy efficiencies and lower exergy destruction rates, it is expected that building exergy destruction cost will be significantly minimised. Figure 7-27 illustrates this phenomenon as the utopian model destruction rates are £3.07/h, compared to £4.24/h for the deep BER and £6.25/h for the baseline case. The biggest reductions can be appreciated in the heating and cooling products thanks to the MVHR, and in the DHW product due to the installation of a more efficient boiler. However, as the utilisation of the MVHR system requires some electricity, the increase in destructions for this product is appreciated in the graph. Nevertheless, the installation of an in-site wind turbine helps reduce the electric-grid destructions, which naturally has a different exergy destruction footprint.

To add to the cost rates (capital cost ***Z*** and revenue ***R***), the deep BER has a ***Z*** of £4.20/h and an ***R*** of £4.01/h while the utopian model presents a much lower ***R*** of £2.88h but with a ***Z*** of just £1.46/h. These values produce an $Exec_{CB}$ indicator of £4.42/h and £1.65/h for the deep BER and the utopian BER respectively, meaning that the latter is a much better solution in thermodynamic terms. Although both presents better exergoeconomic performance compared to the base case ($Exec_{CB}$ = £6.25/h), the utopian BER model shows that better overall performance can be obtained with considerably less capital investment.

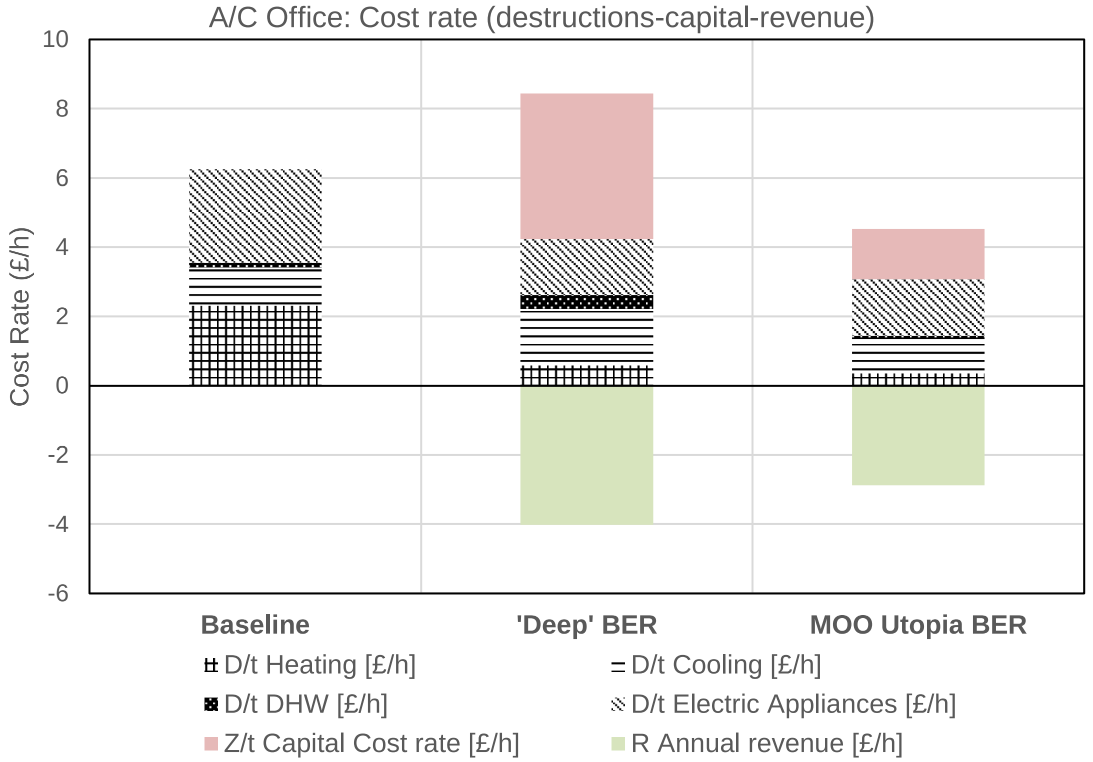


Figure 7-27 A/C Office exergy destruction, BER capital cost and annual revenue cost rate

Unlike in the school's case, the MOO formulation for the specific case of the analysed A/C Office brings better energy, economic, exergy, and exergoeconomic performance, where the multi-objective optimisation model tried to optimise the building energetically and exergetically without compromising the occupants' thermal comfort.

7.5 Discussion of findings

Real world engineering problems, as in the case of BER design, typically involve the optimisation of multiple objectives, where the trade-offs between conflicting criteria have to be considered. In addition, with the intention to have a more robust and comprehensive analysis, building energy systems should be analysed by thermodynamic and economic criteria simultaneously. The main focus of this chapter was to propose the means by which exergy analysis can be integrated into a multi-objective optimisation (MOO) retrofit-oriented problem to strengthen the typical analysis, applied to the comparison and selection of the most optimal building energy retrofit projects. This was achieved by demonstrating the capabilities of the optimisation module within ExRET-Opt by performing a hybrid-thermodynamic MOO problem, considering net present value (First Law), exergy destructions (Second Law), and occupant thermal comfort (non-thermodynamic) as objective functions.

7.5.1 Optimisation of building irreversibilities and economic performance by applying exergy-based MOO-MCDM procedures

Considering the baseline models and deep energy retrofit models developed in Chapter 6, a series of economic and thermodynamic constrains were applied with the intention to push the tool in obtaining major improvements (close to optimal) with regards to the size of the search space. If these constraints were not applied, the designer could expect solutions dominated by measures such as triple-glazing, high envelope insulation thickness, high exergy systems (condensing and electric boilers), while having an air-tight envelope. However, while some low-exergy systems require the highest capital investments, the constraining of an investment budget leads the model missing out on district heating/cooling systems and ground source heat pumps. Nevertheless, the model sought a compromise between the exergy efficiency and economic profitability, while also improving occupant thermal conditions, where the model was able to identify a large space of Pareto solutions for both case studies. For this reason, the Pareto solutions were dominated by typical HVAC systems but connected to low temperature emission systems (wall and underfloor) or supported by a MVHR system, while also finding a trade-off among the heating and cooling set-points, insulation thickness, lighting and glazing systems, and the use of in-site renewable generation.

The results show that even with the imposed constraints, the NSGA-II-based MOO module was successfully applied, finding a large range of better performance BER designs for the two particular analysed cases, compared with their corresponding baseline cases and the manually developed deep retrofit design. The biomass boiler system was a popular choice for the model because of the relatively low cost equipment combined with the support of government incentives via the RHI, due to the generation of renewable heat using biomass as an energy source. However, as seen in the school results, since the biomass is considered to be a high-exergy source, the obtained thermodynamic efficiency was lower than the baseline case (Ψ >0.10). The result shows the necessity to support low-exergy technologies to become more economically feasible, while they have been demonstrated to provide the best thermodynamic performance, carbon emission reduction and internal thermal comfort; however, current market prices make low-exergy systems difficult to implement. This is demonstrated in the office case, where an affordable low exergy technology such as MVHR can dominate the solutions and provide better overall performance if the right conditions are in place (e.g. year-round occupancy, high low-grade energy recovery rates, heating and cooling modes). In addition, the support through incentives that promote not only the reduction of the carbon footprint but also the exergy destructions footprint is necessary.

Considering the central tendency values of the Pareto fronts, the optimal solutions for the school's case were able to reduce the energy use by 46.2%, exergy destructions by 38.6%, and carbon emissions by 53.7%. For the office case, these were in the range of 46.5%, 38.9%, and 40.2% for energy, exergy destructions and carbon emissions respectively. In addition, the approach led to better thermal comfort conditions for the occupants by improving internal conditions by 7.1% and 47.3% for the school and office respectively. Although the single deep BER design developed in the last chapter obtained better outputs, the main difference is that all the Pareto solutions presented positive NPV values under the set time frame of 50 years. Nevertheless, central tendency values of a Pareto front are useless in a practical design as a single BER design has to be provided for implementation.

7.5.2 The importance of multi-criteria decision making tools

The strengths of MOO cannot be demonstrated without the inclusion of a decision support tool (MCDM method). This is fundamental, as in practice a single final solution has to be chosen for implementation. For this reason, a MCDM submodule, based on compromise programming and Tchebyshev distance was necessary in order to locate a single solution, given that the preferences of the decision maker, was implemented. This implementation reduced the space of possible final solutions to nine and sixteen, for the school and office respectively. The difference in the number of optimal models between the case studies shows the impact of similar constraint on different type of buildings. For further analysis of single solutions and comparison with the previous models, the closest to the utopian solution was chosen. This solution represents the model closest to the optimal objectives, if these were optimised separately (Section 7.2.1).

The school's BER close-to-utopian solution was based on a 125 kW biomass boiler connected to underfloor heating, while the office utopian BER solution was based on a 119 kW condensing gas boiler and an 11.5 kW water-based chiller connected to a CAV system plus a

MVHR system. Both models presented medium levels of insulation, double glazing systems and high infiltration rates.

The school's utopian model may have suffered exergetically and exergoeconomically by the imposition of budget constraints in the MOO problem definition. However, ExRET-Opt focusing on both exergy destructions and NPV values was able to find a trade-off between both objectives. These final solutions improved overall building's exergy efficiency and exergy cost formation of building products, resulting in lower exergy destruction cost rates. After analysing the capital investment and revenue rates, the exergoeconomic cost-benefit indicator was also improved for both case studies. Generally, both utopian models presented better performance in all indicators under a reduced capital cost investment, achieving payback periods of 49 and 18 years for the school and office respectively. Therefore, it can be said that within the studied parameters and resources, the performance improvement when using an exergy-based multi-objective optimisation procedure, compared to scenario-by-scenario approach, was successful. After analysing the capital investment and revenue rates, the exergoeconomic cost-benefit indicator developed in this research for the comparison of BER, was considerably improved for both case studies.

7.5.3 Model limitations of using MOO-MCDM methods

Still, limitations of using MOO and MCDM exist. The main one is the computational effort required to obtain reliable and comprehensive outputs. Although the computational time was still high for both experiments (around a week's time), this can be easily improved by using higher performance computers or a cluster of connected cores working simultaneously. This would lead to an extensive research, analysing the genetic algorithm settings (population, crossover, mutation, generations) with the objective to locate the ideal settings for these particular type of problems. However, as shown in the comparison section, within the studied parameters and resources, the performance improvement from a scenario-by-scenario approach to optimisation was successful.

Additionally, practical limitations of the optimisation tool were highlighted in this chapter. Due to the model complexity and software inter-operability within ExRET-Opt, the framework may not capture the actual building physics performance, which affect the outputs regarding the occupant's thermal comfort and the building's energy and economic life cycle performance. These uncertainties could be overcome by developing specific modules; however, this level of detail could affect model's complexity and computation time.

The proposed methodological framework can provide more information than the typical optimisation methods based solely on energy analysis. The application of exergy analysis to building optimisation completes a powerful and robust methodology that should be pursued in everyday BER practice. Outputs demonstrate that by using exergy and NPV as objective functions, it is possible to improve energy and exergy performance, reduce carbon and exergy destructions footprint, while also providing comfortable conditions under cost-effective solutions. This gives practitioners and decision makers more flexibility in the design process. However, as thermoeconomics/exergoeconomics is a valuable tool for optimisation of energy systems under the First and Second Law parameters, the next chapter will present a full exergy-exergoeconomic evaluation, demonstrating its strength and limitations against the typical full energy-economic optimisation (First Law only).

Chapter 8 Benefits of an exergoeconomic-based optimisation for BER design: Evaluation of a ‘Passivhaus’ retrofit building

This chapter presents the application of ExRET-Opt in a real, recently-retrofitted non-domestic building. The selected case study, the Mayville (Mildmay) Community Centre located in the London Borough of Islington, underwent a deep BER in 2011, becoming the first ‘non-domestic Passivhaus’ retrofit in the country. The fact that the building was retrofitted according to Passivhaus standards, which is based solely on First Law analysis, has been intriguing for a further thermodynamic investigation. Therefore, the aim of this chapter is twofold. Firstly, an exergy and exergoeconomic analysis is applied for the first time to a Passivhaus non-domestic building, obtaining new performance indicators for the pre-retrofit and post-retrofit building. These results would give an insight into the thermodynamic impact of the Passivhaus approach, providing a critical assessment of the strengths and limitations of the standard. Secondly, the multi-objective optimisation framework for BER design is applied to the case study. In this case, the MOO study is designed from two different perspectives: a) an energy/economic-based focus and b) an exergy/exergoeconomic-based focus; having the occupants’ thermal comfort as the only common objective in both approaches. The aim is to illustrate through a detailed analysis the differences between the methodologies and results. Although it is expected that both approaches will provide a more informed assessment of BER designs than the actual retrofit design, it is also expected that each approach will deliver different BER designs and outputs due to the differences in calculation methods. The outputs from the exergy/exergoeconomics-based MOO approach should critically expose the strengths and limitations of the Passivhaus Standard, demonstrating how the First Law is only a necessary calculation while the utilisation of the First and Second Law becomes a sufficient condition for the analysis. It is sought that the lessons learned and conclusions from this study may be useful for future retrofit standards across the UK.

8.1 Case Study: The Mayville Community Centre

Located in London, Islington and built in 1890s, the building was used as an electric generation power station for London’s tram network. In 1973, the building was rescued from dereliction by the Mildmay Community Partnership (MCP) and turned into a community centre. The first part of this study focuses on analysing the pre-retrofit building as well as the post-retrofit building, aligned with Passivhaus requirements; thus, energy models have been developed for both cases. More information of the Passivhaus approach and its similarities and differences with the LowEx approach can be found in Appendix F. All actual data for the pre-retrofit and post-retrofit building illustrated in the next sections was kindly provided by the architecture firm through the 'Building Performance Evaluation' report (BERE, 2015).

8.1.1 a) Pre-retrofit building model description

The three-storey building, which is oriented due north-south, had uninsulated 600 mm-thick solid brick walls supported by a concrete frame in the main hall. The pitched roof was covered by leaky asbestos and the windows were made of single pane with metal frame. As a result, the building had an envelope with poor thermal quality, causing cold draughts and uncontrolled heat losses during the winter. In developing the energy model, for simplification the building was divided into six thermal zones, according to the orientation, activity type and the spaces' internal loads. These zones are specified as follows: a) basement floor offices, b) above ground offices, c) music studio, d) main hall, e) reception, and f) kitchen area. The model's geometry (Figure 8-1) was created according to the technical drawings provided in Appendix G.1.

Figure 8-1 Pre-retrofit Mayville building (top: real pre-retrofit building, bottom left: south-west view, bottom right: south-west view (blue areas = above ground level, yellow areas = ground contact)

Regarding the building services, space heating was provided by means of conventional gas boiler and high temperature radiators (80°C/60°C) with no heat recovery. DHW was also covered by the same gas boiler. As there was no artificial cooling system, the building was considered to be ventilated naturally during summer months. A schematic layout of the building system and subsystems is illustrated in Figure 8-2.

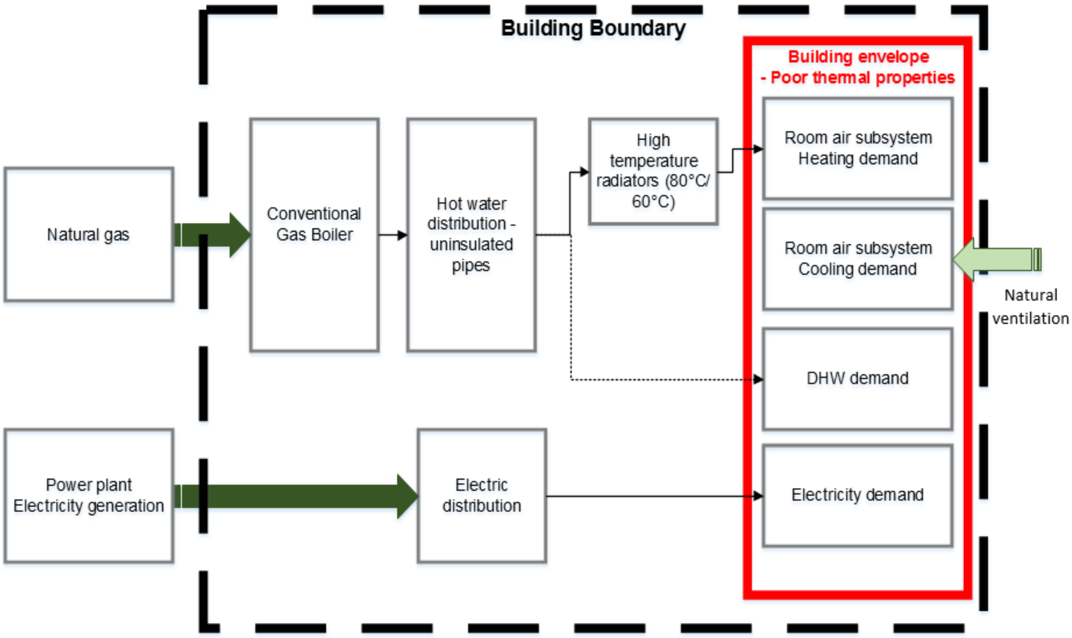


Figure 8-2 Schematic layout of the energy system for the pre-retrofit Mayville Community Centre

According to the report, the combination of the low quality building envelope with a low efficient heating system resulted in energy bills of the total amount of £10,055/year.

8.1.2 b) Post-retrofit building model description

In 2006, Bere Architects[****] committed to retrofit and extend the building in order to improve occupants' thermal comfort and building's energy efficiency. The initial plan was to only change the old boiler for a new biomass condensing boiler; however, the design team then decided to implement a Passivhaus Standard design. This approach suggests to focus first on improving the building's fabric to reduce energy demand before any decision on the building's service is made.

The final BER design resulted in the installation of high levels of insulation. The basement ground floor was insulated with 0.20m of XPS resulting in a U_{value} of 0.17 W/m^2-K , the basement walls with .075m of phenolic foam (U_{value}: 0.16 W/m^2-K) , the above-ground walls with 0.30m of EPS (U_{value}: 0.16 W/m^2-K), the ground-floor ground with 0.30m of Foamglass floorboard (U_{value}: 0.11 W/m^2-K), the main roof was replaced with a zinc-based pitched roof with 0.40m of Rockwool insulation (U_{value}: 0.14 W/m^2-K), while the rest of the roof with 0.30m of glass fibre (U_{value}: 0.13 W/m^2-K).

[****] 54a Newington Green, London N16 9PX, United Kingdom (www.bere.co.uk)

With respect to the glazing system, wooden-framed super clear triple-glazed air filled windows to maximise solar gains during the winter were installed. The carried out airtightness test presented a value of 0.42 ach. Furthermore, an extra 35% of usable area was created (approximately extra 150 m^2) by enlarging the reception block and by making the basement a habitable space, and a well providing a south elevation light. Similar to the pre-retrofit building, the building's energy model was divided into the same six thermal zones. The model's geometry (Figure 8-3) was created according to the technical drawings provided in Appendix G.2.

Figure 8-3 Post-retrofit building model (top: real building after retrofit, bottom left: south-west view, bottom right: south-west view (blue areas = above ground level, yellow areas = ground contact)

With respect to the building's services, to cover the heating demand, an 8.4 kW GSHP with an horizontal ground heat exchanger (PE32 x 2.9 x 4 loop indirect circulation system) at a depth of 1.0m was installed connected to medium temperature radiators designed for a 45 °C flow. In addition, a ventilation system with a 90% efficient MVHR system sized to deliver 8.3 litres/s of fresh air per person for the office areas (5.6 litres/s for other areas) was installed. This provides steady rates of fresh air throughout the most of the building during occupied hours, while it also reclaims exhausted heat from the cross flow heat exchanger when needed. However, depending on the season, different ventilation strategies are required. While in summer, the building operates in a mixed-mode, combining natural ventilation with mechanical extraction (also considering night ventilation), during winter, only mechanical ventilation strategy is used supplying and extracting adequate ventilation rates. For the lighting system, T5 LFC and compact LFC were implemented along the building. In addition, the design also considered the installation of renewable technologies. To cover the demand of DHW, a 3 kW solar thermal system connected to a 300 litres water storage tank was installed. Moreover, the installation of 116 m^2 of grid connected PV panels (18 kWp) to supply/export renewable electricity was also implemented. Data shows that PV panels generated 14,435 kWh/year, of which 11,143 kWh/year were used by the building. A schematic layout of the building system and subsystems is illustrated in Figure 8-4.

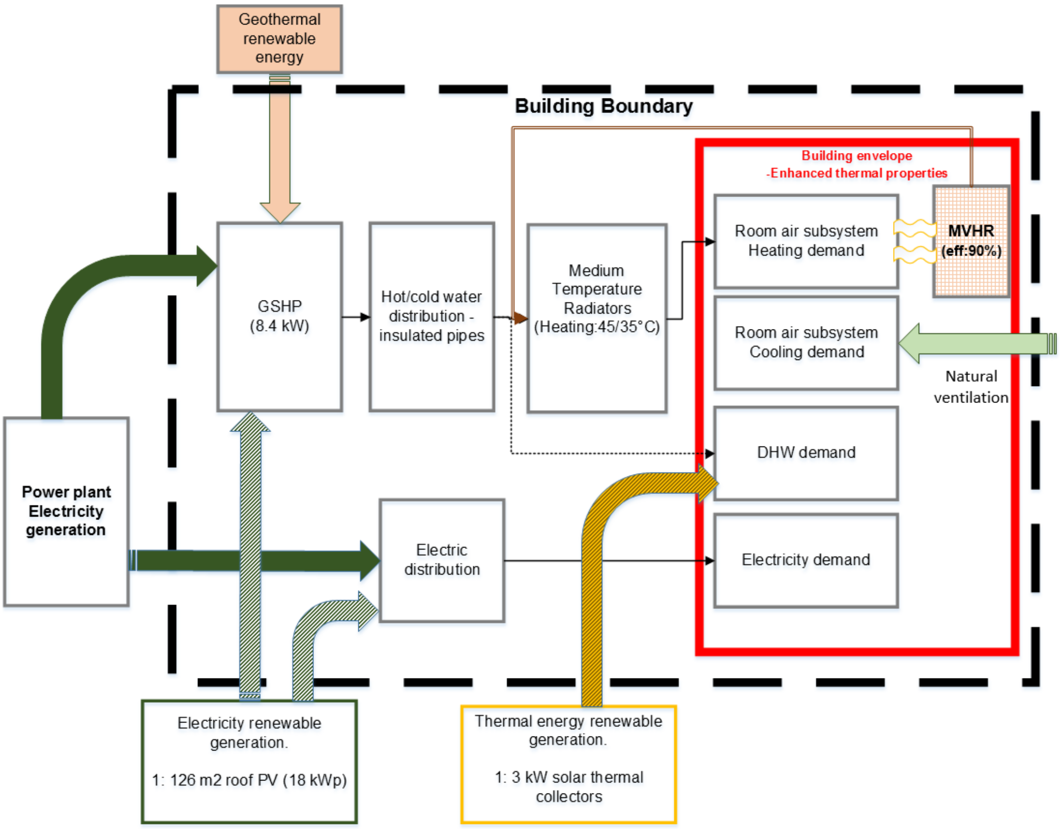


Figure 8-4 Schematic layout of the energy system for the post-retrofit Mayville Community Centre

As mentioned, the building achieved Passivhaus certification (EnerPHit) thanks to high levels of insulation, superior glazing system, a thermal bridge-free design, an airtight construction, and the use of mechanical ventilation system with heat recovery. According to the electricity use actual data, energy bills were around £4,593/year, representing a reduction of 54.3%. Although not reported, if government incentives were considered (FiT and RHI), an extra income potential of £997/year could be expected for this specific design.

8.2 Models' simulation and calibration

8.2.1 Calibration results

As shown in Chapter 5, the next step of the BER framework is the application of calibration module in order to minimise the performance gap between the measured and modelled data.

However, unlike Chapter 6, having real energy use data causes the calibration process to be different. As shown is Section 5.2.2, as monthly data exist for the pre and post retrofit building, the model has to be calibrated in accordance to the ASHRAE 14-2012 Standard. For the selection of the building's model with the better compliance, the mean bias error (MBE) and the coefficient of variation of the root mean squared error CV (RMSE) have to be used. The final model should have an MBE≤5% and a CV (RMSE)≤15% relative to monthly calibration data.

8.2.1.1 Pre-retrofit building calibration

The calibration analysis for the pre-retrofit building was focused on the total annual gas and electricity use. The predicted energy use was then compared to the actual monthly energy consumption data for 2010. Using ExRET-Opt Module 2 (SimLab 2.2 and parametric simulation), the following MBE and CVRMSE coefficients for the selected model were obtained (Table 8-1):

Table 8-1 MBE and CV (RMSE) coefficients for the pre-retrofit Mayville model

Pre-retrofit building	Actual building annual energy use (kWh)	Modelled building annual energy use (kWh)	MBE	CV(RMSE)
Electricity	28,980	30,292	-4.53%	+8.74%
Gas	189,167	181,994	+3.79%	+9.64%

The MBE and CV (RMSE) between the actual and simulated data are within the respective limits of acceptance, therefore the energy model can be considered as a reasonable accurate representation of real conditions. The detailed monthly analysis for each coefficient can be found in Appendix G.1.

8.2.1.2 Post-retrofit building calibration

As the post-retrofit building is fully electrically operated, the calibration analysis was based on the building's annual electricity use (49,120 kWh/year). However, for the post-retrofit building a more comprehensive calibration was performed, as sub-metered data by end-use was available. Therefore, by using the Latin hypercube sampling method in ExRET-Opt Module 2, three hundred cases were simulated for the calibration procedure. The majority of the parameters selected to be varied and simulated were lighting and electrical equipment power density, as these were not available in the report; therefore, some assumptions within comprehensive ranges were made. Figure 8-5 gives a cumulative frequency distribution for all the simulated sample as well as the selected model.

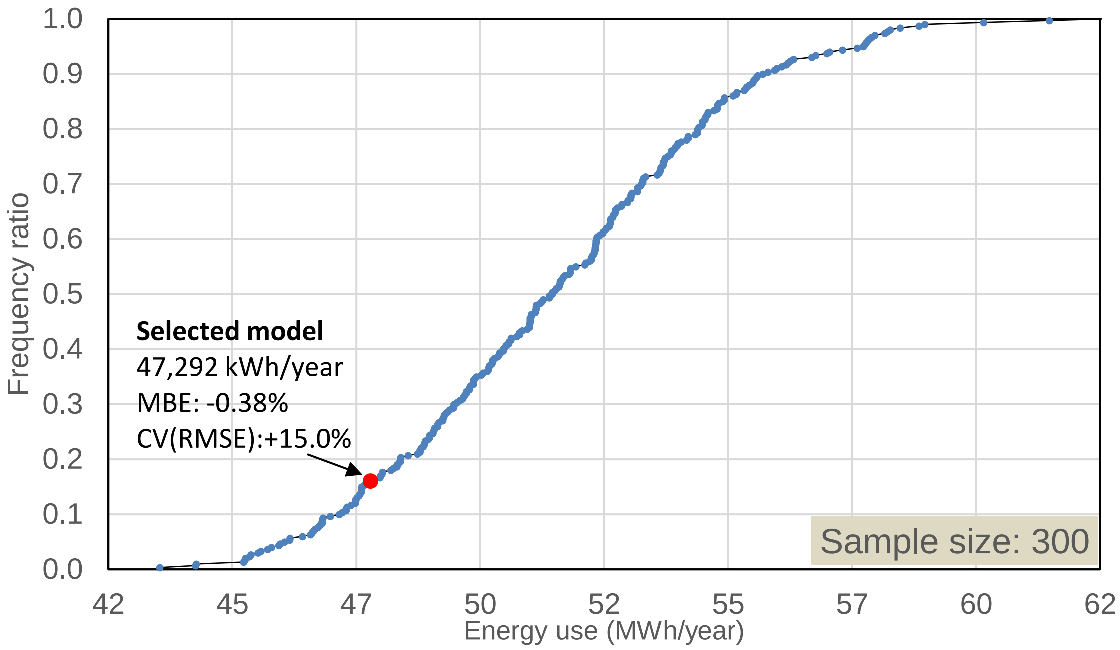


Figure 8-5 Cumulative frequency distribution of the electrical end use for the simulated model using LHS

The red point, which represents the final model, was selected, as it presents the lowest MBE and CV (RMSE) between the actual and the simulated post retrofitted building (Table 8-2).

Table 8-2 MBE and CV (RMSE) coefficients for the post-retrofit Mayville model

Post-retrofit building	Actual building annual energy use (kWh)	Modelled building annual energy use (kWh)	MBE	CV(RMSE)
Electricity	49,120	47,292	-0.38%	15.00%
Gas	--	--	--	--

Overall, the total monthly electricity use between the real and modelled data are very similar (Figure 8-6); however, the calibration process found it difficult to represent the real data during March, September, and October. This could be due to unusual behaviour in the actual building (e.g. high set-points, over use of kitchen equipment or lighting, etc.).

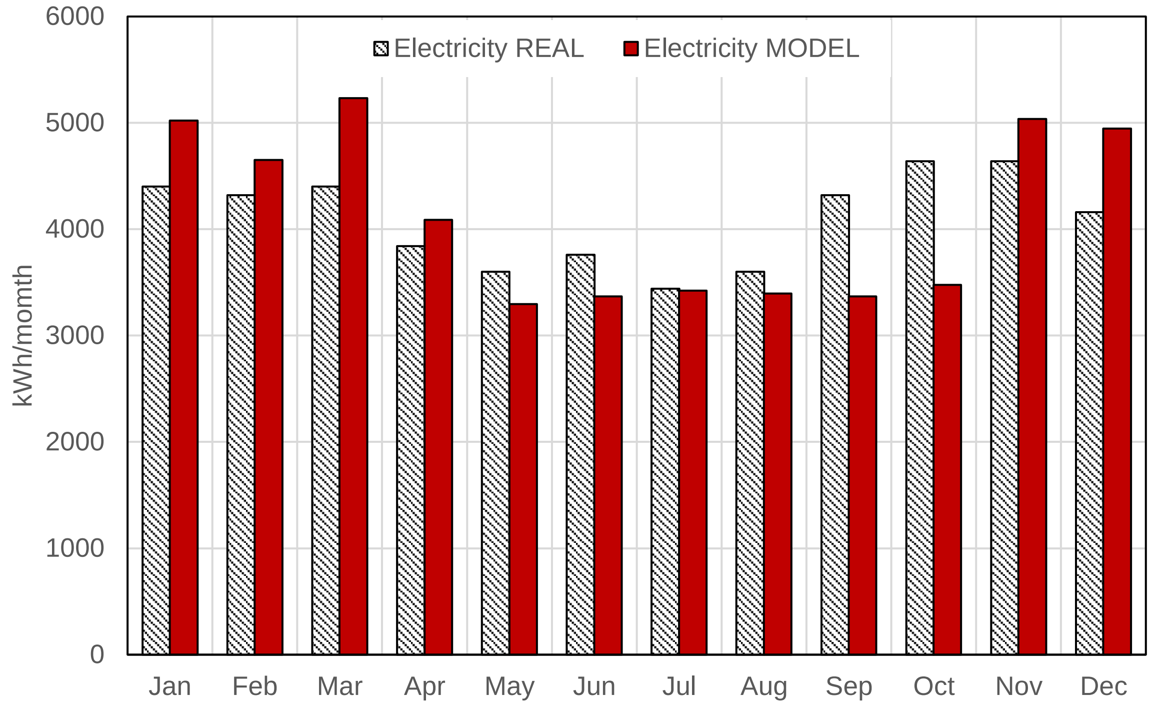


Figure 8-6 Comparison of monthly measured and monthly modelled electricity

Also, by analysing the PV electricity generation, the selected model gives a production of 14,709 kWh/year, just 3.9% more than the real production of 14,160 kWh/year. However, the model calculates an in-site utilisation of 13,527 kWh/year, a larger value than the measured of 10,846 kWh/year. The detailed monthly analysis for each coefficient can be found in Appendix G.2.

Although the MBE and CV (RMSE) between actual and simulated data are within the respective limits of acceptance, the latter presents a value that is on the limit (15.0%). The reason the calibration is more complicated is because the model tried to achieve similar end-uses to those found in the real building. To illustrate this, Figure 8-7 shows an end-use comparison between the data obtained from the building's TM22 report and the energy end-use obtained by the selected model. As shown, the pattern by end-use is similar, having the largest differences at space heating and catering. However, having the MBE and CV (RMSE) coefficients within acceptable range gives the study confidence that the energy model is a good representation of the actual building.

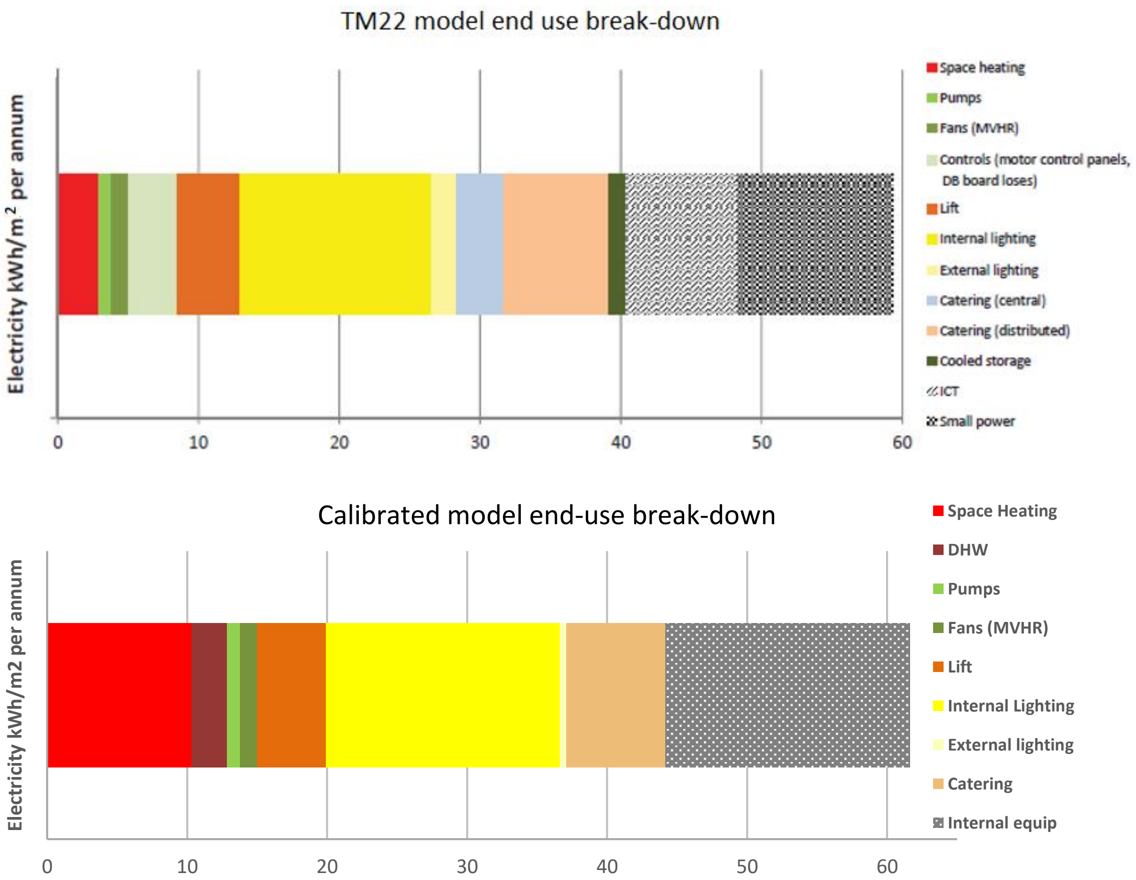


Figure 8-7 Comparison of Measured end use break-down with the selected model

8.2.2 Energy and economic analysis

After having both calibrated cases, a detailed energy and economic analysis has been performed. When comparing both cases, results show big differences in energy values. While the pre-retrofit building requires 30,289 kWh/year of electricity and 181,994 kWh/year of gas (total energy demand: 212,283 kWh/year or 353.8 kWh/m^2-year), the post-retrofit fully-electric building was able to lower the total energy demand to just 47,293 kWh/year (61.6 kWh/m^2-year) of electricity, representing a net reduction of energy use of 77.7%. A breakdown and a comparison of monthly energy use for both cases can be seen in Figure 8-8. It can be seen how during the winter period months the electricity use increased thanks to the GSHP and the MVHR system. On the other hand, when artificial space conditioning is not required during the summer, the monthly electricity demand is reduced thanks to the utilisation of more efficient lighting and interior equipment.

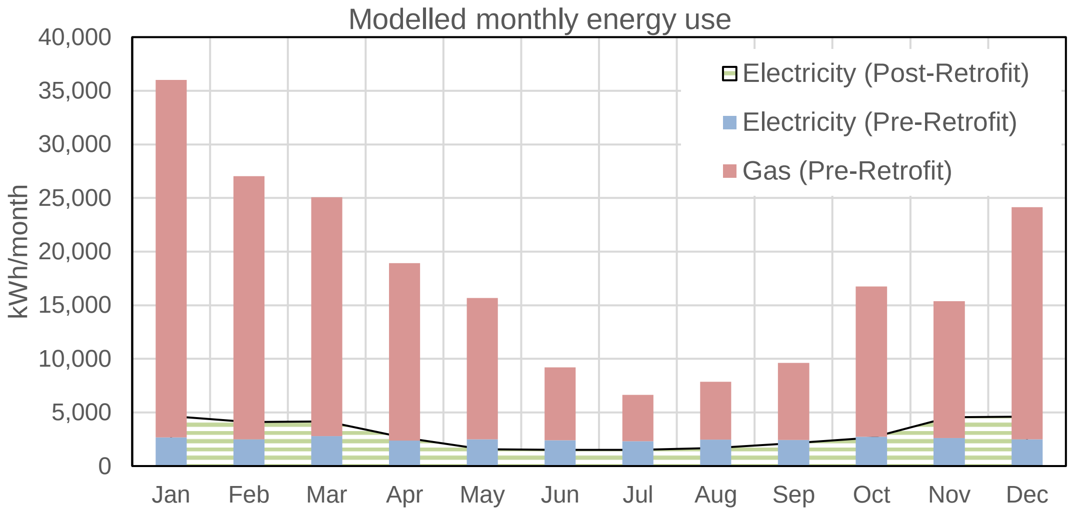


Figure 8-8 Monthly energy use breakdown of modelled pre-retrofit and post-retrofit building

As the post-retrofit design has become a fully-electric building, the annual energy bill savings are not as high as the energy savings due to the higher price of electricity. In this case, the model shows a reduction from £10,026/year (electricity: £3,656/year, gas: £6,370/year) to £4,379/year. However, the model also calculates a potential annual income thanks to the RHI and FiT schemes (government incentives). From the RHI scheme, due to the generation of 'low carbon heat' from the GSHP and the solar collectors, an income of £737.3/year and £251/year respectively is expected. From FiT, an income of £666.3/year is expected from PV generation plus £57.3/year for exported renewable electricity to the grid. Joining energy bill savings and incentives, the post-retrofit building presents a total annual revenue of £7,415.4 (a net decrease of 74.0% from the pre-retrofit energy bill). An energy bill breakdown comparison between cases is illustrated in Figure 8-9.

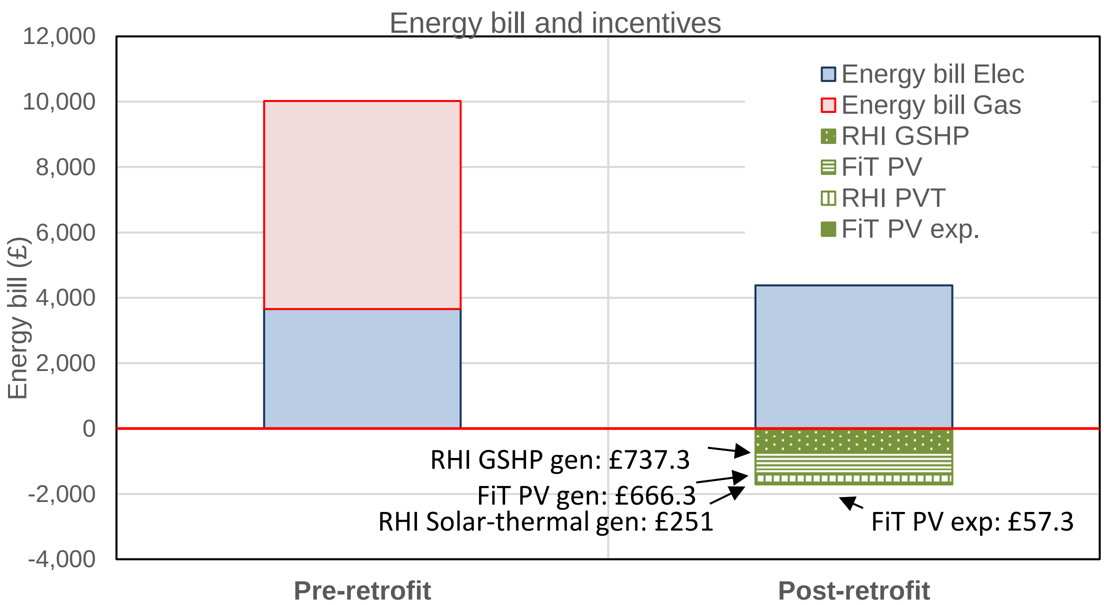


Figure 8-9 Annual energy bill comparison between pre-retrofit and post-retrofit building

The design team has reported a project's total investment in the amount of £1.6 million. Is important to mention that the economic evaluation that would be presented in this section, would not consider the revenue generated from the extra usable space created in the basement (~150 m^2). In this sense, considering a price of £7,964/m^2 [††††] for the Borough of Islington, an extra income of £1,194,600 could be integrated into the economic analysis. If this is the case, then the analysis should be conducted considering the total investment of £1.6 million. However, as the report lacks detailed capital investment data, the analysis would be limited to just energy-related measures neglecting the added value for the property. The capabilities of ExRET-Opt has allowed to estimate the total capital investment for the BER design as well as the investment separated by the type of technology. The model has calculated an investment of £417,028 exclusively for energy related measures. This result is interesting as the difference between the total capital investment (-£1.6 million) and building added value (+£1.2 million) is similar, providing a justification to make the analysis based only on energy-related measures. However, the calculated investment has to be taken with care as large uncertainties may exist between real prices and the modelled prices

The ratio of passive and active technology investment is calculated at 0.41, where almost £169,080 were invested for passive measures (insulation, glazing, sealing). However, as a single measure, PV/T panels represents almost 37% of the total investment, followed by glazing (17.5%) and roof insulation (10.4%). Figure 8-10 illustrates the capital investment for each measure type for the Passivhaus BER design.

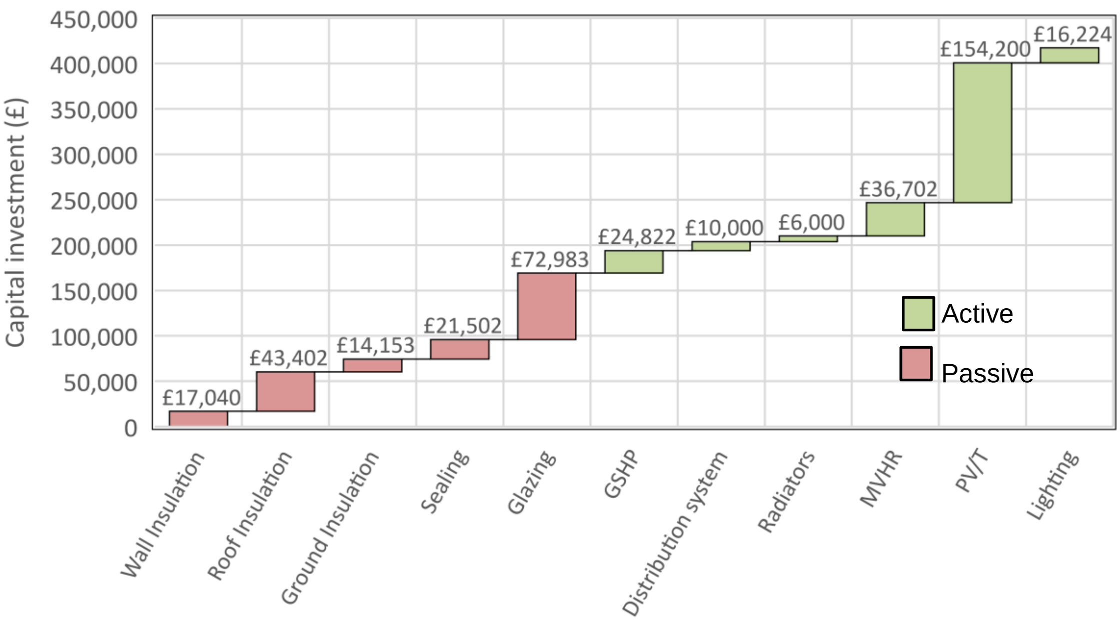


Figure 8-10 BER design capital investment per technology calculated by ExRET-Opt

†††† Price taken from the following article: Butterworth, M. **So what's the REAL price of property in the UK?** www.dailymail.co.uk**.** Accessed on the 19-Feb-2017. The original source is Halifax.

The life cycle cost analysis (50 years) has led to a value of £471,403, resulting in an NPV of negative £213,436 which corresponds to a DPB of 137.2 years. However, to demonstrate the worst-case scenario where government incentives are not accounted for, the LCC value increases to £513,974, worsening the NPV to -£256,007 and resulting in a DPB of 145.7 years. In either case this demonstrates that the project's annual revenues are not sufficient to deliver a cost-effective BER design..

8.2.2.1 Thermal occupant comfort and carbon emissions

Using the tool's occupant thermal model based on the ASHARE-55 guideline, the non-comfortable hours are found at 1,199 and 853 hours per year for the pre and post-retrofit building respectively, representing an improvement of 28.8%. As the Passivhaus requires to have active people, especially in the summer, to control natural ventilation within the building, the outputs could be quite deceiving and have to be taken with care because of ExRET-Opt inability to model in great detail occupants' behaviour.

To calculate carbon emissions, a disaggregation by fuel type has to be considered as each energy source has embedded different emission factors (Table 5-5). With this in mind, the total emissions in the pre-retrofit building represents 108.8 tCO_2, while for the post-retrofit building this was reduced to 38.6 tCO_2, a decrease by 64.5%.

8.2.3 Exergy and exergoeconomic analysis

8.2.3.1 Primary exergy indicators

To the author's knowledge it is the first time that an exergy and exergoeconomic analysis is applied to a Passivhaus building, with the aim to show the standard's actual thermodynamic efficiency. First, an analysis of the pre-retrofit case is necessary to ultimately calculate the overall thermodynamic improvement. Results show that the pre-retrofit building requires a total primary exergy input of 1,056.6 GJ/year. By product type, heating requires the largest share of 48.9%, followed by electric equipment (42.3%) and DHW (8.7%). For the post-retrofit building the primary exergy input is found at 460.5 GJ/year, meaning that the Passivhaus approach reduced exergy input by 56.4%. However, the end-use ratio is switched, having the largest demand for electric-based equipment (83.1%), followed by heating (12.8%), and DHW (4.1%). A comparison by building and a disaggregation by end-use can be seen in Figure 8-11.

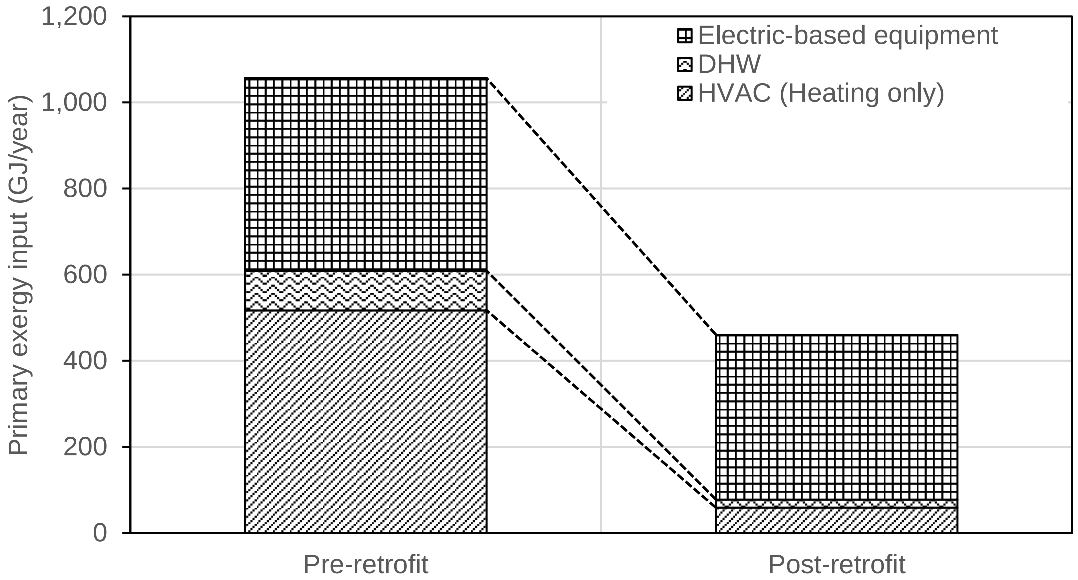


Figure 8-11 A comparison of primary exergy input by end-use for the pre and post-retrofit building

Figure 8-12 illustrates the heating exergy flow throughout the energy supply chain for both building's energy system configurations. As seen, an important reduction is observed in the primary exergy input. While the gas-based boiler system required an annual intake of 517.3 GJ/year, the GSHP, combined with the MVHR system, requires just 60.0 GJ/year. As seen at the last part of the supply chain, the thermal exergy demand was also reduced, from a pre-retrofit value of 19.0 GJ/year to 6.1 GJ/year, demonstrating the impact of the Passivhaus envelope's thermal characteristics.

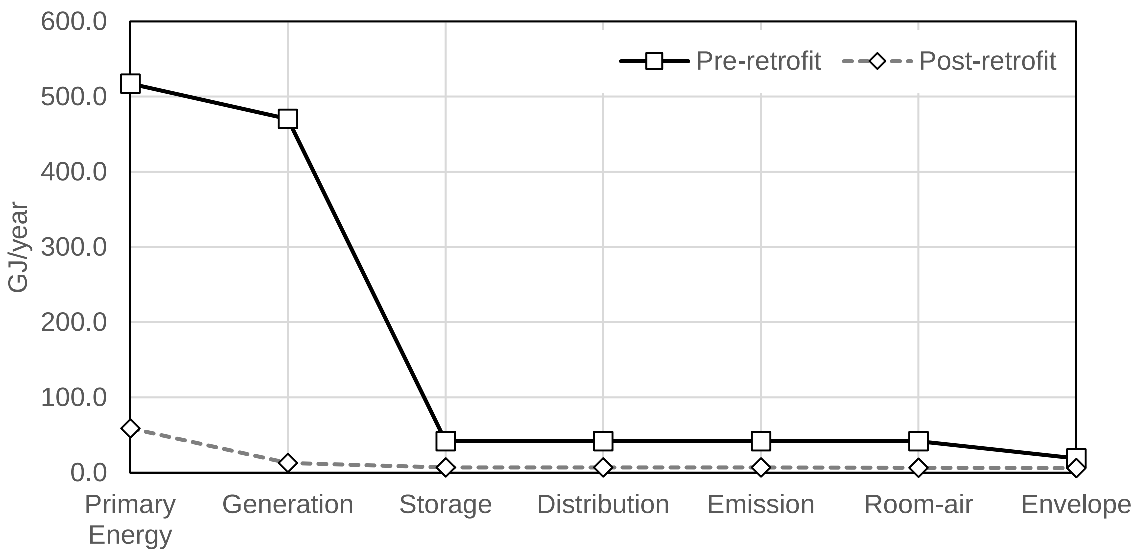


Figure 8-12 Exergy use comparison for heating demand throughout the building energy supply chain

8.2.3.1 Exergy efficiency and exergy destructions breakdown by sub-systems

By analysing the whole building's energy system, a comparison of exergy destructions between the subsystems and the type of buildings can be considered. These results would help determine end-use thermodynamic efficiencies as well as the overall building's exergy efficiency. The total exergy demand considering HVAC, DHW, and electric-based equipment for the pre-retrofit building is found at 103.7 GJ/year with global annual exergy destructions of 952.9 GJ/year, resulting in a total building exergy efficiency (ψ_{bui}) of 0.098. On the other hand, the post-retrofit building has a total exergy demand of 82.8 GJ/year and exergy destructions of 377.7 GJ/year, resulting in an exergy efficiency of 0.180. In a detailed analysis, irreversibilities are found in different ratios for both cases. Figure 8-13 illustrates the differences between the building types, showing the share of destructions per component.

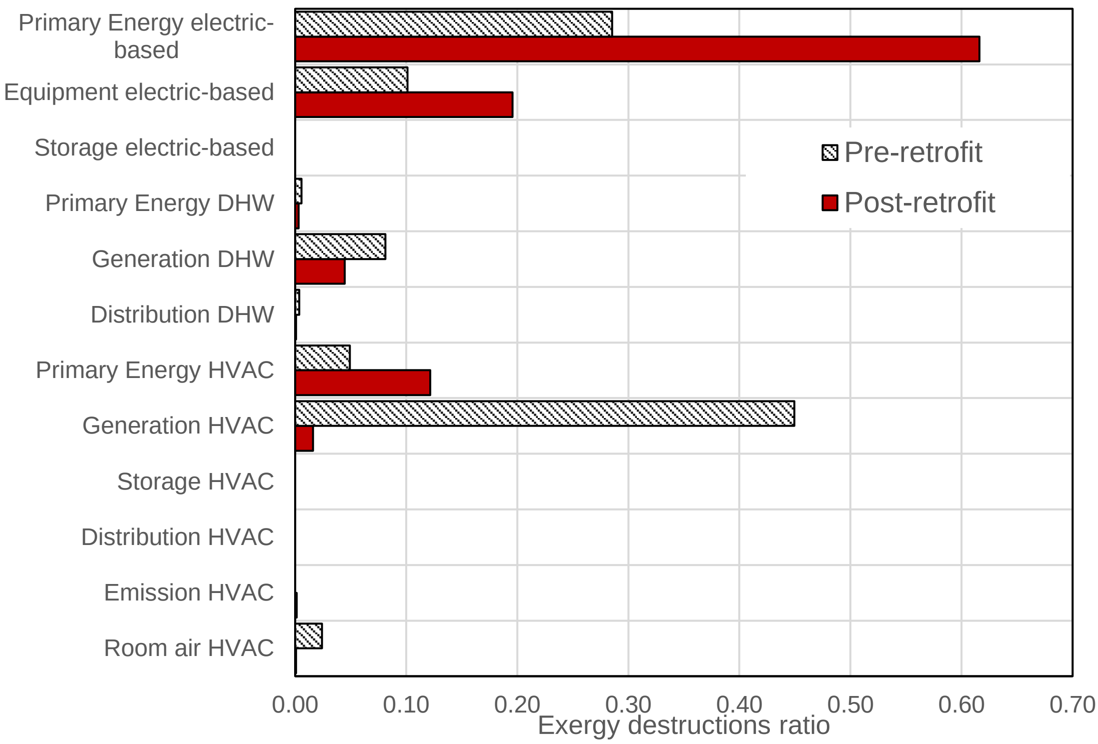


Figure 8-13 Exergy destruction ratio of all energy subsystems for pre and post retrofit building

For the pre-retrofit building, the largest share of irreversibilities occurs in the generation subsystem, where natural gas is burned to heat water at around 80 °C. The retrofit design, thanks to the installation of the GSHP, switch the largest share of irreversibilities to the primary energy generation subsystem, as electricity is required for electric-based appliances in the buildings. In fact, the second largest destructions are found at the appliances itself, as it mainly depends on the equipment's energy efficiency. An analysis of thermodynamic efficiencies (Ψ) by end-use found that for the pre-retrofit building, the HVAC system had an efficiency of 0.037, the DHW of 0.062, and electric-based appliances of 0.177. The post retrofit building improved efficiencies at the HVAC system (Ψ =0.104) and electric appliances (Ψ =0.199), but with a decrease in DHW efficiency (Ψ =0.025). This design, at least from an exergy perspective, can also be considered as a ‘Low-Exergy” design, however exergoeconomic indicators remain to be seen.

8.2.3.2 Exergoeconomic indicators

Figure 8-14 shows the heating product cost formation throughout the energy supply chain for both designs. Without considering any capital investment impact in the pre-retrofit building, the product increases from £0.03/kWh (gas price) to £0.74/kWh, with a total relative cost difference r_k of 23.74. For the post-retrofit building, where exergoeconomics accounts for capital investment at subcomponent level, the initial value starts at 0.12/kWh (electricity price) and finishes at £0.25/kWh, having a r_k of 1.14. These outputs demonstrate that at least for the HVAC system, the Passivhaus design presented good thermoeconomic outcomes, where despite the capital investment, required for the GSHP and the MVHR, important reductions in exergy cost and product price throughout the energy supply chain are obtained.

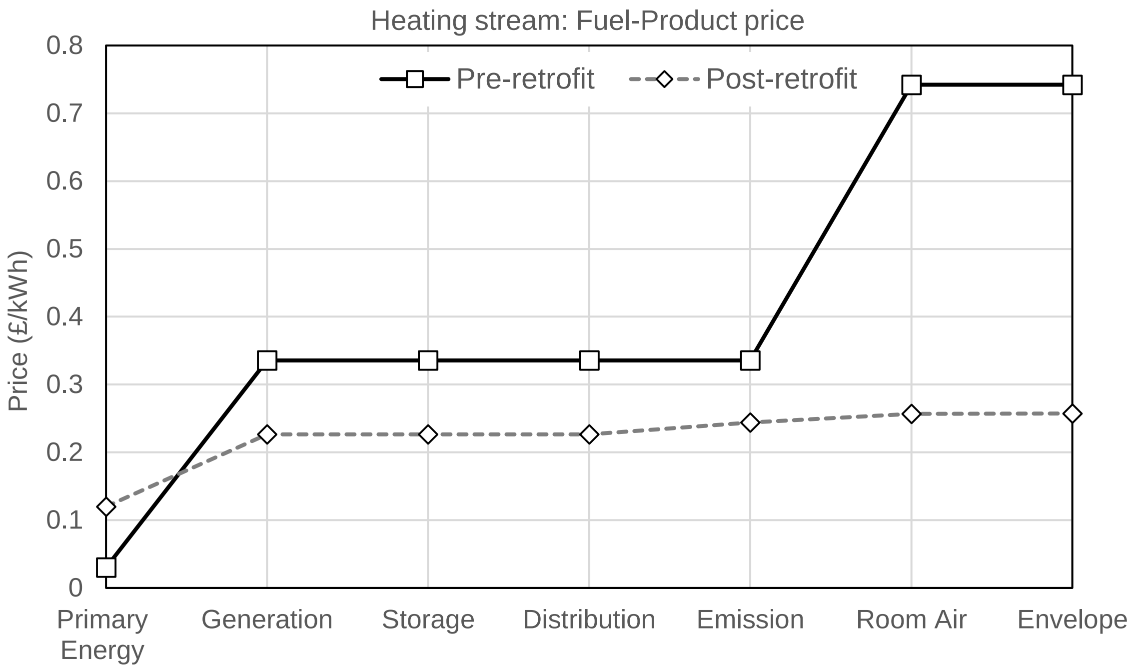


Figure 8-14 Heating stream product cost formation for the pre-retrofit and post-retrofit

The product cost formation for the other end-uses are presented in Table 8-3. The table also presents an overview of all analysed exergy and exergoeconomic indicators obtained for both buildings. As shown, the total exergy destruction cost rate ($\dot{C}_{D,sys}$) for the pre-retrofit building is found at £1.54/h, while the Passivhaus retrofit is able to minimise it to £0.38/h. However, the building presents a high capital cost rate ($\dot{Z}_{sys}$) of £1.78/h with a lower revenue rate ($\boldsymbol{R}$) of £0.84/h. This disparity represents the cost-inefficiency of the project mentioned in the last section. By analysing the exergoeconomic cost-benefit indicator ($Exec_{CB}$) it gives a value of £1.33/h, slightly lower than the baseline case ($\boldsymbol{Exec_{CB,baseline}} = \dot{\boldsymbol{C}}_{\boldsymbol{D,sys}}$) of £1.54/h. This demonstrates that the high capital investment required to achieve Passivhaus standards penalise the project economically. In addition, if government incentives are not considered, the post-retrofit $Exec_{CB}$ increases to £1.52/h.

Table 8-3 A comparison of pre and post-retrofit building exergoeconomic values

Baseline characteristics	Pre-retrofit	Post-retrofit
Exergy input (fuel) (GJ)	1,057	461
Exergy demand (product) (GJ)	104	83
Exergy destructions (GJ)	953	378
Exergy efficiency HVAC	0.037	0.104
Exergy efficiency DHW	0.062	0.025
Exergy efficiency Electric equip.	0.177	0.199
Exergy efficiency Building	0.098	0.180
Exergy cost fuel-prod HEAT (£/kWh) {r_k}	0.03—0.74 {23.74}	0.12—0.25 {1.14}
Exergy cost fuel-prod COLD (£/kWh) {r_k}	----- {---}	----- {---}
Exergy cost fuel-prod DHW (£/kWh) {r_k}	0.03—0.44 {13.66}	0.12—1.90 {14.82}
Exergy cost fuel-prod Elec (£/kWh) {r_k}	0.12—0.27 {1.22}	0.12—0.24 {0.97}
D (£/h) Exergy destructions cost {energy bill £; %D from energy bill}	1.54 {9,577.6; 95.5%}	0.38 {2,947.3; 68.2 %}
Z (£/h) Capital cost	--	1.78
R (£/h) Revenue	--	0.84
Exergoeconomic factor f_k (-)	--	0.82
Exergoeconomic cost-benefit (£/h)	**1.54**	**1.33**

A comparison of the different cost rates for the formation of the exergoeconomic cost-benefit indicator ($\boldsymbol{Exec_{CB}}$) is illustrated in Figure 8-15. The graph clearly illustrates how the project is hampered by the high capital cost and low annual revenues, even though the Passivhaus approach significantly reduces exergy destruction costs. If government incentives are not regarded, this specific project presents similar $\boldsymbol{Exec_{CB}}$ to the pre-retrofit case.

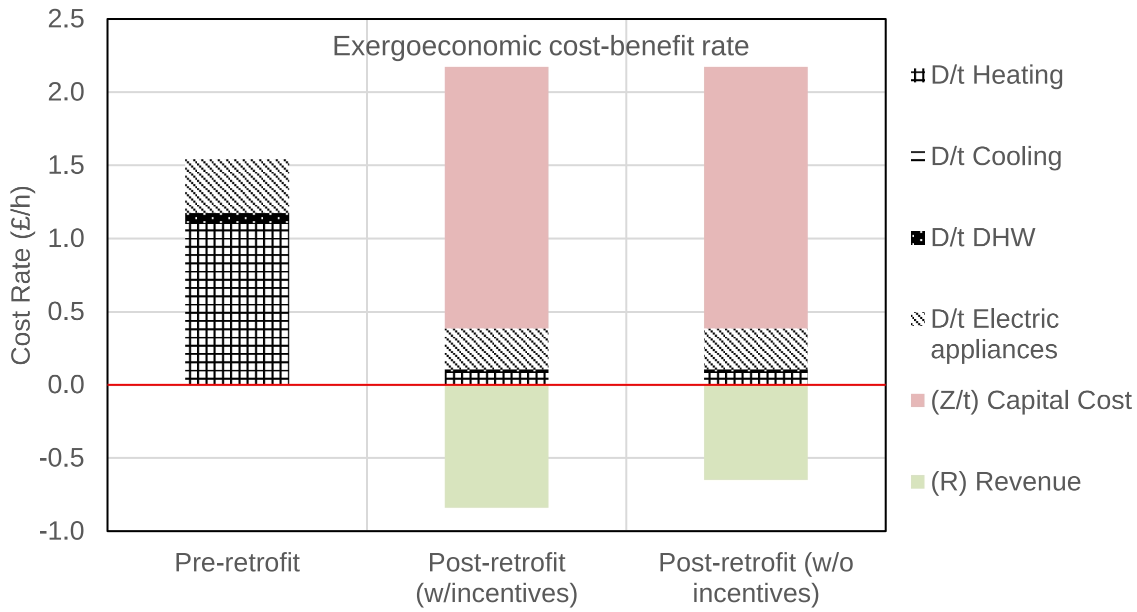


Figure 8-15 A comparison of the exergoeconomic cost-benefit rate breakdown comparison between pre and post retrofit building

8.2.4 The impacts of Passivhaus standards on thermodynamic indicators

Some initial discussion can be drawn from this first analysis of the pre-retrofit and post-retrofit Mayville community centre. As already reported by the architecture firm, First Law outputs show high levels of energy savings (75.6%), reductions in carbon emissions (64.5%), and an improvement of occupant thermal comfort (28.8%). However, the economic analysis demonstrated a design that requires large sums of capital investments yielding a payback of more than 137 years. The main reason is that this specific building presented low energy costs before it was retrofitted, leaving little potential to produce enough revenue to cover the high investment that was made. Nevertheless, other non-energy benefits should be considered such as the improvement of indoor air quality, thermal comfort and building aesthetics.

In this same context, the Passivhaus design proved to deliver good thermodynamic indicators. Second Law outputs presented a primary exergy input reduction of 56.4%, a value even lower than the primary energy reduction. Although just managing to reduce primary exergy demand from 103.7 GJ/year to 82.8 GJ/year, switching the majority of the demand from space heating to electric-based equipment, the Passivhaus design significantly reduces overall exergy destructions from 952.9 GJ/year to 377.7 GJ/year. Overall the building exergy efficiency improved from 0.098 (which can be considered as a typical benchmark for non-domestic buildings) to 0.180. The utilisation of a GSHP-based system combined with MVHR can categorise the retrofit design as a LowEx building. Nevertheless, exergoeconomically the building did not perform as expected. As the exergoeconomic analysis shows, high capital cost, especially needed for measures such as the installation of thick insulation and the 118 m^2 of PV panels, have hurt the design significantly. Although more investigation is required for similar case studies, these outputs suggest that although Passivhaus retrofits provide good energy and exergy performance, the approach is neither economically nor exergoeconomically-attractive solution. In this sense, the Passivhaus approach may well be a tempting individual solution, but it is not a systemic solution that would effectively improve the building thermodynamic sector performance.

8.3 MOO-MCDM simulation study design: Comparison of an energy-economics-based optimisation against an exergoeconomics-based optimisation

So far, as demonstrated in the last chapter, a hybrid approach considering energy and exergy indicators simultaneously has been used for the optimisation process of BER design. In this section, the study is designed to use ExRET-Opt optimisation capabilities into the Mayville Community Centre under two different approaches. The first MOO method is based on the First Law by optimising energy use and a typical economic indicator (NPV). This approach is typically used in industry and research and the literature was already provided in Section 2.2.3. From this point in the study, this approach will be referred to as the *energy/economic optimisation*. The second method, based on the Second Law, optimises exergy destructions and the exergoeconomic cost-benefit indexes. This approach will be referred to as the *exergy/exergoeconomic optimisation*. Although, due to lack of evidence, it remains to be seen if the full exergy/exergoeconomics approach, commonly used in power plants and chemical processes (Rosen, 2002b, Kumar, 2016) where it is regarded as a powerful method for cost-efficient improvement of energy systems, can unlock more sustainable designs when applied to BER design.

Therefore, in order to analyse the design of the Mayville Community Centre, the post-retrofit model presented in the last section has been 'stripped off' of currently installed technologies. By doing this, ExRET-Opt Module 4 can be applied to analyse different BER designs found in the tool's database. The following section describes the study design and the additional assumptions made for this study.

8.3.1 Study design (decision variables, objective functions and constraints)

In this study, the search space or all possible BER design combinations have been increased, compared to the school and office archetypes' case studies. The main reason for a larger search space has been the inclusion of extra BER measures. Firstly, an extra HVAC system (H33) has been created representing the actual design of the Passivhaus building (GSHP combined with a MVHR system). Secondly, following the actual BER design, the envelope is now differentiated into six parts instead of three: 1) above ground wall insulation, 2) basement wall insulation, 3) basement floor insulation, 4) ground floor insulation, 5) pitched roof insulation, and 6) normal roof insulation. Also, thicker values (with their corresponding cost) for all insulation are considered to reach Passivhaus standard U_{values}. Finally, PV panels now can cover a more detailed roof area, ranging from 0 to 100% in 10% steps, (specific base value of 46% has also been included in the parameter variables). The decision variables for the optimisation process are defined in Table 8-4. Therefore, all possible combinations for the case study now are more than seven thousand quadrillion (7,099,580,375,363,174,400), an impossible task for almost any computer due to limited number of cores and processing time.

Table 8-4 Decision variables and vector ID used for the Mayville case study

Decision variables - BER measures	Number of possible solutions	Vector ID
HVAC system	34	X^{HVAC}
Wall insulation (above ground)	116	X^{wall}
Roof Insulation	116	X^{roof}
Ground floor Insulation	111	X^{ground}
Basement Wall insulation	116	$X^{\mathrm{wall\_BS}}$
Pitched Roof Insulation	116	$X^{\mathrm{roof\_Pi}}$
Basement Ground Insulation	111	$X^{\mathrm{ground\_BS}}$
Sealing (infiltration rate)	10	X^{seal}
Glazing	13	X^{glaz}
Lighting	4	X^{light}
Photovoltaic panels	12	X^{PV}
Wind turbines	3	X^{wind}
Heating set-point	5	X^{heat}

8.3.1.1 Objective functions

As mentioned, two approaches, each one at least considering two conflicting objectives, have been considered. These studies take into account three objectives that have to be satisfied simultaneously.

a) *Energy/economic based optimisation*

For the energy/economic approach the objectives are the minimisation of building energy use, reduction of occupant thermal discomfort, and maximisation of project's NPV:

I. Building's annual energy use (kWh/m^2-year):

$$Z_1(x)\, min = \; EUI_{bui} \tag{8.1}$$

II. Occupant discomfort hours:

$$Z_2(x) min = \; \left(\left|PMV\right| > 0.5\right) = \; (|\,(0.303\; e - 0.036M \; + \; 0.028)\; L| \;\; > 0.5) \tag{8.2}$$

III. Net Present Value$_{50\text{ years}}$ (£):

$$Z_3(x) max = \; NPV_{50years} \; = -TCI + \left(\sum_{n=1}^{N} \frac{R}{(1+i)^n}\right) + \frac{SV_N}{(1+i)^N} \tag{8.3}$$

For simplification, the NPV is set to negative to have a full minimisation procedure.

b) Exergy/exergoeconomic-based optimisation

For the exergy/exergoeconomic approach the objectives are the minimisation of overall building exergy destructions, reduction of occupant thermal discomfort, and minimisation of the exergoeconomic cost-benefit index:

I. Building annual exergy destructions (kWh/m²-year):

$$Z_1(x)\,min = Ex_{dest,bui} = \sum Ex_{prim}(t_k) - \sum Ex_{dem,bui}(t_k) \quad (8.4)$$

II. Occupant discomfort hours:

$$Z_2(x)min = \left(|PMV| > 0.5 \right) = (|\,(0.303\,e - 0.036M + 0.028)\,L| > 0.5) \quad (8.5)$$

III. Exergoeconomic cost-benefit 50 years (£/h):

$$Z_3(x)max = Exec_{CB} = \dot{C}_{D,sys} + \dot{Z}_{sys} - \dot{R} \quad (8.6)$$

8.3.1.2 Constraints

Furthermore, based on the single-building energy/exergy analysis of the actual post-retrofit building, it was chosen to subject the optimisation problem to three constraints. First, the capital investment of the BER design base case of £417,028 is taken as a constraint, requiring the model to deliver cheaper designs. In addition, a positive NPV or a DBP of less than 50 years is also a constraint. Finally, the amount of discomfort hours obtained by the actual post-retrofit model (853 hours) is considered as the third constraint. Hence, the optimisation problems for both approaches can be generally formulated as follows:

Given a thirteen-dimensional decision variable vector

$x = \{X^{\mathrm{HVAC}}, X^{\mathrm{wall}}, X^{\mathrm{roof}}, X^{\mathrm{ground}}, X^{\mathrm{wall\_BS}}, X^{\mathrm{roof\_Pi}}, X^{\mathrm{ground\_BS}},$
$X^{\mathrm{seal}}, X^{\mathrm{glaz}}, X^{\mathrm{light}}, X^{\mathrm{PV}}, X^{\mathrm{wind}}, X^{\mathrm{heat}}\}$, in the solution space X, find the vector(s) x^* that:

Minimise: $Z(x^*) = \{Z_1(x*), Z_2(x*), Z_3(x*)\}$

Subject to follow inequality constraints: $\begin{cases} TCI \leq £417{,}028 \\ DPB \leq 50\ years \\ Discomfort \leq 853 \end{cases}$ {constraints}

8.3.1.3 NSGA-II parameters

Table 8-5 presents the NSGA-II settings defined for both studies. The only difference with the last Chapter's study is the mutation rate, which is increased from 20% to 40%, hoping to obtain more variability among simulation models:

Table 8-5 Algorithm parameters and stopping criteria for optimisation with GA

Parameters	
Encoding scheme	Integer encoding (discretisation)
Population type	Double-Vector
Population size	100
Crossover Rate	100%
Mutation Rate	40%
Selection process	Stochastic – fitness influenced
Tournament Selection	2
Elitism size	Pareto optimal solutions
Stopping criteria	
Max Generations	100
Time limit (s)	10^6
Fitness limit	10^{-6}

Each procedure will then perform ~10,000 simulations, or will terminate either if the objective functions converge or a time limit is reached.

8.3.2 Optimisation results

Following 9 days of simulation, the energy-based MOO collected 9,815 simulations, while the exergy-based MOO simulated 9,747 models. However, the constrained results are 475 and 344 solutions for the energy-based and exergy-based MOO respectively. This demonstrates that around 3-5% of the simulated solutions have a better thermal comfort and economic performance than the actual retrofitted building.

8.3.2.1 Single-objective analysis

Each objective from the non-dominated solutions were individually optimised for both approaches. The single objective optimal BER designs are shown in Table 8-6 for the energy/economic based approach and Table 8-7 for the exergy/exergoeconomics-based approach.

Table 8-6 BER retrofit design for single-objective optimisation using energy/economics-based approach

Obj.	X^{HVAC}	X^{wall} Wall Insulation (m) {U-value}	X^{roof} Roof Insulation (m) {U-value}	X^{ground} Ground Insulation (m) {U-value}	X^{wall_BS} Basement Wall Insulation (m) {U-value}	X^{roof_Pi} Pitched Roof Insulation (m) {U-value}	X^{ground_BS} Basement Ground Insulation (m) {U-value}	X^{seal} Infiltration Reduction % (ach)	X^{glaz} (glass-gap-glass, in mm)	X^{light} Light tech	X^{PV} % Roof panels	X^{wind} (kW)	X^{heat} (°C)	EUI_{bui} (kWh/m²-year)	***Discom-fort*** (hours)	NPV_{50y} (£/h) {DPB-years}
[min] EUI_{bui}	H21: GSHP + Underfloor Heat.	Polyure-thane (0.25m) {U: 0.09}	Phenolic (0.03m) {U: 0.32}	Phenolic (0.05m) {U: 0.15}	Cellular Glass (0.30m) {U: 0.13}	Phenolic (0.08m) {U: 0.25}	Phenolic (0.10m) {U: 0.11}	50% (0.5 ach)	Double Glazed Krypton (6-13-6)	T8 LFC	0	20	21	**58.4**	841	+8,488 {50.0}
[min] *Discom-fort*	H28: Biomass Boiler + Wall Heat.	XPS (0.01m) {U: 1.18}	Aerogel (0.04m) {U: 0.29}	Cellular Glass (0.04m) {U: 0.34}	DuPont PCM (0.01m) {U: 0.30}	Phenolic (0.13m) {U: 0.26}	Cork Board (0.02m) {U: 0.40}	0% (1 ach)	Double Glazed Krypton (6-6-6)	T8 LFC	10	20	19	340.8	**550**	+71,296 {35.3}
[max] NPV_{50y}	H31: mCHP + CAV	Glass Fibre (0.15m) {U: 0.21}	XPS (0.03m) {U: 0.85}	Cork Board (0.14m) {U: 0.18}	XPS (0.04m) {U: 0.60}	XPS (0.08m) {U: 0.41}	Phenolic (0.07m) {U: 0.26}	20% (0.8 ach)	Double Glazed Air (6-13-6)	T5 LFC	10	20	21	272.4	853	**+209,006** **{23.7}**

Table 8-7 BER retrofit design for single-objective optimisation using exergy/exergoeconomics-based approach

Obj.	X^{HVAC}	X^{wall} Wall Insulation (m) {U-value}	X^{roof} Roof Insulation (m) {U-value}	X^{ground} Ground Insulation (m) {U-value}	X^{wall_BS} Basement Wall Insulation (m) {U-value}	X^{roof_Pi} Pitched Roof Insulation (m) {U-value}	X^{ground_BS} Basement Ground Insulation (m) {U-value}	X^{seal} Infiltration Reduction % (ach)	X^{glaz} (glass-gap-glass, in mm)	X^{light} Light tech	X^{PV} % Roof panels	X^{wind} (kW)	X^{heat} (°C)	Ex_{dest} (kWh/m²-year)	***Discom-fort*** (hours)	$Exec_{CB}$ (£/h) {DPB (years)}
[min] $Ex_{dest,bui}$	H15: District Heating + Wall Heat.	Polyure-thane (0.03m) {U: 0.56}	Phenolic (0.05m) {U: 0.37}	Polyure-thane (0.06m) {U: 0.23}	Glass Fibre (0.20m) {U: 0.16}	EPS (0.09m) {U: 0.37}	Aerogel (0.025m) {U: 0.26}	20% (0.8 ach)	Single glazed (6)	T8 LED	0	20	20	**102.9**	791	0.23 {50.0}
[min] *Discom-fort*	H28: Biomass Boiler + Wall Heat.	Cork Board (0.20m) {U: 0.17}	Cork Board (0.06m) {U: 0.53}	XPS (0.14m) {U: 0.17}	DuPont PCM (0.01m) {U: 0.17}	Cork Board (0.12m) {U: 0.30}	Polyure-thane (0.12m) {U: 0.15}	10% (0.9 ach)	Double Glazed Air (6-13-6)	T5 LFC	20	0	19	238.8	**584**	0.90 {38.7}
[min] $Exec_{CB}$	H29: Biomass Boiler + Underfloor Heat.	Glass Fibre (0.065m) {U: 0.42}	Polyure-thane (0.12m) {U: 0.19}	Phenolic (0.03m) {U: 0.17}	XPS (0.03m) {U: 0.72}	Polyure-thane (0.04m) {U: 0.57}	Polyure-thane (0.07m) {U: 0.14}	10% (0.9 ach)	Single glazing	T5 LFC	20	0	19	114.0	666	**-0.11** **{26.7}**

I. Energy-based single objective results

For the energy-based optimisation, when single-optimising building's EUI, the design demonstrates a BER design similar to the actual retrofit building, indicating that the designers were focused on optimising energy use only. The modelled design is also based on a GSHP, differing in that instead of considering a MVHR the model suggests the installation of underfloor heating. In addition, the wall insulation is similar to that found in the actual BER, having 0.25m of Polyurethane for the above ground walls and 0.30m of cellular glass for the basement walls. All envelope parts but the roof's meet the Passivhaus insulation standards (U_{values}<0.15). In terms of infiltration rate, again, the model suggests a similar value to the one in the real design (model: 0.50 ach, real: 0.42 ach). However, to lower the capital cost, the model reduced the glazing system to double-glazed Krypton-filled windows instead of the triple-glazed air-filled of the original design. The lighting system is based on T8 LFC, similarly to the actual building. The biggest change comes in the PV panels, where the model does not consider its installation, and instead, a 20 kW turbine is proposed. The outputs from this design was able to lower energy use from 47,293 kWh/year (61.6 kWh/m^2-year) to 44,845 kWh/year (58.4 kWh/m^2-year). It also improves thermal comfort by 1.4% (from 853 to 841 discomfort hours), while delivering a positive $NPV_{50\ years}$ of £8,488. The project's total capital investment is calculated of £271,738, reducing original budget by 34.8%.

When single-optimising thermal comfort, the model suggests the installation of H28: Biomass boiler with wall heating to improve overall thermal comfort conditions. However, compared to the last case, insulation levels are much lower, with the roof as the only envelope element with U_{value} less than 0.30 W/m^2-K. In addition, the model suggests the wall basement to be insulated with 0.01m of DuPont phase change material (PCM), a rather expensive technology. The model also considers leaving a leaky envelope, with a value of 1.0 ach. For the glazing, installation of double-glazed Krypton-filled windows is considered. T8 LFC lighting is considered along the implementation of 3.9 kWp PV panels and a 20 kW turbine. This results in a high energy use of 261,529 kWh/year (340.8 kWh/m^2-year), but reduces discomfort hours to 550. This BER has a capital investment of £316,444 and a DPB of 35.3 years.

Finally, by single-optimising NPV, the model considers H31: microCHP and gas boiler connected to a CAV system. The solution also considers low insulation levels (with some parts not even meeting minimum Part L2B requirements) and an improvement on the airtightness of the building of just 20% (0.8 ach). In the model, the windows are retrofitted to double-glazed air-filled, while considering a more efficient lighting system of T5 LFCs. It also suggests the installation of 3.9 kWp of PV panels and a 20 kW turbine. With this design, the building demands 209,006 kWh/year (272.4 kWh/m2-year) and keeps thermal comfort at the same level as the original design (853 discomfort hours). However, it has the best economic performance with a payback of 23.7 years requiring a capital investment of £262,992.

II. Exergy/exergoeconomics-based single objective results

In the exergy/exergoeconomics-based approach, by single-optimising building exergy destructions, the optimisation procedure delivers a BER design composed of H15: District heating connected to a wall heating system. From a Second Law perspective, district systems (especially waste heat-based) are considered as the most ideal low-exergy supplying systems due to their high efficiency in using low grade heat. The BER design is combined with low levels of insulation, where just the basement walls and ground insulation meet Part L2 requirements. The design also proposes a reduction of 20% in the air leakage (0.8ach) with no retrofit in the glazing system. The lighting system is changed to T8 LED, with no PV panels and a 20 kW wind turbine. The model was able to reduce thermodynamic irreversibilities from the actual retrofit of 104,918 kWh/year (136.8 kWh/m2-year) to 78,938 kWh/year (102.9 kWh/m2-year) and improve exergy efficiency (Ψ) from an already high value of 0.180 to 0.222. Discomfort levels and the exergoeconomic cost-benefit indicator are also reduced to 791 hours and £0.23/h respectively. This BER design has a capital investment of £179,250 and a DPB of 50 years.

By single-optimising discomfort under a full Second Law approach, the model suggests a similar design as its energy approach counterpart. The BER design is based on a H28: Biomass boiler with wall panel heating. However, insulation levels are higher, suggesting the installation of 0.20m of cork board for the above ground walls, 0.14m XPS for the ground floor and 0.12m of cork board for the pitched roof. It also suggests a 0.01m of DuPont PCM for the basement walls. This is combined with a slight improvement in the airtightness of 10% (0.9 ach) and the installation of double-glazed air filled windows. For active systems it recommends the installation of T5 LFC and 7.8 kWp PV panels. This design increments exergy destructions to 183,184 kWh/year (238.8 kWh/m2-year) and reduces exergy efficiency to 0.110. In addition, it reduces discomfort hours to 584 hours and minimises exergoeconomic cost-benefit value to £0.90/h. The design requires an investment of £256,761 delivering a payback of 38.7 years.

Finally, of great interest are the results obtained from the single optimisation of the novel exergoeconomic cost-benefit indicator. This design suggests an HVAC system based on H29: Biomass boiler connected to underfloor heating. The envelope is characterised by high levels of insulation in the roof and ground floors and low levels in the walls and pitched roof. A building airtightness of 0.9 *ach* and the utilisation of the pre-retrofit single glazing is also considered by the model. For active systems, the models suggest the installation of highly efficient T5 LFC lighting and the implementation of 7.8 kWp of PV panels. This design results in exergy destructions of 87,405 kWh/year (114.0 kWh/m^2-year) and an exergy efficiency of 0.199. Discomfort values are reduced to 666 hours per year. Moreover, the exergoeconomic cost-benefit indicator reaches a value of -£0.11/h, meaning that the project is exergetically and exergoeconomically efficient. This is supported by a low cost BER design (£180,017) with a payback of 26.7 years, similar to the one obtained by optimising NPV in the energy-based approach.

Table 8-8 provides a comparative study of the main studied indicators (including carbon emissions and exergy destruction costs) from each single optimisation model. As seen in the results, the solution that reduces the most carbon emissions is the single optimisation of the exergoeconomic cost-benefit indicator. This large reduction was achieved thanks to the installation of the biomass-based (0.039 $kgCO2_e$/kWh) boiler working with low temperature floor systems combined with the 7.8 kWp of PV panels (0.075 $kgCO2_e$/kWh). As expected the NPV single optimisation provides the best economic outcomes, however presents the worst performance in five other indicators related to carbon emissions and exergy use. Another interesting result is provided by the exergy-destructions minimisation model, which delivers the worst economic performance by having the lowest annual revenue (£6,879/year) and the largest $LCC_{50years}$ (£254,123) among optimised models; however, the model successfully reduces primary exergy input and building exergy destructions, improves exergy efficiency (0.222) and obtains the cheapest heating product price with a value of £0.12/kWh (just a slight increment from the district energy market price of £0.066/kWh). However, it is the exergoeconomic cost-benefit single optimisation model which has the best overall performance, obtaining the best outcomes in three main indicators without delivering indicators showing unsatisfactory performance.

Table 8-8 A comparison of main indicators among single optimisation models from both MOO approaches (best performance in green, worst performance in red)

Model	EUI (kWh/ m² - year)	Annual Carbon (tCO_2)	Discom-fort (hours)	LCC (50 years) (£)	BER Total Capital Invest. (£)	Annual Revenue (with incentives) (£)	NPV (50 years) (£)	Primary exergy input (kWh_{ex}/ m²-year)	Exergy dest. (kWh_{ex}/ m²-year)	Exergy eff. Building (-)	Exergy dest. cost rate (£/h)	Heating fuel-product price (£/kWh)	$Exec_{CB}$ (£/h)
Energy/economic-based optimisation													
[min] EUI_{bui}	58.4	37.0	841	249,478	271,738	10,530	8,489	222.1	194.7	0.123	2.06	0.12--4.98	2.03
[min] *Discom-fort*	340.8	31.1	550	186,670	316,444	14,649	71,297	276.5	246.6	0.108	1.05	0.04--1.14	0.73
[max] NPV_{50y}	272.4	81.0	853	109,300	262,992	15,650	148,667	294.5	255.9	0.131	5.05	0.15--4.46	4.39
Exergy/exergoeconomics-based optimisation													
[min] $Ex_{dest,bui}$	118.3	53.6	791	254,123	179,250	6,878	3,844	132.2	102.9	0.222	0.25	0.07--0.12	0.23
[min] *Discom-fort*	309.6	25.0	584	214,962	256,761	11,309	43,005	268.4	238.8	0.110	1.09	0.04--1.13	0.90
[min] $Exec_{CB}$	123.3	14.4	666	177,333	180,018	9,891	80,633	142.2	114.0	0.199	0.25	0.04--0.19	-0.11

8.3.2.2 Triple-objective analysis

As mentioned, the number of constrained models, obtained in the energy/economic-based MOO procedure, are 474, which represent less than 4.8% of all the simulated models. In this case the Pareto front is composed of just nine solutions. The sample is dominated by H21: GSHP and underfloor heating, appearing in 66.6% of the solutions. H31: MicroCHP and condensing boiler with CAV and H28: Biomass boiler and wall heating also appear in the Pareto front. For envelope's insulation, not a single technology appears to dominate the solutions, with XPS and polyurethane being the most common solutions. The rest of the envelope is mainly dominated from high levels of infiltration (>0.7 ach) and single-glazing. For renewable energy, 20 kW turbine and 13.8 kWp of PV panels appear most frequently. The detailed Pareto results by technology type and outputs' values can be found in Appendix H.1.

On the other hand, the exergy/exergoeconomics-based optimisation delivers an even smaller constrained search space with 343 models, representing 3.5% of the simulated space; however, it was able to deliver more Pareto optimal solutions with fourteen non-dominated models. This suggests that an exergy/exergoeconomics-based optimisation presents better performance and more variability among models, locating solutions in a wider spectrum. The most frequent HVAC system is H29: Biomass boiler and underfloor heating with a frequency of 64.2%. This is followed by H26: Condensing Gas boiler with underfloor heating with a frequency of 21.4%. For the insulation measures, high variability exists among technologies and thicknesses, with XPS and EPS being the most common measures. The air tightness of the building is characterised for solutions with 0.8 *ach* or more. In terms of glazing systems, single and double glazing technologies are the most frequent. For renewable technologies, 20 kW wind turbines and 11.7 kWp are the most common measures. The detailed Pareto results by technology type and outputs' values can be found in Appendix H.2.

Figure 8-16 and Figure 8-17 shows a comparison of all the constrained solutions and the non-dominated Pareto fronts for the energy/economics and exergy/exergoeconomics based approaches respectively. For both graphs, the current retrofitted building can be located. In this case, every single Pareto point presents a better overall performance compared to the baseline model.

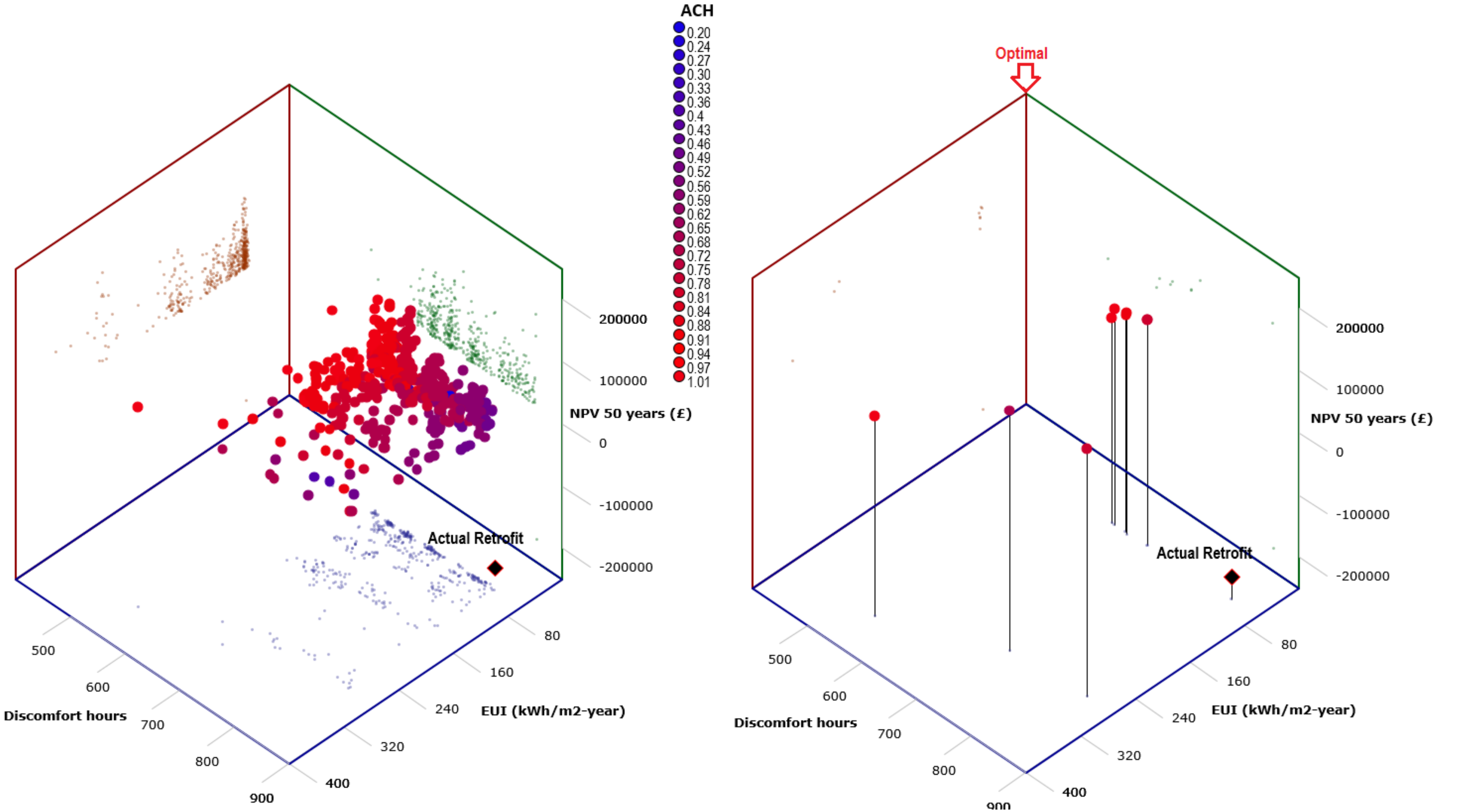


Figure 8-16 Constrained results from the multi-objective optimisation (left) and the Pareto optimal solutions (right). Energy/economics- based optimisation

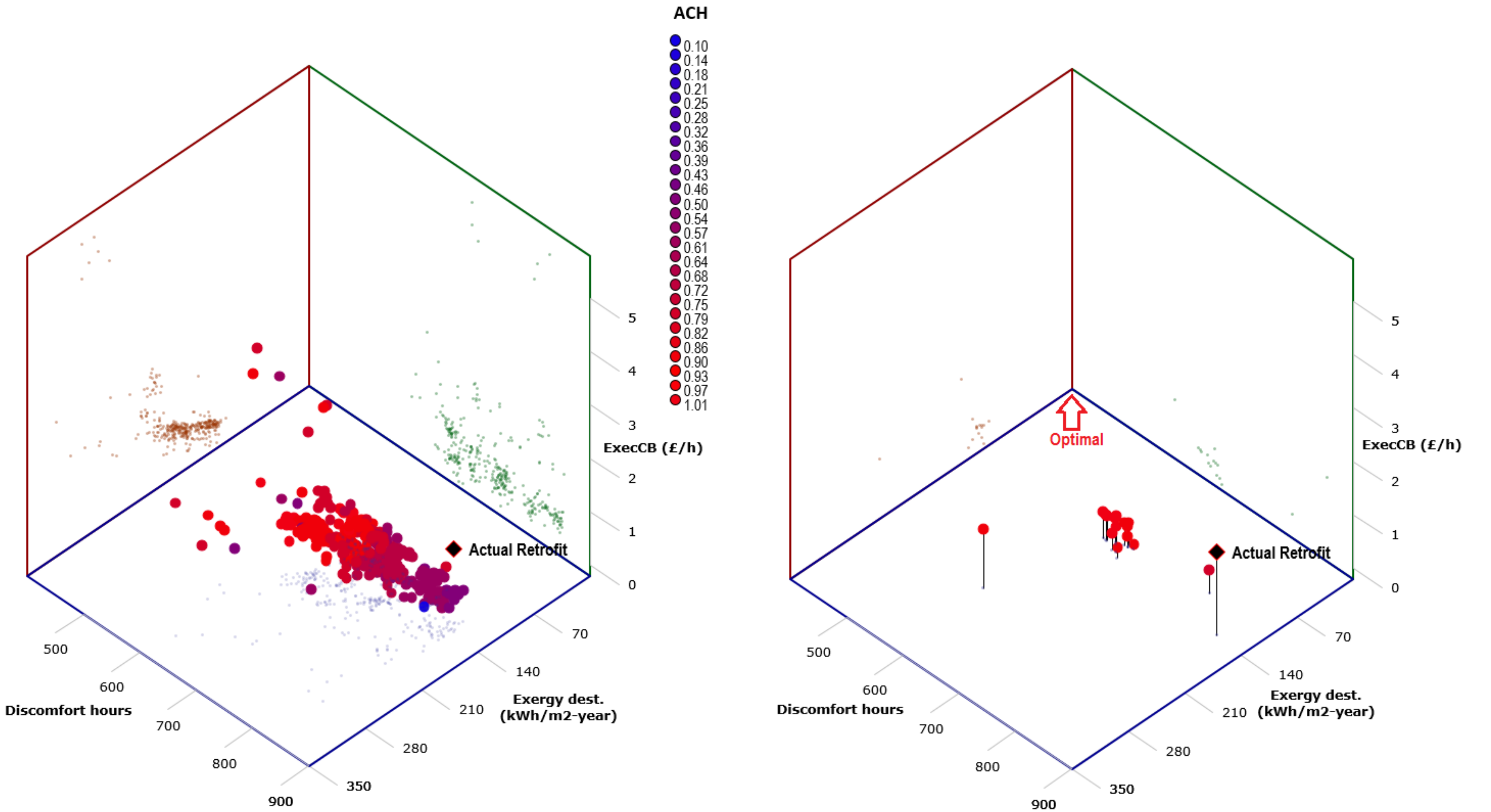


Figure 8-17 Constrained results from the multi-objective optimisation (left) and the Pareto optimal solutions (right). Exergy/exergoeconomics-based optimisation

8.3.2.3 Algorithm behaviour – Convergence study

To check convergence in objectives, a comparison in the algorithm behaviour for both approaches is presented. Figure 8-18 illustrates the convergence rates for the three studied objectives for the energy/economic optimisation. The results demonstrate that energy use converged rather early reaching the minimum value at the 28th generation. However, the discomfort hours and NPV converged at a much later stage (around the 60th generation).

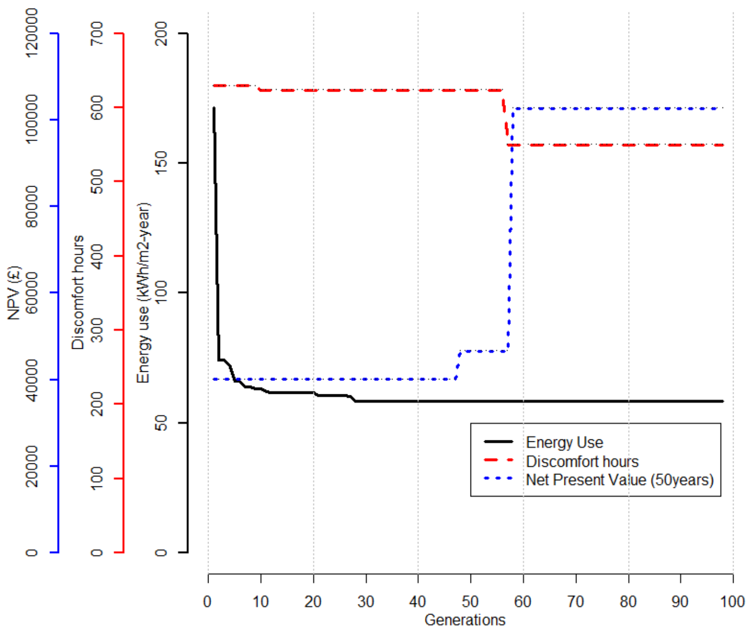


Figure 8-18 Convergence of energy/economic optimisation procedure for the three objective functions

Figure 8-19 illustrated the convergence rates for the exergy/exergoeconomic optimisation. Although it might seem that exergy destruction rate converged late in the optimisation process (generation 77th), the values at the initial generation already present similar values to the optimised one. The same behaviour is found for the discomfort hours, reaching convergence after the 8th generation. In the case of the exergoeconomic cost-benefit indicator the initial value of £0.20/h already represents a major improvement from the actual Passivhaus retrofit (£1.33/h); however, it is after generation 74th when it reaches the best outcome (-£0.11/h).

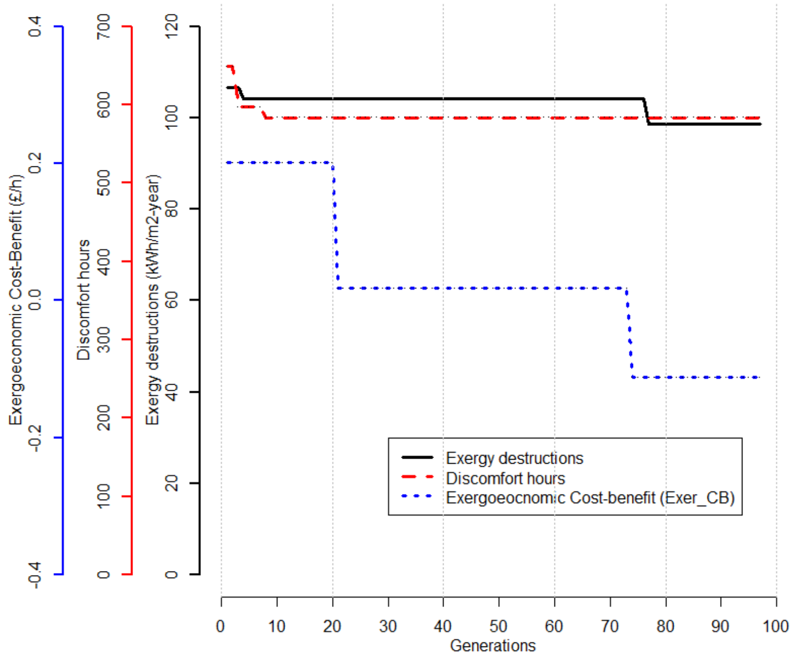


Figure 8-19 Convergence of exergy/exergoeconomic optimisation procedure for the three-objective functions

8.3.2.4 A statistical comparison of optimisation outputs

To make a comparison of both approaches' main outputs, an independent two sample t-test is performed. An independent t-test is used to compare the mean values from the two sample gathered and test whether it is likely that the samples are from populations having different mean values. The t-test calculates the probability of getting the modelled outputs' values under the null hypothesis. This initial output data, provided by the optimisation procedures, should show which approach delivers better overall performance on main indicators. It was initially planned to perform the analysis on the Pareto front samples, and although there is no minimum sample size for the t-test to be valid, it was considered that the Pareto fronts were too small (sample sizes: 9 and 14). Therefore, it was decided to perform the analysis in the constrained solutions (474 and 343 samples). For the test, the analysed indicators are the same as presented in Table 8-8. For the data check, Figure 8-20 presents boxplots for each output. A comparison between approaches is illustrated to show a preliminary outcome. The boxplots will also help to determine each output's variability, median values (skewness), and outliers.

Although not conclusive, the test should provide an initial evidence to exhibit that, on average, either approach delivers better outcomes. Although the t-test requires normally distributed samples, the test is not sensitive to deviation if the distribution of both samples' outputs is similar (as shown in Figure 8-20) and the sample size is large enough (>50). Nevertheless, data transformation is required to make the output samples more normally distributed, meaning to remove some extreme outliers.

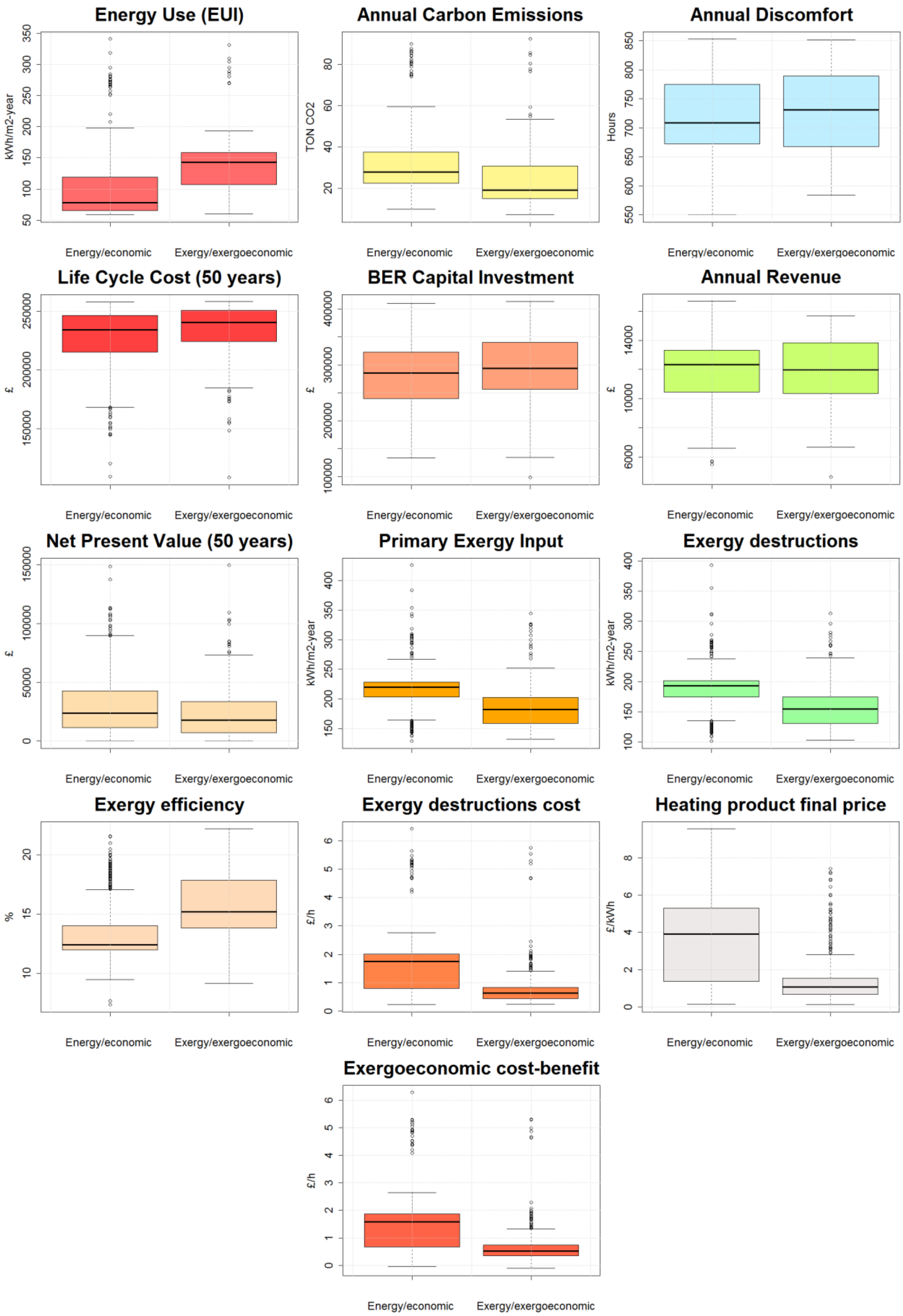


Figure 8-20 Boxplots representing each output gathered for both optimisation approaches

The independent t-test results are displayed in Table 8-9. The outputs show the samples' means (energy/economic approach mean and exergy/exergoeconomic approach mean), an estimation difference, 95% confidence interval for the difference between the means, as well as the t and p-values. The table highlights the approach with the best indicator performance, complemented by the analysis of the t-value and most importantly the p-value. It is expected that each approach dominates its related outputs, meaning that the energy/economic optimisation delivers better indicators such as energy, NPV, LCC, while the exergy/exergoeconomic optimisation performs better in indexes such as exergy destruction cost, exergy efficiency, etc. However, there are outputs such as discomfort and carbon emissions which are of great interest for this study.

Table 8-9 Independent t-test analysis on main indicators from both optimisation approaches (best performance in green)

Indicator	Mean energy/ economic approach	Mean exergy/ exergoeconomic approach	Estimation difference	95% Confidence interval		t-value	p-value
EUI (kWh/m^2year)	102.4	135.0	-32.4	-39.1	-26.0	-9.78	2.2E-16
Carbon emissions ($tCO_2/year$)	31.65	23.98	7.67	5.8	9.6	7.94	7.2E-15
Discomfort (Hours)	726	729	-3	-11.6	6.2	-0.59	0.5507
LCC (£)	226,694	233,946	-7252	-10,576	-3,928	-4.28	2.1E-05
BER Capital Investment (£)	282,047	292,534	-10487	-18,640	-234	-2.53	0.01177
Annual Revenue (£)	11,802	11,914	-112	-421	198	-0.71	0.4787
NPV (£)	31,273	24,021	7252	3,928	10,576	4.28	2.1E-05
Primary exergy input (kWh/m^2year)	215.9	186.4	29.5	24.4	34.6	11.35	2.2E-16
Exergy destructions (kWh/m^2year)	187.6	158.0	29.6	24.6	34.6	11.72	2.2E-16
Exergy efficiency (-)	0.134	0.156	-0.022	-0.025	-0.018	-12.3	2.2E-16
Exergy destructions cost (£/h)	1.59	0.80	0.79	0.67	0.9	13.12	2.2E-16
Heating product final price (£/kWh)	3.64	1.47	2.17	1.92	2.42	17.19	2.2E-16
Exergoeconomic Cost-benefit (£/h)	1.15	0.70	0.45	0.64	0.87	12.86	2.2E-16

According to the results, discomfort hours and annual revenue p-values demonstrate that the difference between the approaches' means, at a significance level of 5%, does not have statistically significant difference from zero; therefore, there is insufficient evidence to suggest that either approach has a better performance. The discomfort hours' indicator t-test index was expected, as this objective was optimised in both approaches; however, the fact that the annual revenue's energy/economic optimisation does not seem to outperform its exergy/exergoeconomic counterpart, suggests that exergoeconomic optimisation can also deliver cost-effective solutions without the need to investigate much larger amounts, as shown in the NPV t-test outputs.

As expected, all the exergy and exergoeconomic t-test results (primary exergy input, exergy destructions, exergy efficiency, heating product final price, and exergoeconomic cost-benefit) present better mean values and small p-values (<0.05) concluding that there is a statistically significant difference between the mean values. However, the indicator that seems to provide the most meaningful outcome is the annual carbon emissions. Some first evidence was already provided in Section 8.3.2.1, when the outputs from the single optimisation of the exergoeconomic cost-benefit objective already suggested a lower carbon footprint than all of the energy/economic single optimisation models. This evidence can now be supported by the statistical analysis of the constrained solutions, where there is an average difference in annual emissions of 7.67 tCO_2 in favour of the exergy/exergoeconomic solutions. The t-test provides a 95% confidence interval of the mean difference between 5.8 and 9.78 $tCO_{2\ and}$ a small p-value of 7.16E-15, therefore the null-hypothesis can be rejected and conclude that the exergy/exergoeconomic optimisation approach, at least for this specific case study, provides larger carbon emission reductions.

8.3.3 Multiple-criteria decision analysis (Utopia solutions)

To perform a more refined comparison, the ExRET-Opt MCDM module is applied to the Pareto solutions for both optimisation cases. The entire range of defined criteria and different weights of coefficient values is summarised in Appendix H.3 for the energy/economic approach and Appendix H.4 for the exergy/exergoeconomic approach. However, to perform a final comparative analysis with a single final design, a single model for each optimisation approach needs to be selected. As in Chapter 7, it was decided to analyse the equal weight solutions ($\boldsymbol{p_1}$ =0.33, $\boldsymbol{p_2}$=0.33, and $\boldsymbol{p_3}$=0.33) or the so called 'closest to utopia point model'. From this point, these models will be referred to as '*energy/economic utopia model'* and '*exergy/exergoeconomic utopia model'*.

The energy/economic utopian BER model characteristics and objective outputs are presented in Table 8-10 while the energy system schematic diagram can be seen in Figure 8-21. The envelope is composed of 0.06m of cork board for the above ground walls, 0.05m of EPS for the normal roof, 0.11m for the pitched roof, 0.08m of EPS for the ground floor, 0.16m of cork board for the basement walls, and 0.05m cork board for the basement ground floor. Just the ground floor U_{value} accomplishes Passivhaus standards, while the roof, basement walls, and basement floor accomplishes Part L regulations. On the other hand, the model suggests worse U_{values} than the minimum requirements for the above ground walls and pitched roof. The utopian BER design is also composed of an envelope with an air-tightness of 0.9 *ach* combined with single glazing. This has led to an HVAC system based on a 33 kW GSHP, while the actual BER had an 8.9 kW GSHP[‡‡‡‡]. In the utopian model, the heat pump is connected to low-temperature underfloor heating radiators providing hot water at around 35°C. The lighting system is proposed to be changed to T5 LFC. The installation of renewable electricity through a 3.9 kWp PV and a 20 kW wind turbine is also considered. The design requires a capital investment of £220,404 (47% less than the original design).

In contrast, Table 8-11 and Figure 8-22 presents the BER design and energy system diagram respectively for the exergy/exergoeconomic utopia model. The design considers a system based on a 266 kW biomass boiler connected to a low temperature underfloor heating system. In this case, the envelope is refurbished to include 0.30m of glass fibre for the above ground walls, 0.08m XPS for the normal roof, 0.11 of polyurethane for the pitched roof, 0.01m of aerogel for the ground floor, 0.25m of EPS for the basement walls, and 0.12m of polyurethane for the basement ground floor. Three elements achieve Passivhaus U_{values} requirements (above ground walls, basement walls, basement floor), while the rest of the envelope, except for the pitched roof, meets Part L2 minimum requirements. The air-tightness of the envelope is improved by 10% (0.9 ach) while the glazing system is changed to a double-pane with a 13mm air-filled gap. For the rest of the active systems it is suggested to install high efficient T5 LFC lamps, implement 7.8 kWp PV panels, and a 20 kW wind turbine. This design represents a total capital investment of £318,223 (24% less than the original design).

[‡‡‡‡] In practical terms, it can be argued if in the current building's layout exist space to accommodate a larger GSHP equipment. The modelling tool is unable to consider space constraints. This is part of the practical issues arising from the modelling tool.

Table 8-10 Closest to ‘utopia’ solution discovered in the energy/economic optimisation Pareto front

p_{eui}	p_{com}	p_{NPV}	[min] α_{cheb}	EUI (kWh/m^2-year)	*Dis-comfort* (hours)	NPV_{50y} (£)	X^{HVAC} (Type)	X^{wall} (m)	X^{roof} (m)	X^{ground} (m)	$X^{\mathrm{wall\_BS}}$ (m)	$X^{\mathrm{roof\_Pi}}$ (m)	$X^{\mathrm{ground\_BS}}$ (m)	X^{seal} (ach)	X^{glaz} type	X^{light} Light techn	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)
0.33	**0.33**	**0.33**	0.32	67.8	669	105,952	21	6.06 U_{val}: 0.47	3.05 U_{val}: 0.29	3.08 U_{val}: 0.15	6.16 U_{val}: 0.21	2.11 U_{val}: 0.64	6.05 U_{val}: 0.17	0.9	0	2	10	20	18

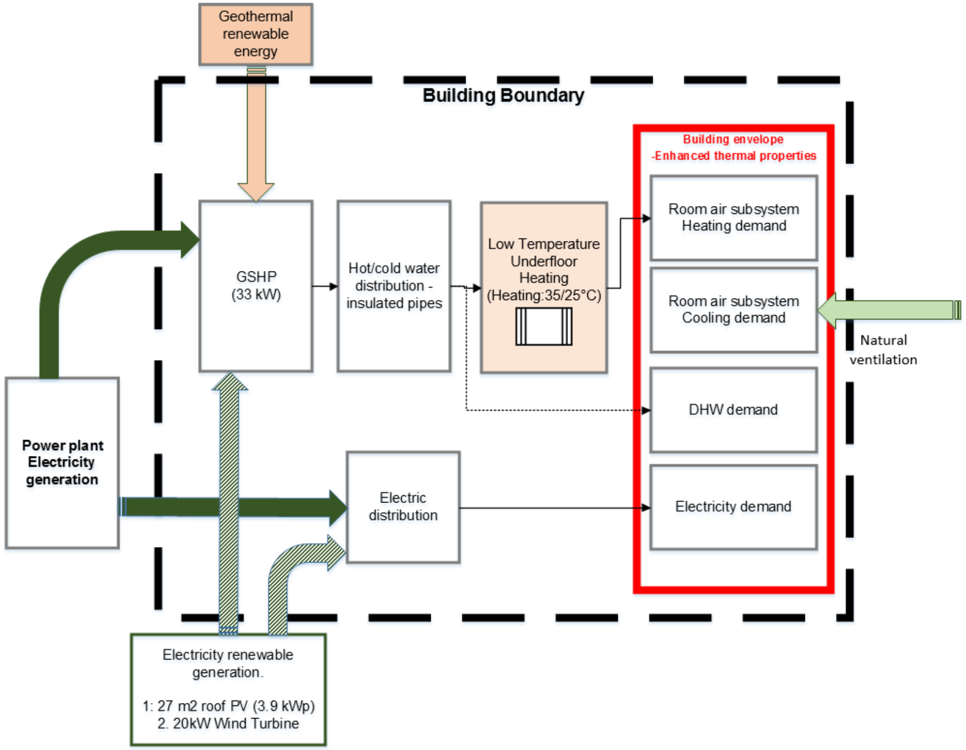


Figure 8-21 Schematic layout of the energy system for the ‘energy/economic utopia’ BER model

Table 8-11 Closest to ‘utopia’ solution discovered in the exergy/exergoeconomic optimisation Pareto front

p_{eui}	p_{com}	p_{NPV}	[min] α_{cheb}	$Ex_{dest,bu}$ (kWh/ m^2-year)	*Dis-comfort* (hours)	$Exec_{CB}$ (£/h)	X^{HVAC} (Type)	X^{wall} (m)	X^{roof} (m)	X^{ground} (m)	X^{wall_BS} (m)	X^{roof_Pi} (m)	X^{ground_BS} (m)	X^{seal} (ach)	X^{glaz} type	X^{light} Light techn	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)
0.33	**0.33**	**0.33**	0.18	111.4	658	0.02	29	5.30 U_{val}: 0.11	2.08 U_{val}: 0.21	8.01 U_{val}: 0.19	3.25 U_{val}: 0.13	1.11 U_{val}: 0.41	1.12 U_{val}: 0.11	0.9	2	2	20	20	19

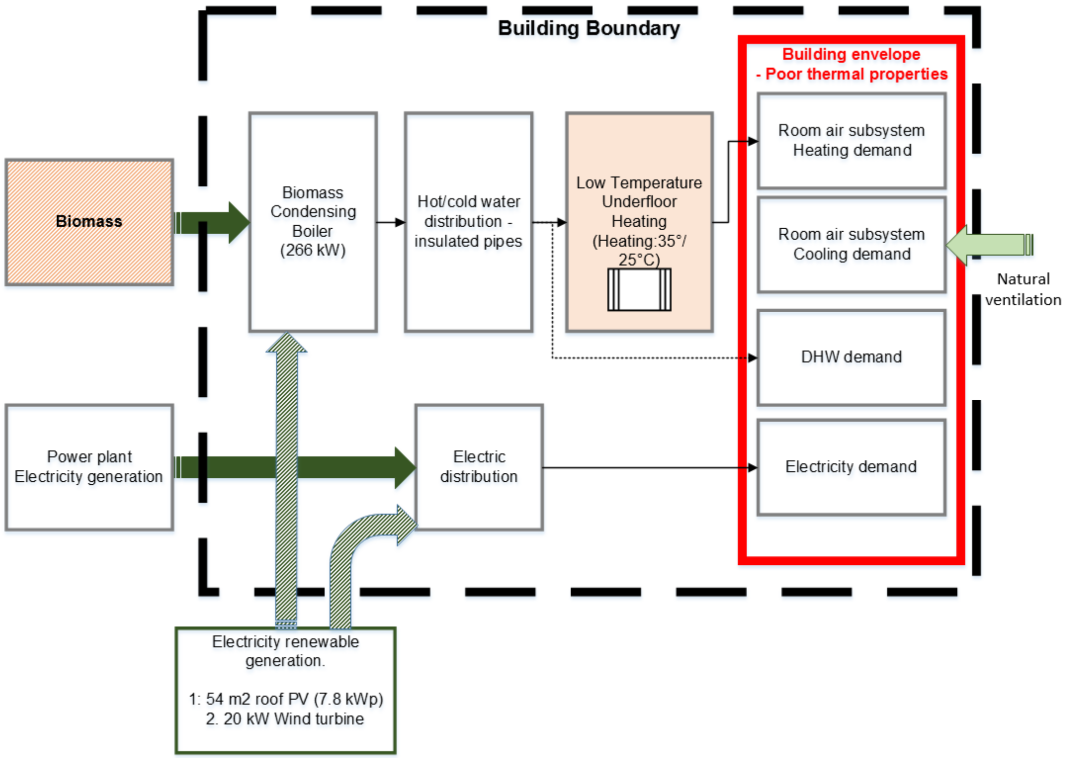


Figure 8-22 Schematic layout of the energy system for the ‘exergy/exergoeconomic utopia’ BER model

8.4 Detailed comparison between actual retrofitted building and optimised BER designs

This section presents a detailed comparison analysing energy, economic, exergy, and exergoeconomic indicators of the actual Passivhaus BER against both utopian models.

8.4.1 Energy and economic analysis

Figure 8-23 illustrates a detailed energy use from each BER design. In this case, the actual BER case presents the lowest EUI with a value of 61.6 kWh/m²-year, followed by the energy/economic utopia model with 67.8 kWh/m²-year, and finally by the exergy/exergoeconomic utopia with 116.7 kWh/m²-year. However, it is the energy/economic utopia that achieves the lowest net energy use (8.9 kWh/m²-year) thanks to the generation and in-site use of renewable electricity. The other models are able to have a net energy final use of 43.2 and 51.8 kWh/m²-year for the actual BER and exergy/exergoeconomic utopia BER respectively. The graph illustrates the high demand of biomass required for heating space for the exergy/exergoeconomic utopia BER; however, the design also presents the lowest values for total electricity demand.

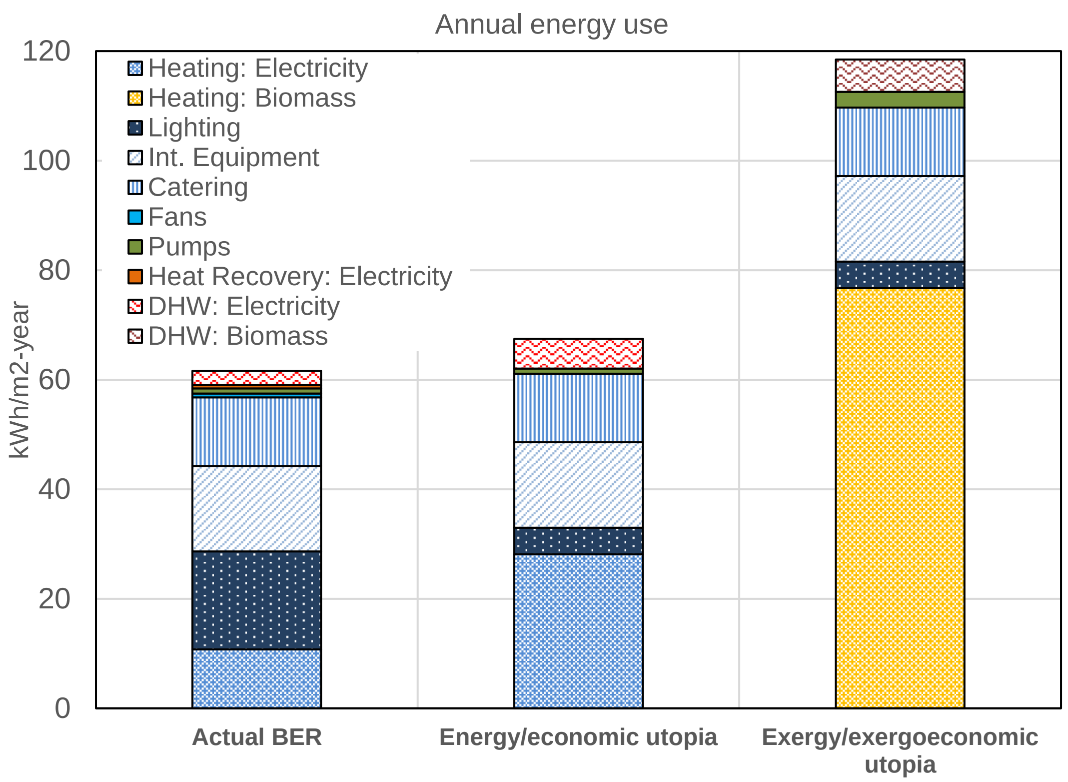


Figure 8-23 Annual energy use by end-use comparison between actual and optimised BER different designs

Figure 8-24 presents the total capital investment separated by the type of measure. It has to be said that the actual BER capital investment was used as a constraint in the optimisation process, and as expected, it is the energy/economic utopia BER design that has the lowest capital investment. The figure illustrates that the biomass boiler, even when it has an installed capacity of at least 10x times bigger compared to the other systems, has a similar capital investment to the GSHPs. From the graph it is evident that large budget was allocated in the actual Passivhaus design towards measures such as insulation, sealing, and glazing systems, as well as the large amount of money dedicated to PV/T panels. The actual design presents a passive/active cost ratio of 0.41, meaning that 59% of the budget is allocated to active measures. Meanwhile the energy/economic utopia has a ratio of 0.10 and the exergy/exergoeconomic utopia of 0.22. Before the analysis it was expected the Second Law based model to have the smallest active/passive ratio, however the investment on the double-glazed system increased the passive costs.

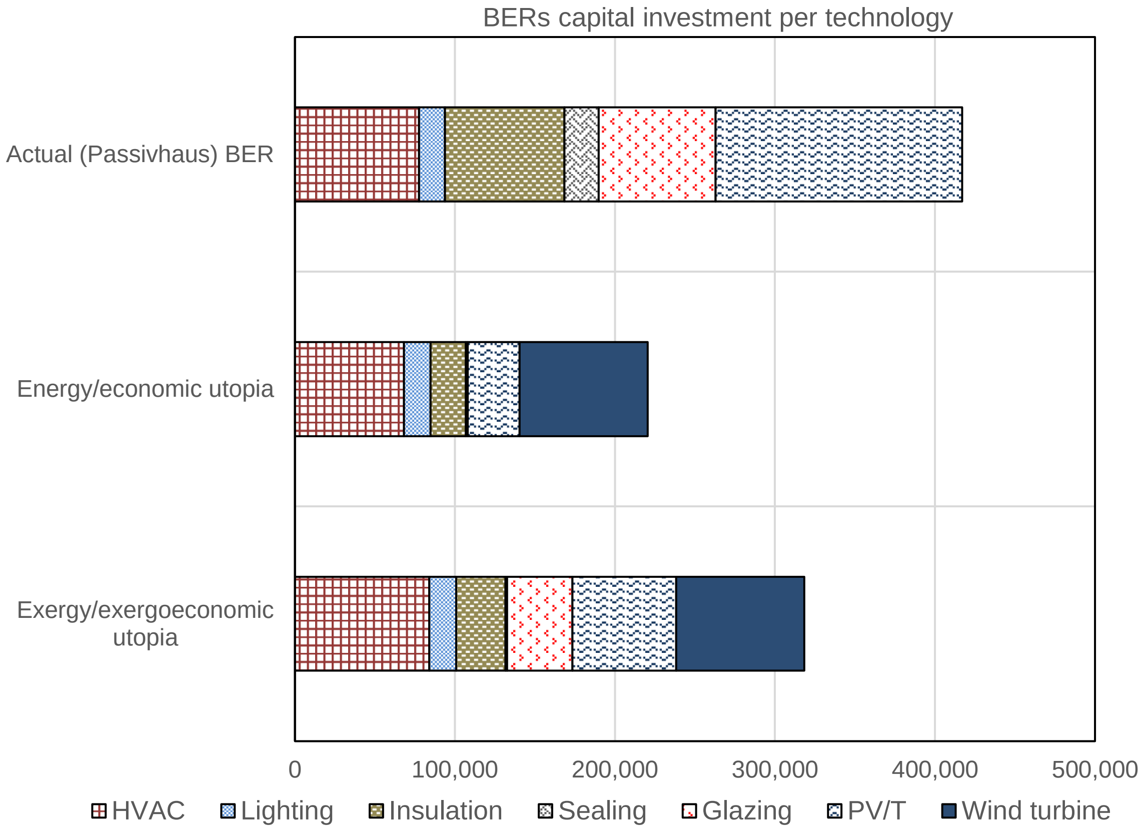


Figure 8-24 A comparison of capital investment by measure between actual and optimised BER designs

A comparison of the annual energy bills and income from government incentives can be seen in Figure 8-25. The outcomes illustrate the strengths of ExRET-Opt optimisation procedure, as both optimised designs provide lower energy bills and higher incentives with cheaper solutions. In fact, both optimised models present more annual profit than energy bill payments. For the energy/economic utopia model, large part of the incentives come from the 'renewable' heat generation from the heat pump (RHI: £1,929) and the electricity generation from the 20 kW wind turbine (FiT: £2,630). On the other hand, the exergy/exergoeconomic utopia designs benefit the most from the biomass renewable heat generation and the PV and wind turbines renewable electricity generation, as it receives an annual average income of £3,083 from RHI and £2,864 from FiT.

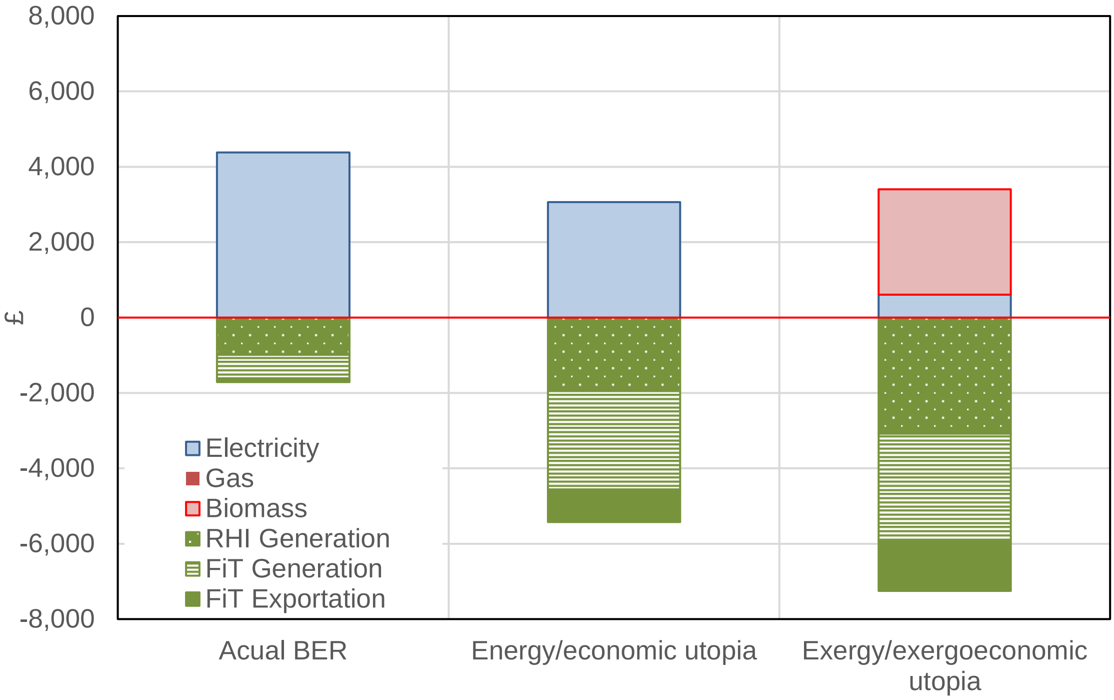


Figure 8-25 Annual energy bill comparison between actual and optimised BER designs

After accounting for the annual energy bills and incentives, Table 8-12 shows a summary of the main economic indicators for each design.

Table 8-12 A comparison of economic indicators among actual and optimised BER designs

BER Design	Annual revenue (£)	LCC (50 years) (£)	NPV (50 years) (£)	DPB (years)
Actual design (Passivhaus)	7,358	471,403	-213,436	137.2
Energy/economic utopia	12,391	152,015	105,952	25.3
Exergy/exergoeconomic utopia	13,880	208,194	49,773	38.2

8.4.2 Exergy and exergoeconomic analysis

Figure 8-26 presents a comparison of the models' annual exergy demand and exergy destruction rates. As can be seen, the exergy demand is similar among BER designs. However, it is important to note that great part of the exergy demand, especially in low energy buildings, comes from electric-based equipment. As illustrated in the right-hand side of the graph, the energy/economic model presents the largest exergy destructions with the highest share at the HVAC system due to the utilisation of electricity for heating purposes. This is also combined with a lower than expected COP of the heat pump, as the model presents an average value of 2.5. On the other hand, the Passivhaus approach has the lowest destructions in HVAC exergy derived from a small GSHP working with a COP of 2.8 and the re-utilising waste heat thanks to the MVHR system. The exergy/exergoeconomic utopia, by using a high-quality energy source such as biomass, presents the second highest exergy destructions rate at the HVAC system; however, system destructions are minimised thanks to the implementation of underfloor heating. In addition, this design minimises HVAC exergy destructions by not selecting an electric-based HVAC system and by not requiring large amounts of auxiliary energy; therefore, high quality sources are used as smartly as possible. In terms of exergy efficiency, the exergy/exergoeconomic approach achieved an efficiency of 0.200, followed by the Passivhaus approach with 0.180 and the energy/economic utopian BER with 0.118.

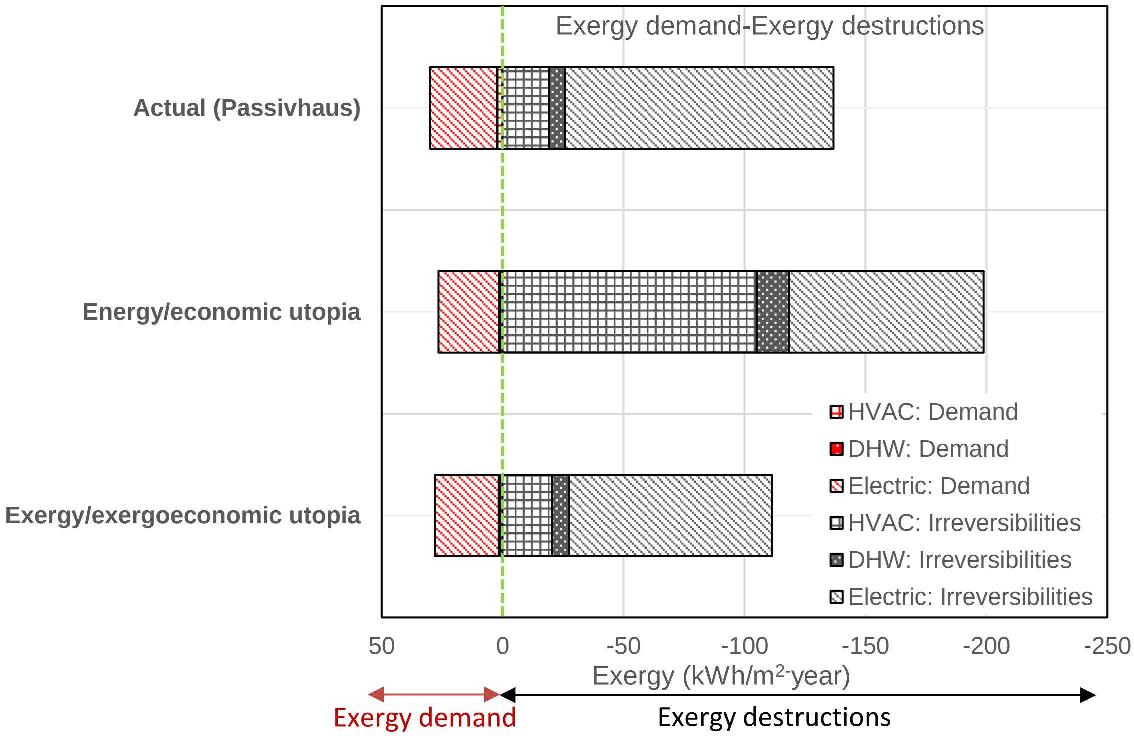


Figure 8-26 A comparison of exergy demand and exergy destructions by product for the actual and optimised BER designs

Figure 8-27 illustrates the heating product cost formation for the three designs. The product price for the energy/economic utopia point increases from an electricity market value of 0.12 £/kWh to 3.59 £/kWh, having a relative cost difference (r_k) of 28.97. As expected the largest increase occurs after the generation subsystem, when electricity is required to drive the heat pumps compressor; however, the increase is not as large in the Passivhaus design which also uses a GSHP. The reason for the former to have such a large increase is the fact that more exergy destructions are located at this stage combined with a higher capital investment for the heat pump. Furthermore, a cost increase can be seen after the distribution and emission system due to high investment for the underfloor system.

On the other hand, the exergy/exergoeconomic utopia product price rose from an initial market value of 0.04 £/kWh to £0.19 £/kWh, having a relative cost difference (r_k) of 3.72. Again, the largest increases occur where the higher investments are made; however, due to a lower amount of irreversibilities, the price maintains stability along the energy supply chain. The use of a boiler as a heat source for low-exergy is not considered thermodynamically efficient; nevertheless, due to the imposed constraint and the low capital cost required for its installation, it became a popular selection among the non-dominated solutions.

Finally, the Passivhaus heating product price increased from 0.12 £/kWh to 0.26 £/kWh, having a relative cost difference (r_k) of 1.14. In this case, the MVHR system helped maintain a lower product price due to the utilisation of 'free-exergy'. However, if the electricity (exergy) input to move the MVHR exceeds the exergy cost of the recovered energy, then the solution can no longer be considered thermodynamically efficient.

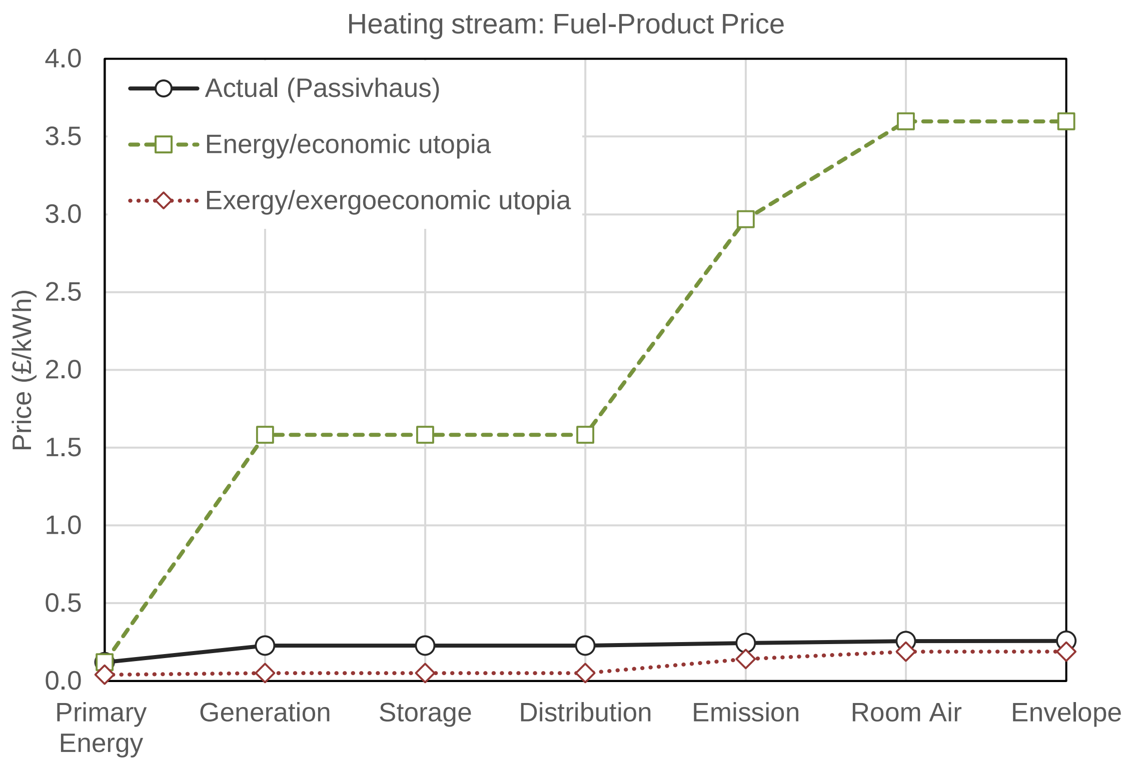


Figure 8-27 Heating stream cost formation for the actual and optimised BER designs

Figure 8-28 shows the exergy destruction cost rate, the capital investment rate and revenue rate for the analysed cases. As seen, high heating product cost has caused a large exergy destruction cost rate for the energy/economic utopian BER design (£2.02/h), while the actual

BER and the exergy/exergoeconomic utopian BER present values of £0.39/h and £0.24/h respectively. By accounting for capital cost and revenue, the energy/economic model obtains an exergy/exergoeconomic cost-benefit index ($Exec_{CB}$) of £1.54/h, a similar value to the original pre-retrofitted building ($Exec_{CB}$=1.55).

As already described in Section 8.2.3, the Passivhaus BER design by having a large capital cost rate and a low revenue rate, obtains an $Exec_{CB}$ =£1.33/h , also similar to the pre-retrofitted case. On the other hand, the exergy/exergoeconomic utopia design obtains the best performance with an $Exec_{CB}$ of £0.02/h, thanks to a smarter energy resources and budget allocation combined with extra income from government incentives.

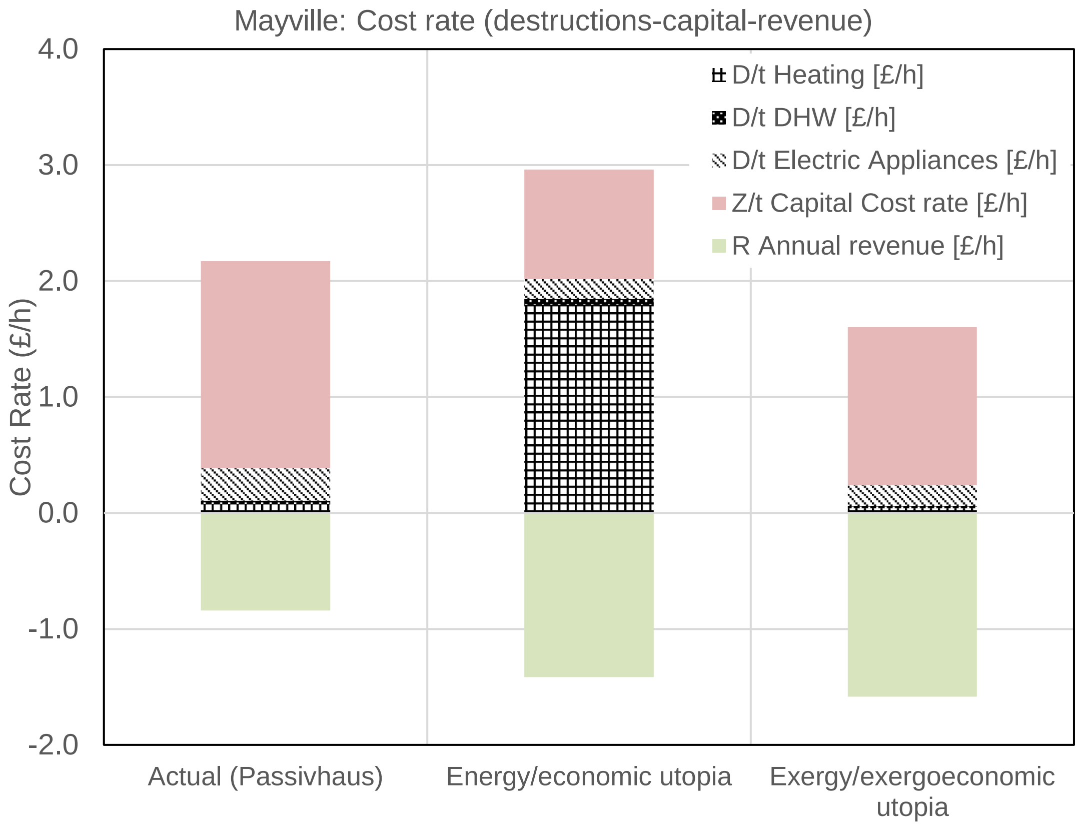


Figure 8-28 Exergy destruction, BER capital cost and annual revenue cost rates for the actual and optimised BER designs

Table 8-13 shows the main exergy and exergoeconomic values as well as the main non-thermodynamic outputs such as thermal comfort and carbon emissions. The energy/economic utopia BER design is able to reduce exergy demands to a minimum level of 26.6 kWh/m2-year; however, as the whole supply chain is analysed, it requires the largest share of primary exergy input (considering gas as primary energy source for electricity generation at the power plant) and thus it has the largest exergy destructions footprint.

Another important indicator is the exergoeconomic factor (f_k) which in this case shows the ratio of the BER design capital cost to the BER design 'total cost', composed of capital and exergy destruction costs. The exergoeconomic factors (f_k) are found at 0.82 for the Passivhaus, 0.32 for the energy/economic utopian BER, and 0.85 for the exergy/exergoeconomic utopian BER. When the value is close to one it means that the BER design capital cost is the main origin of expenditure, while if the value is close to zero it means that the exergy destruction costs are the main origin of expenditure. This index allows designers to choose between reducing the capital investment and/or increase the component exergy efficiency. In this case, both the Passivhaus and exergy/exergoeconomic design are able to reduce exergy destructions to minimum values, however it is the latter that achieves this outcome with three quarters of the budget required for the Passivhaus design. In addition, the design also presents the best indicators for carbon emissions and thermal comfort. Therefore, the exergy/exergoeconomic utopia design based on the biomass boiler and underfloor heating provides the best overall solution.

Table 8-13 Main exergy/exergoeconomic indicators for the actual and optimised BER designs (best performance in green)

Properties	Actual BER (Passivhaus)	Energy/ economic utopia BER	Exergy/ exergoeconomic utopia BER
Exergy demand (kWh/m^2-year)	30.0	26.6	27.9
Exergy input (kWh/m^2-year)	166.8	225.4	139.3
Exergy destructions (kWh/m^2-year)	136.8	198.8	111.4
Exergy efficiency (whole building)	0.180	0.117	0.200
Exergy price fuel-prod HEAT (£/kWh) (r_k)	0.12->0.26 (1.14)	0.12->3.60 (30.81)	0.4->0.19 (3.72)
Exergy price fuel-prod DHW (£/kWh) (r_k)	0.12->1.90 (14.82)	0.12->1.57 (12.06)	0.04->0.61 (14.20)
Exergy price fuel-prod Elec (£/kWh) (r_k)	0.12->0.24 (0.97)	0.12->0.20 (0.65)	0.12->0.20 (0.64)
D cost destructions (£/h)	0.38	2.01	0.24
Capital investment (£)	417,028	220,404	318,235
Investment rate Z (£/h)	1.79	0.94	1.36
Annual revenue rate R (£/h)	0.84	1.41	1.58
Exec_CB (£/h)	1.33	1.55	0.02
Exergoeconomic factor f_k (-)	**0.82**	**0.32**	**0.85**
Carbon emissions (tCO_2)	38.6	29.7	14.1
Thermal discomfort (hours)	853	669	658

8.5 Discussion of findings

8.5.1 Assessing Passivhaus design under exergy and exergoeconomic analysis

An exergy and exergoeconomic analysis, through the utilisation of ExRET-Opt simulation tool, has been applied for the first time to a Passivhaus non-domestic retrofitted building (Mayville Community Centre). First, a comparison is made between the pre-retrofitted building and the actual Passivhaus BER design. To accomplish this, two calibrated building models, using actual monthly data, were created. The characteristics of ExRET-Opt have allowed to calculate the exact investment required for energy-related measures of the actual retrofit, as well as a detailed quantification of energy prices and income from government incentives, which has a significant effect on the cost optimality of projects.

According to the results, the Passivhaus design, apart from reducing annual energy use by 75.6%, increasing thermal comfort by 28.8%, and reducing carbon emissions to 64.5%, seemed to provide a building with improved thermodynamic performance by reducing primary exergy input by 56.4%, exergy destructions by 60.4%, and increasing building exergy efficiency from 0.098 to 0.180. This was accomplished by a design based on a GSHP connected to medium temperature radiators and supported by a 90% efficient MVHR system. The re-utilisation of low-grade warm air is one of the most thermodynamically efficient building energy solutions, unless the required electricity (exergy) to move the MVHR fans is greater than the exergy cost of the recovered energy. These outcomes do not present a novelty since similar research has been carried out in the past (Meggers et al., 2012); however, the application of exergoeconomics with the support of LCCA have given new interesting outcomes.

The tool has calculated a required investment for the Passivhaus BER of £417,028. Nevertheless, passive technologies only account for 41% of the project's capital investment, while the PV/T panels, comprised by 18 kWp of PV and 3 m2 of solar collectors, represents 37% of the total investment. Typical economic indexes, consisting of 50-year period (which already can be considered long and impractical for BER practice) LCC, NPV and DPB, demonstrated that the Passivhaus design is not cost-effective under the current market conditions (energy and technology price) and government incentives. The LCCA estimates an overall turnover of £471,403, resulting in a DPB of 137.2 years. Therefore, It can be inferred that designers considered energy savings, aesthetics, and thermal comfort as main drivers, rather than the retrofit economics alone.

Furthermore, the application of exergoeconomic analysis has demonstrated the poor overall performance of the actual design. Exergoeconomically the building presented a non-ideal performance. The BER high capital costs, especially needed for measures such as thick insulation levels and the 118 m^2 of PV panels have hurt the design significantly (in economic terms). On one hand, the product cost formation shows a minimisation in final product prices for heating (from 0.74 to 0.25 £/kWh) and electricity end-use (from 0.27 to 0.24 £/kWh), and an increment in domestic hot water (from 0.44 to 1.90 £/kWh). In addition, high rates of exergy destruction were still found at the electric equipment subsystems.

The total pre-retrofit exergy destruction cost rate ($\dot{C}_{D,sys}$), which represent the benchmark value to be improved by a BER was found at £1.54/h. The results from the Passivhaus BER shows that the design was able to reduce it to £0.38/h. However, the BER design presented a capital cost rate ($\dot{Z}_{sys}$) of £1.78/h combined with a low revenue rate (R) of £0.84/h. Therefore, the exergoeconomic cost-benefit indicator ($Exec_{CB}$) is found at £1.33/h, slightly lower than the baseline case ($Exec_{CB,baseline} = \dot{C}_{D,sys}$) of £1.54/h. Therefore, it can be said that the design did not achieve an acceptable exergoeconomic performance and is far from the optimum solution. To lower the exergoeconomic cost-benefit index, a design needs lower capital investment cost, lower exergy destructions, and higher revenue rates. However, the improvement potential can only be discovered by analysing more BER designs.

8.5.2 The strengths of applying an exergoeconomic-oriented optimisation for deeper decarbonisation of BER designs

As a result of the poor thermoeconomic performance of the Passivhaus design, ExRET-Opt optimisation capabilities were required for a large search space analysis. Notwithstanding, a simulation-based experiment was designed, where two different multi-objective optimisation approaches were applied for the simulation of ~10,000 models for each approach. The first, based on the First Law only, simultaneously optimised energy use and NPV. The second, based on the First and the Second Law, simultaneously optimised exergy destructions and the exergoeconomic cost-benefit index. Occupant thermal comfort was considered as a common objective function. The purpose was to assess the difference between the methods and calculate the performance among the main indicators, considering the same decision variables and constraints. In this case, constraints were selected from the actual Passivhaus BER performance, as maximum budget, maximum discomfort hours, and minimum payback period were set for both optimisation procedures.

Similar to previous chapter's findings, a strict budget constraint yielded solutions based on high exergy primary HVAC systems. However, both approaches drove BER designs towards other efficient active measures and suggesting U_{values} not as strict as Part L or Passivhaus requirements, finding solutions considered optimal under the set conditions.

Considering the practical limitations that ExRET-Opt might present, initial results suggest that both approaches are related, the inclusion of exergy/exergoeconomics as objective functions into the optimisation procedure has resulted in buildings with better overall performance. This is demonstrated in Section 8.3.2.1, where a statistical analysis on the constrained search space solutions was conducted. Although as expected, results show that each approach obtains better performance in their related indicators (e.g. energy/economic approach on energy use and NPV, while exergy/exergoeconomic approach on exergy destructions and exergoeconomic indexes), the independent t-test outputs (Table 8-9) show that the exergy/exergoeconomic approach had similar First Law and thermal comfort outputs, while providing solutions with less environmental impact under similar capital investments (Figure 8-29). This result suggests that Second Law indicators could be used to deliver more energy-efficient and cost-efficient designs as it has the capability to locate exact sources of inefficiency, while reducing carbon emission and exergy destructions footprints.

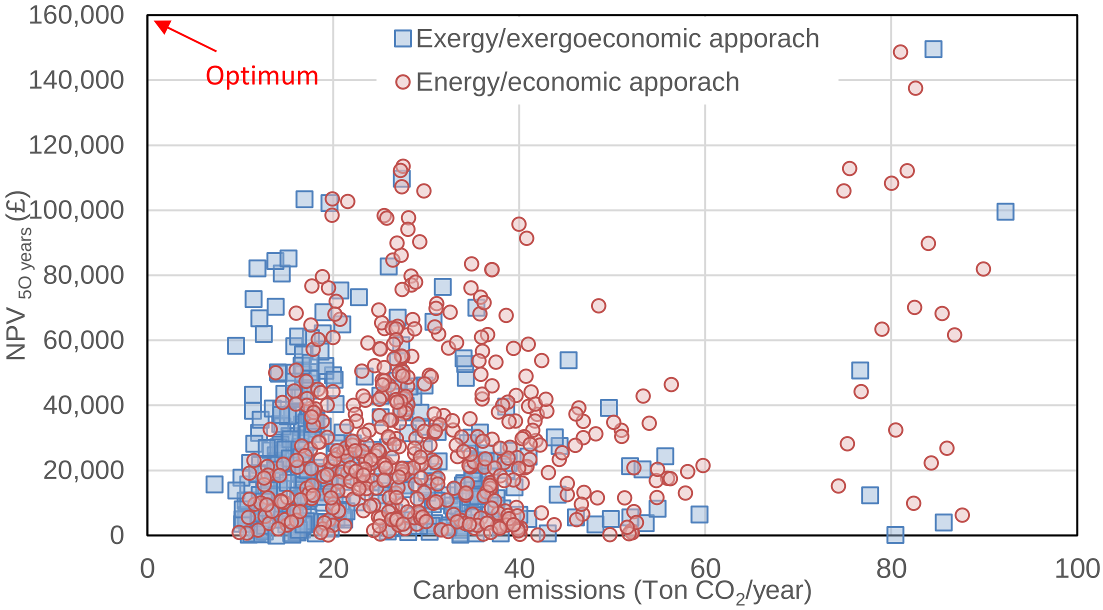


Figure 8-29 A comparison of carbon emission and NPV results among optimisation approaches

8.5.3 Comparison of actual retrofit design against optimised (utopian) models

Finally, the MCDM module was applied to the Pareto solutions to obtain single solutions for further detailed analysis comparison. The final models were selected by weighting objective functions with the same value (p=0.33). These models represent the closest to utopia point. The energy/economic utopia model is based on a GSHP connected to an underfloor heating system, while the exergy/exergoeconomic utopia model is based on a biomass boiler also connected to an underfloor heating system. However, it is the Second Law model that had more investments in passive systems such as insulation and multi-pane glazing systems. Nevertheless, if both optimised models are compared to the actual Passivhaus BER, these have lower investment in thermal insulation as well as PV panels, thus considerably reducing the initial budget of £417,028. Even with least investment, both utopian models improved most energetic and exergetic indicators; however, the exergy/exergoeconomic utopian model had better overall performance, achieving larger reductions in exergy destruction and carbon emission footprints in a cost-effective way.

Results show that the GSHP (energy/economic model) did not perform well under the analysed London weather conditions, obtaining a simulated average COP of 2.5. Overall, although heat pumps present better thermodynamic performance than condensing boilers, for the heat pumps to be beneficial in the UK context, there is a minimum COP value of 2.55 that is required (considering the actual grid electricity emission factor). In addition, the model considers that the in-site renewable electricity is first directed to electrical equipment (lighting, computers, etc.); therefore, for this specific model, all the electricity required for the GSHP came from the national grid. On one hand this has resulted in high irreversibilities in the primary transformation and generation processes, due to inefficiencies in power generation and the necessity of using this electricity to power GSHP's compressors. On the other hand, the exergy/exergoeconomic utopia BER delivered a design based on a biomass boiler, which in fact is considered as a less exergy-efficient system due to the boiler's combustion process. However, as the renewability factor for biomass is also considered, actual exergy destructions were not as high as for a 2.5 COP GSHP connected to the grid.

In terms of the heating emission system, the optimised models did not consider the installation of the MVHR and instead changed the actual radiator-MVHR system for an underfloor system. As the choice of the terminal unit has a direct and significant effect on the thermal comfort of the occupants, the underfloor system improved conditions by 22% compared to the actual design. Also, since the underfloor system requires less auxiliary energy (pumps and fans) and the fact that the heat exchanging process is done with a relatively small ΔT, optimised models preferred these designs as they have the lowest exergy destruction rates.

In an ideal thermodynamic situation, the BER system design would be based on either a high efficiency low-temperature lift GSHP or on a waste-heat or low-carbon-based district system networks connected to low temperature emission systems. This designs would be combined with medium levels of envelope's thermal insulation and infiltration rates. However, as the conducted optimisation procedure was highly constrained in terms of capital investment, combined with current energy prices for electricity and district heating[§§§§] and high technology costs, deprived the optimisation model from suggesting more efficient low exergy designs.

As discussed in the previous chapter, the optimisation process may not capture the realism of issues regarding the occupants thermal comfort and the actual building thermodynamic performance. While some practical limitations have already been discussed in the previous chapter, new limitations, such as the model's issues with the heat pump's COP calculation, which could have a major effect in the selection of a system during the optimisation process, have been discovered. Additionally, the model might fail to fully capture the thermal performance of large areas' emission systems (e.g. wall heating). Finally, the model also fails to account for the higher maintenance levels of complex energy systems, which in turn could have a considerable impact on the buildings life cycle cost. Therefore, additional modelling will be required to cover these limitations

As final remarks, it is suggested that BER designs have to come from a more holistic analysis. Exergy and exergoeconomic analysis has demonstrated to provide designs with an appropriate balance between the active and passive measures. It also provides a consistent accounting for irreversibilities and its costs along every subsystem in the building's energy system. Meanwhile, the application of the exergoeconomic cost-benefit index was able to provide more consistent outputs among a large variety of indicators. This index could be a practical solution as it supports building designers in making informed and robust economic decisions. In this regard, the use of exergoeconomics is necessary for the development of incentives and taxes based on exergy destruction footprints. Such policies could help highly thermodynamically efficient BER designs to become more available.

[§§§§] Nevertheless, District Heating (DH) could be a valuable techno-economic option for an individual building in the case of of an existing DH system in the vicinity, as capital cost can be dramatically reduced.

Chapter 9 Conclusions

9.1 Overview and main findings

Building energy retrofit (BER) is a strategy that has been shown to significantly reduce sectoral emissions. The recast of the EPBD highlights the importance of improving existing buildings under energy-efficient and cost-optimal solutions. However, selecting BER measures that are able to deliver high energy efficiency combined with low capital cost and high return of investment is still a challenge. High technological cost, market barriers, current taxation and incentives, and lack of appropriate calculation methods and tools have been just some of the reasons hampering the sector's improvement potential. Therefore, there is a pressing need to rethink the way in which buildings are designed and refurbished.

Among the different existing approaches to improve energy use in existing buildings, exergy analysis, which has until now mainly remained within the realms of academic research and the power generation and industrial processes, has through the preliminary insights generated through this study been shown to provide a powerful method for improving building's energy efficiency. Although studies have shown the applicability of the exergy concept in buildings, demonstrating it to be probably the most rational basis for evaluation, exergoeconomics has been considered on a limited basis. An extensive literature review has shown that no practical link exists between the buildings' energy design optimisation with exergy/exergoeconomic analysis and optimisation, where only recommendations for its implementation are regarded.

For the aforementioned reason, the main aim of this research has been to develop a systematic methodological framework, integrating a comprehensive and holistic exergy/exergoeconomic analysis into building energy design optimisation, with a specific focus on BER designs. In this sense, the term holistic refers to an analysis method that encompasses for the majority of energy end-uses products encountered in building energy systems (heating, cooling, DHW, and electric-based equipment). To achieve this, several exergy methodologies focusing on thermal systems, electric systems, and renewable generation systems have been combined. This has resulted in the abstraction of the building's energy system conformed by thirteen energy streams and eleven subsystems. Additionally, an exergoeconomic analysis framework was developed, capable of assessing each component and stream. The exergoeconomic analysis has been merged with Life Cycle Cost Analysis (LCCA) method, thus allowing the use of exergy and cost accounting in the evaluation of retrofit designs. In order for exergoeconomics to be applicable for BER design, a novel levelised exergoeconomic indicator was presented, called the exergoeconomic cost-benefit indicator ($Exec_{CB}$), which considers the economics of energy use, exergy destructions, and capital investments. This indicator appears promising, as it presents a new methodology to measure economic/exergoeconomic coherence of BER designs. Additionally, it may be used to evaluate how far a specific BER design is far from an exergoeconomic optimum, stating the level of exergy destruction cost and capital cost ratio of a given design.

The proposed retrofit-oriented framework suggests the integration of exergy/exergoeconomic analysis at three levels in the BER design process, starting from the i) diagnosis and auditing of the current building, ii) the evaluation of retrofit solutions, and iii) the optimisation and ranking of the best solutions. To provide a tool that potentially could be used by practitioners and researchers, this research sought to apply the exergy/exergoeconomics framework into a typical dynamic simulation tool, as it seems to be a promising approach to introduce the Second Law into building energy practice. Therefore, the framework was coded as an add-on into a widely-used dynamic building energy simulation tool. One of the novelties of this research was to consider dynamic exergy equations into the analysis. Dynamic physics-based modelling can give more meaningful results than steady-state models, as the former not only considers transient reference temperatures (essential for dynamic exergy analysis), but also provides less uncertainties as future changes in environmental factors and technologies can be assessed. Although the dynamic exergy analysis method could be more time consuming than steady-state methods, the adoption of dynamic calculation is important if the cooling season is considered and when climates are not that extreme that building works closer to the reference environment. When building internal environment operates close to the reference temperature, exergy outputs are more sensitive.

The proposed simulation tool, called ExRET-Opt, is based on EnergyPlus (building energy performance tool) combined with jEPlus (parametric analysis and optimisation) and Python subroutines (exergy/exergoeconomic analysis). ExRET-Opt, apart from providing the user with energy and exergy data and pinpointing sources of inefficiencies along the energy supply chain, also gives the possibility to perform a comprehensive exploration of a wide range state-of-the-art building energy technologies, with the intention to minimise energy use and improve thermodynamic efficiency of the existing buildings. As the tool was oriented to tackle retrofit project specifically, a comprehensive BER database considering a wide range of technologies and their prices was built. The retrofit technologies include low and high-exergy HVAC systems, envelope insulation technologies, glazing systems, efficient lighting systems, and energy renewable generation technologies.

Additionally, ExRET-Opt included a multi-objective optimisation (MOO) and multi-criteria decision making (MCDM) module. This has allowed to deliver a novel automated tool capable to perform thermodynamic/exergoeconomic optimisation, an area that was limited mainly to process and power generation simulation. Moreover, the tool's flexibility allows the modeller to optimise any objective function, where indicators related to energy, exergy, economic (capital cost, NPV), occupants' thermal comfort, and carbon emissions can also be used as objective functions or constraints. Therefore, the tool can be differentiated by five detailed modules: 1) input data and baseline modelling, 2) model calibration, 3) energy/exergy and exergoeconomic 4) retrofit scenarios, and 5) optimisation and decision making.

The methodology and materials presented in this research provides an improvement in the traditional process by supporting modellers and decision makers with a framework/tool, aiming at designing thermodynamically-efficient buildings solutions under real economic constraints. The application of the tool has been demonstrated along three chapters which have resulted in findings discussed in the following sections.

9.1.1 Exergy and exergoeconomic evaluation of typical UK non-domestic buildings

Using what can be considered typical UK non-domestic building models as case studies (a Primary School and an A/C Office), a comprehensive energy, exergy and exergoeconomic performance evaluation was conducted as a first test of the framework and tool. The obtained exergy/exergoeconomic benchmark values represent novel outputs that can be regarded as representative of the UK non-domestic sector.

By accounting for exergy destructions and its costs, it has resulted in the calculation of the product cost formation. These outputs help to understand how the energy price for a specific product increases throughout the energy supply chain until it reaches the demand side. This cost formation analysis locates exact location where the energy stream price increases due to high exergy destructions and/or high capital investments. In this regard, where the building has not been through a refurbishment process, the increase generally comes from high rates of exergy destructions.

Thanks to the calculation of the products' cost formation and the building's exergy destruction cost, the novel exergoeconomic cost-benefit indicator $Exec_{CB}$, developed in this research for the comparison of retrofit measures, was presented. When it comes to the base case building (pre-retrofit), the exergoeconomic cost-benefit index is represented by the building's exergy destructions cost rate only ($Exec_{CB,baseline}$= $\dot{C}_{D,sys}$), as no capital investment and therefore no retrofit revenue exists. This value can be regarded as a real economic efficiency indicator of a building.

9.1.2 Effect of different reference environments on exergoeconomic indicators

Considering the same archetype building energy models, a sensitivity analysis of the reference temperature was carried out by modelling different climatic regions within the UK's context, showing the impact of changing the reference temperature on the exergoeconomic results. Regardless of the outcomes of the sensitivity analysis, the importance of the reference temperature on exergoeconomic indicators was highlighted, concluding that robust weather data is necessary to reduce uncertainty in the design outputs. This is especially important for exergy analysis, which is highly dependent on the reference environment.

9.1.3 Parametric analysis of active and passive BER measures on energy, exergy and exergoeconomic indices

A parametric study was carried out to explore a wide range of active and passive BER technologies applied to both archetype buildings. On one hand, results obtained for the specific case studies showed that active components, such as efficient HVAC systems based on GSHP and district systems, connected to low temperature emissions systems, have the best exergy performance if applied correctly; therefore, are more likely to improve overall thermodynamic performance. This shows that electricity, a high-exergy source, needs to be used correctly, considering a supply-demand quality match in the design. Using electricity for space conditioning is a practice that should be avoided and heavily penalised by appropriate taxation. However, if the energy supply context does not allow any other options, renewable generated electricity should be highly promoted. On the other hand, non-HVAC solutions *(insulation, glazing, sealing, set-points control, lighting and renewable systems)* did not achieve any significant system exergy efficiency improvement; however, outputs demonstrated that some have high potential to reduce building's total exergy destructions footprint by lowering the building's energy demand. Some insulation technologies, air-infiltration control measures, and electric-based equipment improvement were found to provide the best exergy/exergoeconomic outputs.

In typical practice, it is believed that buildings with better performance are those that tend to have a good passive design and a tighter envelope. But the obtained results showed that active components could have better energy, economic, exergy, and exergoeconomic performance, and are therefore more likely to improve overall thermodynamic performance. For this reason, before any major passive refurbishment is undertaken, findings suggest that active and passive measures should be co-optimised.

9.1.4 Developing deep-BER measures with exergy and exergoeconomic indicators

After gathering the outputs from the parametric active and passive BER measures assessment and under an engineering judgement, the novel exergoeconomic cost-benefit index combined with NPV, energy use, exergy efficiency, thermal comfort and carbon emissions, were used to design deep energy/exergy retrofits. Overall, the proposed exergoeconomic cost-benefit indicator presented a good correlation with typical economic indicators, suggesting that the former could also be reliable for decision making. Results showed that final product costs for heating and cooling were notably reduced together with exergy destruction costs.

Nevertheless, to achieve high thermodynamic performances, high capital investments were required, demonstrating that low exergy designs are still expensive in the current market conditions. The proposed deep-BER scenarios failed to provide good economic outcomes, as payback periods were outside the time frame analysis. In this sense, exergy based taxation and incentives could help unlock unconventional technologies and provide more flexibility in the design process, where high performance buildings, combined with low exergy supply structures, are key for a future sustainable development of the building sector

9.1.5 Optimisation of building irreversibilities and economic performance by applying exergy-based MOO-MCDM procedures

Since the engineering judgement of deep energy/exergy retrofit design failed to provide cost-efficient solutions, the ExRET-Opt multi-objective optimisation capabilities, based on genetic algorithms, were used. This research sought to tackle the challenge of obtaining exergy-efficient and cost-optimal solutions under heavily constrained conditions by applying to the optimisation process a series of economic (capital investment) and thermodynamic constraints with the intention to obtain major improvements in the payback periods (>50 years).

The results showed that even with the imposed constraints, the NSGA-II-based MOO module was successfully applied, finding a large range of better performance BER designs for the two particular analysed cases. However, a tight budget means missing out on some low-exergy systems, which require higher capital investment, such as district heating/cooling systems and ground source heat pumps.

However, the strengths of MOO cannot be demonstrated without the inclusion of a decision support tool. For this reason, a MCDM submodule based on compromise programming and Tchebyshev distance was necessary in order to locate a single solution, given that the preferences of the decision maker were included. For further analysis of single solutions and comparison with the previous models, the closest to the utopian solutions were chosen. This solution represents the model closest to the optimal objectives, if they were optimised separately. These final selected solutions improved overall building's energy performance, exergy efficiency and buildings' life cycle cost while having lower initial capital investments.

9.1.6 Thermodynamic analysis of Passivhaus design

The last case study in this research was based on an actual, recently retrofitted Passivhaus building (Mayville Community Centre). For the first time, an exergy and exergoeconomic analysis was performed for a Passivhaus building with the aim to analyse its performance under First and Second Law values simultaneously. In terms of exergy, the Passivhaus approach seemed to provide a building with improved thermodynamic performance by reducing primary exergy input and exergy destructions. However, exergoeconomically the retrofitted building presented a non-ideal performance as the trade-off between exergy destruction costs, capital cost and revenue rate did not compensate the pre-retrofit exergy destruction cost levels.

Outputs suggest that the Passivhaus approach, while it seems to prove good energy/exergy indicators, is not an economically-attractive solution. In this sense, the Passivhaus approach may well be a tempting individual solution due to its exceptional energy performance, but it is not a systemic solution that would effectively improve the building sector's thermodynamic performance in a cost-effective way.

9.1.7 Comparing energy/economic-based optimisation against an exergoeconomic-based optimisation for BER designs

Finally, using the Passivhaus building as a case study, the strengths of using a full exergy/exergoeconomic-based (first and second law analysis) optimisation against a typical energy/economic approach (first law analysis only) were demonstrated. Nevertheless, both approaches had a common third objective function: occupant thermal comfort.

Although initial results suggested that both approaches are related, the inclusion of exergy/exergoeconomic indices as objective functions into the optimisation procedure resulted in buildings with better overall performance. Outputs demonstrated that even under tight budget constraints, it was possible to double the thermodynamic efficiency. These results suggest that Second Law indicators, as they have the capability to locate exact sources of inefficiency, could be used more effectively as objective functions and constraints in optimisation procedures, delivering more energy/exergy-efficient and cost-efficient BER designs while delivering high levels of thermal comfort. This was demonstrated with a statistical analysis on the constrained search space solutions. An independent t-test, analysing the two samples under thirteen main outputs, showed that the exergy/exergoeconomic approach had similar energy and thermal comfort outputs, while providing solutions with less environmental impact (lower CO_2 emissions) under similar capital investments. It should be noted that these results cannot be taken as definitive, as the study design only considered a single case study and just one optimisation run.

9.1.8 Suggestions to industry and policy makers

It is suggested that BER designs should result from a more holistic analysis. Exergy and exergoeconomics could have an important future role in the building industry if some practical barriers were overcome. The proposed methodological framework can provide more information than the typical optimisation methods based solely on energy analysis, and should be pursued in everyday BER practice. The framework developed in this research has demonstrated to provide designs with an appropriate balance between active and passive measures, while consistently accounting for energy use, irreversibilities, and exergetic and economic costs along every subsystem in the building energy system. Meanwhile, the application of the exergoeconomic cost-benefit index was able to provide more consistent outputs among a large variety of indicators. This index could be a practical solution as it supports building designers in making informed and robust economic decisions.

Outputs have also demonstrated that even hybrid approaches, such as optimising exergy and NPV (Chapter 7), were able to drastically improve energy and exergy performance, reduce carbon and exergy destructions footprints, while also providing comfortable conditions under cost-effective solutions. As shown in Chapter 8, the improvement of exergy/exergoeconomics gives a good correlation to CO_2 emissions reduction, locating a relationship between carbon footprint reduction and exergy destructions footprint reductions. Therefore, in practice, a decision maker does not have to depend on primary factors that have the limitation of being dynamic through time. This gives practitioners more flexibility in the design process.

In this regard, it is also recommended to use exergy and exergoeconomics for the development of policies, incentives, and taxes based on exergy destruction footprints. Minimising exergy destructions at a national level provides greater energy security for the country as high quality sources can be used more efficiently in sectors with high exergy demand, such as the industrial and the transport sector. Extended research has shown that by following an energy/exergy-oriented approach, by 2050 the UK non-domestic sector has a potential to reduce sectoral energy demand by 81%, exergy destructions by almost 30%, while achieving reductions in carbon emissions up to 88%. If typical energy (First Law only) oriented analysis is followed, the carbon emission abatement potential is reduced to just 50%.

The introduction of an exergy-based tax may provide a valid measure to improve energy systems in buildings, where it can be used as a tool to identify and 'penalise' inefficient systems with high exergy destructions. Such policies could help highly thermodynamically-efficient or low-exergy BER designs to become more available.

9.2 Contribution to knowledge

In achieving the main research aim and objectives, this research has made the following original contributions to knowledge:

- Identification of main reasons for limited exergy and exergoeconomic theory implementation into building energy design. Additionally, a discussion of the main strengths and limitations of including a holistic exergy/exergoeconomic analysis into life cycle cost evaluation for buildings' energy retrofit design was provided.

- The previous point has led to the development of a systematic exergy/exergoeconomic-based methodological framework specifically adapted to buildings' energy retrofit design. A new exergoeconomic cost-benefit indicator that considers the project's life cycle exergy destruction cost, capital cost, and annual revenue was formulated. The index can provide a wider performance comparison among BER designs.

- To support the methodological framework, ExRET-Opt, which integrates dynamic exergy calculations as well as exergoeconomic analysis into a typical building energy simulation tool (EnergyPlus), has been developed. Additionally, a comprehensive retrofit-oriented module, as well as a multi-objective and a multi-criteria decision making modules were integrated within the tool.

- Provision of exergy and exergoeconomic benchmark performance for two UK non-domestic archetype buildings (an office and a primary school) as well as a 'Passivhaus' retrofitted building (a community centre). Additionally, an exergy/exergoeconomic assessment of a wide range of active and passive BER technologies and identification of best performance technologies under different indices was investigated.

- Increased knowledge on the impact of an exergoeconomic-based multi-objective optimisation and multi-criteria decision making (MOO-MCDM) study, applied to buildings energy design, considering a large search space solution. This provided new insights into the effects of different conflicting objective functions such as energy use, exergy destructions, occupant thermal comfort, exergoeconomic cost-benefit, and life cycle costs.

- Finally, a comparison of an energy/economic-based optimisation against an exergy/exergoeconomics-based optimisation applied to buildings' energy design was presented, locating strengths and limitations of each approach.

9.3 Limitations of study

This study has taken a step in the direction of making exergy/exergoeconomics more practical in the BER design. While the approaches adopted in this research advocated many advantages compared to typical methods, inevitably some limitations to the work exist. Apart from the common limitations of using modelling tools for BER assessment, the following are the most important limitations of this particular research:

- First, the exergy analysis used in this study presents some limitations. In this regard, only thermal exergy is considered neglecting the calculation of chemical and mechanical exergy. In addition, electric exergy analysis has to be expanded to provide a more detailed analysis of subsystems. Therefore, the calculated exergy efficiencies, exergy destructions, exergoeconomic cost-benefit index among others, are highly dependent on the utilised procedures, equations and formulas. Additionally, the exergy calculation methodology does not differentiate between avoidable and unavoidable exergy destructions as well as endogenous and exogenous irreversibilities. Therefore, outputs highlighting the improvement potential for a given system could be misleading by not showing these indicators. This has to be considered when interpreting the obtained results.

- There are several components such as boilers, CHP, PV/T panels, heat pumps, etc., that in this research are treated as black boxes for a simplified analysis. However, in reality a more detailed analysis can be applied locating exact inefficiencies and improvement potential at a subcomponent level.

- It is important to highlight the practical limitations of building simulation tools such as EnergyPlus and ExRET-Opt. The linking of different modules is only reliable to a certain extent. In this sense, the application of ExRET-Opt and the obtained outputs has shown several practical limitations. Given the model's complexity and interactivity among different simulation tools, the whole framework may not capture all the issues of occupant's thermal comfort, energy systems maintenance, and actual building energy and economic performance. For example, single pane glazing and high ventilation rates, which were frequent among optimal results, can lead to higher discomfort levels and maintenance issues, which in turn could lead to higher life cycle costs. Among active systems, wind turbines and PV panels might not perform well in urban environments due to several physical and infrastructure factors. Nevertheless, these limitations could be overcome if ExRET-Opt is expanded by developing more modules; however, this level of detail could affect model's complexity and computation time.

- The employed economic lifespan analysis used in this research (50 years) can be considered too long. Typically, insulation measures can have a lifespan of maximum 40 years while building services of around 20 years. In addition, technology cost, energy prices for district heating and biomass, and government incentives were considered static where in reality they are changing over time. These limitations can have significant impacts on the overall economic/exergoeconomic analysis.

- The model has not included neither Life Cycle Carbon Analysis (LCCA) nor Life Cycle Exergetic Analysis (LCExA). As large levels of embodied carbon and exergy can be found in building technologies (especially insulation materials), the model fails to provide an indicator showing whether the carbon or exergy saved from a given BER design offsets the embedded carbon or exergy of the BER measures.

- The MOO was limited to a single algorithm (NSGA-II), where other algorithms such as Particle Swarm Optimisation (PSO), Harmony Search (HS), Ant Colony Optimisation (ACO), Simulated Annealing (SA), among others, might provide different Pareto outputs. In addition, the MCDM was also limited to a single strategy based on Compromise Programming and Tchebyshev distance. Other methods such as Analytical Hierarchy Prices (AHP), Global Criterion (GC), Goal Programming (GP), Multi-Attribute Utility Theory (MUAT), among others, might provide different optimal final solutions.

9.4 Recommendations for Future Work

The research presented the addition of exergy/exergoeconomic into typical building energy optimisation practice. However, some future work is still needed to broaden the understanding of implementing exergy/exergoeconomics as a fundamental method in building energy design. In continuation, the following further research is suggested:

- Expansion of the presented exergy calculation methodology by a more robust exergy-entropy calculation. It is suggested to include the '*extended exergy method'*, accounting for avoidable, unavoidable, endogenous and exogenous irreversibilities, by adding the corresponding equations into ExRET-Opt.

- Development of a graphical user input interface (GUI) for ExRET-Opt as well as the expansion of the technological database to cover more retrofit technologies. It is also necessary to regularly update the economic module as market prices for technologies and energy carriers are in constant change.

- Further experiment testing of different settings for the provided NSGA-II optimisation algorithm. This will lead to an extensive research with the objective to locate the ideal settings for this particular type of problems.

- Expansion of MOO algorithms and MCDM methods that could be used by ExRET-Opt. Several MOO-MCDM combinations could be investigated (e.g. Particle Swarm Optimisation (PSO) combined with Multi-Attribute Utility Theory (MUAT)).

- Further investigation of the framework/tool implementation potential into building energy retrofit practice or its potential for the advocating of exergy-based outputs at a policy level. This could include a comprehensive sensitivity and uncertainty analysis of energy prices, technology cost, occupant behaviour, among others.

- Inclusion of Exergetic Life Cycle Analysis to understand the impact of the exergy destruction footprint on resource depletion. It is expected that passive measures, such as insulation, will have poor life cycle results as a large quantity of resources and high exergy demand is needed for manufacturing. Some research has investigated this issue (De Meester et al., 2009, Zhou and Gong, 2011) but further research is required where development of applied tools is needed for its practical application.

9.5 Dissemination Activities

The main contribution to knowledge and findings of this research have been discussed through the publication of peer-reviewed journal papers as well as peer-reviewed conference papers. Nevertheless, further publications based on the simulation tool details (Chapter 5) and the findings from the Passivhaus building case study (Chapter 8) are being prepared.

As the framework and tool seeks to contribute to typical practice, this has been tested among a first set of Masters' students, resulting in successful completion of their projects. However, further dissemination, training and teaching of the tool as well as the showcase of the outputs is set out as one of the major activities required, in order to bring the framework/tool to the level of the BER practitioner and a decision maker at a policy level.

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Appendices

Appendix A: A review of BER-oriented IEA-EBC Annexes

Table A - 1 IEA EBC Annex projects dedicated to the promotion of energy efficiency and energy renovation in non-domestic buildings

Annex	Status	Aims and description
Annex 15 **Energy Efficiency in Schools**	Completed (1988-1990)	• Develop a methodology for energy management in schools. • Produce recommendations on the use of energy management systems. • Develop case studies for passive solar and retrofit measures.
Annex 35 **Control Strategies for Hybrid Ventilation in New and Retrofitted Office Buildings (HYBVENT)**	Completed (1998-2002)	• Develop control strategies for hybrid ventilation systems for new build and retrofit of office and educational buildings. • Promote energy and cost-effective hybrid ventilation systems in office and educational buildings.
Annex 36 **Retrofitting in Educational Buildings - Energy Concept Adviser for Technical Retrofit Measures**	Completed (1999-2003)	• Develop simple prediction tools for retrofit concepts which allow the decision maker to evaluate integrated construction, installation and lighting measures. • Promote energy and cost efficient retrofit measures and to support the decision makers in evaluating the efficiency and acceptance of available concepts.
Annex 46 **Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo)**	Completed (2005-2010)	• Provide tools and guidelines for decision makers and energy managers, performance contractors and designers. • Improve the working environment of Government buildings through energy-efficient retrofitting projects.
Annex 55 **Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance & Cost (RAP-RETRO)**	Completed (2010-2015)	• Develop and validate probabilistic methods and tools for prediction of energy use, lifecycle cost and functional performance based on assessment of energy retrofitting measures. • Create guidelines for practitioners, including assessment of common retrofitting techniques.
Annex 56 **Cost-Effective Energy & CO2 Emissions Optimisation in Building Renovation**	Ongoing (2010-2016)	• Define a methodology for establishing cost optimised targets for energy consumption and CO2 emissions in building renovation. • Determine cost effective combinations of energy efficiency and renewable energy supply measures.
Annex 61 **Business and Technical Concepts for Deep Energy Retrofit of Public Buildings**	Ongoing (2012-2016)	• Provide a framework and selected tools to reduce energy use and improve indoor environment quality in government and public buildings undergoing renovation. • Develop and demonstrate innovative, highly resource-efficient business models for retrofitting buildings' systems using appropriate combinations of public and private funding such as ESPCs.

Appendix B: ExRET-Opt submodules characteristics

B.1 List of outputs required by ExRET-Opt from EnergyPlus

Table B - 1 Energy Plus variable outputs required by ExRET-Opt

Output:Variable	Site Outdoor Air Drybulb Temperature Hourly;
Output:Variable	Zone Mean Air Temperature Hourly;
Output:Variable	Zone Thermal Comfort ASHRAE 55 Simple Model Summer or Winter Clothes Not Comfortable Time Hourly;
Output:Variable	Zone Predicted Sensible Load to Setpoint Heat Transfer RateHourly;
Output:Variable	Facility Thermal Comfort ASHRAE 55 Simple Model Summer or Winter Clothes Not Comfortable Time Hourly;
Output:Variable	Facility Thermal Comfort ASHRAE 55 Simple Model Summer or Winter Clothes Not Comfortable Time Annual;
Output:Variable	Zone Infiltration Sensible Heat Loss Energy Hourly;
Output:Variable	Zone Infiltration Sensible Heat Gain Energy Hourly;
Output:Variable	System Node Temperature Hourly;
Output:Variable	Heating Coil Heating Energy Hourly;
Output:Variable	Heating Coil Air Heating Energy Hourly;
Output:Variable	Cooling Coil Sensible Cooling Energy Hourly;
Output:Variable	Cooling Coil Total Cooling Energy Hourly;
Output:Variable	System Node Mass Flow Rate Hourly;
Output:Variable	System Node Enthalpy Hourly;
Output:Variable	Boiler Inlet Temperature Hourly;
Output:Variable	Boiler Outlet Temperature Hourly;
Output:Variable	Water Heater Heating Energy Hourly;
Output:Variable	Water Heater Source Side Inlet Temperature Hourly;
Output:Variable	Water Heater Source Side Outlet Temperature Hourly;
Output:Variable	Water Heater Use Side Inlet Temperature Hourly;
Output:Variable	Water Heater Use Side Outlet Temperature Hourly;
Output:Variable	Water Heater Use Side Inlet Temperature Hourly;
Output:Variable	Water Use Equipment Cold Water Temperature Hourly;
Output:Variable	Water Heater Use Side Outlet Temperature Hourly;
Output:Variable	Zone VRF Air Terminal Total Cooling Energy Hourly;
Output:Variable	Zone VRF Air Terminal Total Heating Energy Hourly;
Output:Variable	Zone Air System Sensible Heating Energy Hourly;
Output:Variable	Zone Air System Sensible Cooling Energy Hourly;
Output:Variable	VRF Heat Pump COP Hourly;
Output:Variable	VRF Heat Pump Heating Electric Energy Hourly;
Output:Variable	VRF Heat Pump Condenser Inlet Temperature Hourly;
Output:Variable	VRF Heat Pump Condenser Outlet Temperature Hourly;
Output:Variable	Zone Radiant HVAC Heating Energy Hourly;
Output:Variable	Zone Radiant HVAC Cooling Energy Hourly;
Output:Variable	District Heating Inlet Temperature Hourly;
Output:Variable	District Heating Outlet Temperature Hourly;
Output:Variable	District Heating Mass Flow Rate Hourly;
Output:Variable	District Heating Hot Water Energy Hourly;
Output:Variable	District Cooling Chilled Water Energy Hourly;
Output:Variable	District Cooling Inlet Temperature Hourly;
Output:Variable	District Cooling Outlet Temperature Hourly;

Table B - 1 cont. Energy Plus variable outputs required by ExRET-Opt

Output:Variable	District Cooling Mass Flow Rate Hourly;
Output:Variable	Water to Water Heat Pump Electric Energy Hourly;
Output:Variable	Air System Total Heating Energy Hourly;
Output:Variable	Air System Total Cooling Energy Hourly;
Output:Variable	Cooling Coil Electric Energy Hourly;
Output:Variable	Heating Coil Electric Energy Hourly;
Output:Variable	Heat Exchanger Total Heating Energy Hourly;
Output:Variable	Heat Exchanger Total Cooling Energy Hourly;
Output:Variable	Baseboard Total Heating Energy Hourly;
Output:Variable	Zone Window Air Conditioner Total Cooling Energy Hourly;

Table B - 2 Energy Plus meter outputs required by ExRET-Opt

Output:Meter	Electricity:FacilityHourly;
Output:Meter	Electricity:FacilityAnnual;
Output:Meter	Gas:Facility Hourly;
Output:Meter	Gas:Facility Annual;
Output:Meter	FuelOil#1:Facility Hourly;
Output:Meter	OtherFuel1:Facility Hourly;
Output:Meter	DistrictHeating:Facility Hourly;
Output:Meter	DistrictCooling:Facility Hourly;
Output:Meter	InteriorLights:ElectricityHourly;
Output:Meter	InteriorEquipment:ElectricityHourly;
Output:Meter	InteriorEquipment:GasHourly;
Output:Meter	Fans:ElectricityHourly;
Output:Meter	ExteriorLights:Electricity Hourly;
Output:Meter	Gas:PlantHourly;
Output:Meter	Boiler:Heating:GasHourly;
Output:Meter	Boiler:Heating:Electricity Hourly;
Output:Meter	Pumps:ElectricityHourly;
Output:Meter	DistrictHeating:FacilityHourly;
Output:Meter	Catering:InteriorEquipment:Electricity Hourly;
Output:Meter	Cooling:Electricity Hourly;
Output:Meter	Cooling:DistrictCooling Hourly;
Output:Meter	Electricity:Plant Hourly;
Output:Meter	Electricity:HVAC Hourly;
Output:Meter	General:InteriorEquipment:Electricity Hourly;
Output:Meter	HeatRejection:Electricity Hourly;
Output:Meter	Catering:InteriorEquipment:Electricity Hourly;
Output:Meter	Heating:Gas Hourly;
Output:Meter	Heating:Electricity Hourly;
Output:Meter	Heating:FuelOil#1 Hourly;
Output:Meter	Heating:OtherFuel1 Hourly;
Output:Meter	Heating:DistrictHeating Hourly;
Output:Meter	Water Heater:WaterSystems:Gas Hourly;
Output:Meter	Water Heater:WaterSystems:FuelOil#1 Hourly;
Output:Meter	Water Heater:WaterSystems:Electricity Hourly;
Output:Meter	Water Heater:WaterSystems:OtherFuel1 Hourly;
Output:Meter	Water Heater:WaterSystems:DistrictHeating Hourly;
Output:Meter	Cogeneration:ElectricityPurchased Hourly;
Output:Meter	Cogeneration:ElectricitySurplusSold Hourly;
Output:Meter	Cogeneration:ElectricityNet Hourly;
Output:Meter	Cogeneration:ElectricityProduced Hourly;
Output:Meter	Cogeneration:Gas Hourly;
Output:Meter	WaterSystems:Gas Hourly;
Output:Meter	HeatRecovery:Electricity Hourly;

B.2 Extraction file within ExRET-Opt

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Figure B - 1 RVX extraction file commands to connect ExRET-Opt with EnergyPlus and jEPlus

```
    "scripts" : [
        {
            "fileName" : "SUBROUTINE:dynamicexergy.py",
            "pythonVersion" : "python2",
            "onEachJob" : true,
            "arguments" : "Outputs",
            "tableName" : "a_Exergy_Calculations_TOTAL"
        },
        {
            "fileName" : "SUBROUTINE:exergoeconomics.py",
            "pythonVersion" : "python2",
            "onEachJob" : true,
            "arguments" : "Outputs",
            "tableName" : "a_Exergoeconomics_Calculations_TOTAL"
        }
    ],

    "userVars" : [
        {
            "identifier" : "vc1",
            "formula" : "c2*.765",
            "caption" : "Source Energy [kWh/m2]",
            "report" : true
        },

        {
            "identifier" : "vc2",
            "formula" : "c4*.765",
            "caption" : "Total Site Energy [kWh/m2]",
            "report" : true
        },
        {
            "identifier" : "vc3",
            "formula" : "c3*.765",
            "caption" : "Net Site Energy [kWh/m2]",
            "report" : true
        },
        {
            "identifier" : "vc4",
            "formula" : "c5*.765",
            "caption" : "Electricity EUI [kWh/m2]",
            "report" : true
        },
        {
            "identifier" : "vc5",
            "formula" : "c6*.765",
            "caption" : "Gas EUI [kWh/m2]",
            "report" : true
```

Figure B - 1 cont. RVX extraction file commands to connect ExRET-Opt with EnergyPlus and **jEPlus**

```
    "constraints" : [
        {
            "identifier" : "s1",
            "formula" : "v26",
            "caption" : "Total Cost RETROFIT [£]",
            "scaling" : true,
            "lb" : 0,
            "ub" : 3000000,
            "min" : 0,
            "max" : 3,
            "weight" : 1.0
        },
        {
            "identifier" : "s2",
            "formula" : "v27",
            "caption" : "SimplePB",
            "scaling" : true,
            "lb" : 0,
            "ub" : 200,
            "min" : 0,
            "max" : 200,
            "weight" : 1.0
        },
        {
            "identifier" : "s3",
            "formula" : "c_x2",
            "caption" : "Expanded Thermoeconomic indicator",
            "scaling" : true,
            "lb" : -10,
            "ub" : 30,
            "min" : -10,
            "max" : 30,
            "weight" : 1.0
        }
    ],

    "objectives" : [
        {
            "identifier" : "t1",
            "formula" : "c4*0.765",
            "caption" : "EUI (total)[kWh/m2]",
            "scaling" : false,
            "min" : 0,
            "max" : 1500,
            "weight" : 1.0
        },
        {
            "identifier" : "t2",
            "formula" : "v37",
            "caption" : "Discomfort PMV [Hr]",
            "scaling" : false,
            "min" : 0,
            "max" : 3000,
            "weight" : 1.0
        },
        {
            "identifier" : "t3",
            "formula" : "-v29",
            "caption" : "NPV [£]",
            "scaling" : false,
            "min" : -10000000,
            "max" : 10000000,
            "weight" : 1.0
        }
```

Figure B- 1 cont. RVX extraction file commands to connect ExRET-Opt with EnergyPlus and jEPlus

B.3 ExRET-Opt Outputs

Table B - 3 List of outputs provided by ExRET-Opt

Output id	Type	Output	Output id	Type	Output
1	Energy (1st Law)	Source Energy (kWh/m2)	28	Energy (1st Law)	Refrigeration: Electricity (kWh)
2	Energy (1st Law)	Total Site Energy (kWh/m2)	29	Energy (1st Law)	GENERATION: Electricity (kWh)
3	Energy (1st Law)	Net Site Energy (kWh/m2)	30	Energy (1st Law)	GENERATION: Gas (kWh)
4	Energy (1st Law)	Electricity EUI (kWh/m2)	31	Energy (1st Law)	GENERATION: Oil or Biomass (kWh)
5	Energy (1st Law)	Gas EUI (kWh/m2)	32	Energy (1st Law)	PV GENERATION: Electricity (kWh)
6	Energy (1st Law)	Oil or Biomass EUI (kWh/m2)	33	Energy (1st Law)	Wind GENERATION: Electricity (kWh)
7	Energy (1st Law)	District Heating EUI (kWh/m2)	34	Energy (1st Law)	Storage: Electricity (kWh)
8	Energy (1st Law)	District Cooling EUI (kWh/m2)	35	Energy (1st Law)	From Utility: Electricity (kWh)
9	Energy (1st Law)	Heating: Electricity (kWh)	36	Energy (1st Law)	To Utility: Electricity (kWh)
10	Energy (1st Law)	Heating: Gas (kWh)	37	Energy (1st Law)	Net Utility: Electricity (kWh)
11	Energy (1st Law)	Heating: Oil or Biomass (kWh)	38	Energy (1st Law)	Solar Thermal: Hot Water Produced (kWh)
12	Energy (1st Law)	Heating: District (kWh)	39	Energy (1st Law)	Solar Thermal: Hot Air Produced (kWh)
13	Energy (1st Law)	Cooling: Elec (kWh)	40	Energy (1st Law)	Heat Recovery: Water (kWh)
14	Energy (1st Law)	Cooling: Gas (kWh)	41	Energy (1st Law)	Heat Recovery: Air (Heating) [kWh]
15	Energy (1st Law)	Cooling: District (kWh)	42	Energy (1st Law)	Heat Recovery: Air (Cooling) [kWh]
16	Energy (1st Law)	Light Interior: Electricity (kWh)	43	Economic	Energy Cost: Total Electricity [£]
17	Energy (1st Law)	Light Exterior: Electricity (kWh)	44	Economic	Energy Cost: Grid Electricity [£]
18	Energy (1st Law)	Int. Equipment: Electricity (kWh)	45	Economic	Energy Cost: Sold Electricity to Grid [£]
19	Energy (1st Law)	Catering: Electricity (kWh)	46	Economic	Energy Cost: Gas [£]
20	Energy (1st Law)	Fans: Electricity (kWh)	47	Economic	Energy Cost: Oil or Biomass [£]
21	Energy (1st Law)	Pumps: Electricity (kWh)	48	Economic	Energy Cost: District or Biomass or other [£]
22	Energy (1st Law)	Heat Rejection: Electricity (kWh)	49	Economic	RHI Energy Cost Income: PVT Air Thermal Generation [£]
23	Energy (1st Law)	Heat Recovery: Electricity (kWh)	50	Economic	RHI Energy Cost Income: PVT Water Thermal Generation [£]
24	Energy (1st Law)	DHW: Electricity (kWh)	51	Economic	RHI Energy Cost Income: Biomass heat generation [£]
25	Energy (1st Law)	DHW: Gas (kWh)	52	Economic	Total Energy Cost (with RHI but without FiT) [£]
26	Energy (1st Law)	DHW: District (kWh)	53	Economic	Total Energy Cost (without RHI and without FiT) [£]
27	Energy (1st Law)	DHW: Oil or Biomass (kWh)	54	Economic	Feed in Tariff Income: PV [£]

Table B - 3 cont. List of outputs provided by ExRET-Opt

Output id	Type	Output	Output id	Type	Output
55	Economic	Feed In Tariff Income: CHP (£)	104	Economic	Annual Capital Cost PROJECT (£)
56	Economic	Feed In Tariff Income: Wind (£)	105	Economic	Annual Capital Cost PROJECT Per Hour (£/H)
57	Non-thermodynamic indicator	CO2 Building (Annual) (Kg)	106	Economic	NPV (50 Years) (£)
58	Economic	Capital Investment Elec Boiler (£)	107	Economic	NPV (50 Years) (£) No Incentives
79	Economic	Capital Investment Wall Insulation (£)	108	Energy (1st Law)	Energy Savings (%)
80	Economic	Capital Investment Roof Insulation (£)	109	Exergy (2nd Law)	Exergy Destructions Savings (%)
81	Economic	Capital Investment Ground Insulation (£)	110	Exergy (2nd Law)	Exergy Input Savings (%)
82	Economic	GSHP Rhi (£)	111	Exergy (2nd Law)	Exergy Efficiency Improvement (%)
83	Economic	ASHP Rhi (£)	112	Exergy (2nd Law)	HVAC Exergy Destructions Savings (%)
84	Economic	PV Feed In Tariff (£)	113	Exergy (2nd Law)	HVAC Exergy Input Savings (%)
85	Economic	CHP Feed In Tariff (£)	114	Exergy (2nd Law)	HVAC Exergy Efficiency Improvement (%)
86	Economic	Wind Feed In Tariff (£)	115	Non-Thermodynamic Indicator	Average Non-Comfortable Hours (Hr)
87	Economic	Annual Income (Energy Savings + Tariffs) (£)	116	Non-Thermodynamic Indicator	Comfort Improvement (%)
88	Economic	Annual Income (Energy Savings No Incentives) (£)	117	Non-Thermodynamic Indicator	Total Annual tCo2 Emissions (Incl. Renew) 2015ind (tCO2)
89	Economic	Annual Energy Bill (£)	118	Non-Thermodynamic Indicator	% Annual Ton Co2 Reduction (%)
90	Economic	Annual Energy Bill (£) No Incentives	119	Economic	Real Life Cycle Cost (50 Years) (£)
91	Economic	Total Cost Retrofit Project (£)	120	Economic	Real Life Cycle Cost (50 Years) (£) No Incentives
92	Economic	Total Cost Retrofit Active (£)	121	Economic	Life Cycle Cost Difference With Benchmark (50 Years) (£)
93	Economic	Total Cost Retrofit Passive (£)	122	Economic	Life Cycle Cost Difference With Benchmark (50 Years) No Incentives (£)
94	Economic	Passive/Active Cost Ratio (£)	101	Economic	Present Factor Retrofit Equip. TCI-(SV*PWF) (£)
95	Economic	Discounted Payback (Years)	102	Economic	Present Value Savage Factor (SV*PWF) (£)
96	Economic	Discounted Payback (Years) NO INCENTIVES	123	Exergy (2nd Law)	Exergy Demand Thermal (Envelope in)(kWh)
97	Economic	Interest Rate (%)	124	Exergy (2nd Law)	Exergy Room In (kWh)
98	Economic	Total Capital Investment (£)	125	Exergy (2nd Law)	Exergy Efficiency Room (-)
99	Economic	Salvage Factor (15%) (£)	126	Exergy (2nd Law)	Exergy Emission In (kWh)
100	Economic	Present Worth Factor (15%) (£)	127	Exergy (2nd Law)	Exergy Efficiency Emission (-)
103	Economic	Capital Recovery Factor 50 Years ()	128	Exergy (2nd Law)	Exergy Distribution In (kWh)

Table B - 3 cont. List of outputs provided by ExRET-Opt

Output id	Type	Output	Output id	Type	Output
129	Exergy (2nd Law)	Exergy Efficiency Distribution (-)	155	Exergy (2nd Law)	ELEC Generation Destructions Ratio (%)
130	Exergy (2nd Law)	Exergy Storage In (kWh)	156	Exergy (2nd Law)	ELEC PET Destructions Ratio (%)
131	Exergy (2nd Law)	Exergy Efficiency Storage (-)	157	Exergy (2nd Law)	Total Exergy Demand (Product) (kWh)
132	Exergy (2nd Law)	Exergy Generation In (kWh)	158	Exergy (2nd Law)	Total Exergy Input (Fuel) (kWh)
133	Exergy (2nd Law)	Exergy Efficiency Generation (-)	159	Exergy (2nd Law)	Total Exergy Destructions (kWh)
134	Exergy (2nd Law)	Exergy Primary Transformation in (kWh)	160	Exergy (2nd Law)	System Exergy Efficiency (%)
135	Exergy (2nd Law)	Exergy Efficiency Primary Transformation (-)	161	Exergy (2nd Law)	Room/TOTAL Exergy Destructions HVAC system (%)
136	Exergy (2nd Law)	Exergy Efficiency Building (-)	162	Exergy (2nd Law)	Emission/TOTAL Exergy Destructions HVAC system (%)
137	Exergy (2nd Law)	Exergy Efficiency HVAC System (-)	163	Exergy (2nd Law)	Distribution/TOTAL Exergy Destructions HVAC system (%)
138	Exergy (2nd Law)	Exergy Destructions HVAC system (kWh)	164	Exergy (2nd Law)	Distribution/TOTAL Exergy Destructions HVAC system (%)
139	Exergy (2nd Law)	Exergy Demand DHW (kWh)	165	Exergy (2nd Law)	Generation/TOTAL Exergy Destructions HVAC system (%)
140	Exergy (2nd Law)	Exergy DHW Load (kWh)	166	Exergy (2nd Law)	Primary Transformation/TOTAL Exergy Destructions HVAC system (%)
141	Exergy (2nd Law)	Exergy Efficiency DHW in bui. (-)	167	Exergy (2nd Law)	DHW Generation/TOTAL Destructions Ratio (%)
142	Exergy (2nd Law)	Exergy DHW Primary (kWh)	168	Exergy (2nd Law)	DHW PET/TOTAL Destructions Ratio (%)
143	Exergy (2nd Law)	Exergy Efficiency DHW PET (-)	169	Exergy (2nd Law)	ELEC Generation/TOTAL Destructions Ratio (%)
144	Exergy (2nd Law)	Exergy Efficiency DHW PET (-)	170	Exergy (2nd Law)	ELEC PET/TOTAL Destructions Ratio (%)
145	Exergy (2nd Law)	Exergy DHW Destructions (kWh)	171	Exergy (2nd Law)	Exergy Destructions Savings (%)
146	Exergy (2nd Law)	DHW Generation Destructions Ratio (%)	172	Exergy (2nd Law)	Exergy Input Savings (%)
147	Exergy (2nd Law)	DHW PET Destructions Ratio (%)	173	Exergy (2nd Law)	Exergy Efficiency Improvement (%)
148	Exergy (2nd Law)	Exergy Demand ELECTRIC (kWh)	174	Exergy (2nd Law)	HVAC Exergy Destructions Savings (%)
149	Exergy (2nd Law)	Exergy DHW Load (kWh)	175	Exergy (2nd Law)	HVAC Exergy Input Savings (%)
150	Exergy (2nd Law)	Exergy Efficiency ELEC in bui. (-)	176	Exergy (2nd Law)	HVAC Exergy Efficiency Improvement (%)
151	Exergy (2nd Law)	Exergy ELEC Primary (kWh)	177	Exergoeconomics	Z Generation Heat (£/h)
152	Exergy (2nd Law)	Exergy Efficiency ELEC PET (-)	178	Exergoeconomics	Z Generation Cold (£/h)
153	Exergy (2nd Law)	Exergy Efficiency ELEC PET (-)	179	Exergoeconomics	Z Storage Heat (£/h)
154	Exergy (2nd Law)	Exergy ELEC Destructions (kWh)	180	Exergoeconomics	Z Storage Cold (£/h)

Table B - 3 cont. List of outputs provided by ExRET-Opt

Output id	Type	Output	Output id	Type	Output
181	Exergoeconomics	Z Distribution Heat (£/h)	206	Exergoeconomics	D Cost Destruction Storage Cold (£)
182	Exergoeconomics	Z Distribution Cold (£/h)	207	Exergoeconomics	Z/(Z+D)Exergoeconomic factor storage heating (-)
183	Exergoeconomics	Z Emission Heat (£/h)	208	Exergoeconomics	Z/(Z+D)Exergoeconomic factor storage cooling (-)
184	Exergoeconomics	Z Emission Cold (£/h)	209	Exergoeconomics	C Cost Product Storage Heat (£/kWh)
185	Exergoeconomics	Z Room Heat (£/h)	210	Exergoeconomics	C Cost Product Storage Cold (£/kWh)
186	Exergoeconomics	Z Room Cold (£/h)	211	Exergoeconomics	rK Relative Cost Difference Gen-Sto Heat ()
187	Exergoeconomics	Z Envelope Heat (£/h)	212	Exergoeconomics	rK Relative Cost Difference Gen-Sto Cold ()
188	Exergoeconomics	Z Envelope Cold (£/h)	213	Exergoeconomics	D Cost Destruction Distribution Heat (£)
189	Exergoeconomics	Z Total HVAC_Heat (£/h)	214	Exergoeconomics	D Cost Destruction Distribution Cold (£)
190	Exergoeconomics	Z Total HVAC_Cold (£/h)	215	Exergoeconomics	Z/(Z+D)Exergoeconomic factor distribution heating (-)
191	Exergoeconomics	Z Total HVAC_TRUE (£/h)	216	Exergoeconomics	Z/(Z+D)Exergoeconomic factor distribution cooling (-)
192	Exergoeconomics	Z DHW Generation (£/h)	217	Exergoeconomics	C Cost Product Distribution Heat (£/kWh)
193	Exergoeconomics	Z DHW Distribution (£/h)	218	Exergoeconomics	C Cost Product Distribution Cold (£/kWh)
194	Exergoeconomics	Z Electric Equipment (£/h)	219	Exergoeconomics	rK Relative Cist Difference Stor-Dist Heat ()
195	Exergoeconomics	C Cost Fuel Generation Heat (£/kWh)	220	Exergoeconomics	rK Relative Cist Difference Stor-Dist Cold ()
196	Exergoeconomics	C Cost Fuel Generation Cold (£/kWh)	221	Exergoeconomics	D Cost Destruction Emission Heat (£)
197	Exergoeconomics	D Cost Destruction Generation Heat (£)	222	Exergoeconomics	D Cost Destruction Emission Cold (£)
198	Exergoeconomics	D Cost Destruction Generation Cold (£)	223	Exergoeconomics	Z/(Z+D)Exergoeconomic factor emission heating (-)
199	Exergoeconomics	Z/(Z+D)Exergoecono mic factor generation heating (-)	224	Exergoeconomics	Z/(Z+D)Exergoeconomic factor emission cooling (-)
200	Exergoeconomics	Z/(Z+D)Exergoecono mic factor generation cooling (-)	225	Exergoeconomics	C Cost Product Emission Heat (£/kWh)
201	Exergoeconomics	C Cost Product Generation Heat (£/kWh)	226	Exergoeconomics	C Cost Product Emission Cold (£/kWh)
202	Exergoeconomics	C Cost Product Generation Cold (£/kWh)	227	Exergoeconomics	rK Relative Cost Difference Dist-Emm Heat ()
203	Exergoeconomics	rK Relative Cost Difference Prim-Gen Heat ()	228	Exergoeconomics	rK Relative Cost Difference Dist-Emm Cold ()
204	Exergoeconomics	rK Relative Cost Difference Prim-Gen Cold ()	229	Exergoeconomics	D Cost Destruction Room Heat (£)
205	Exergoeconomics	D Cost Destruction Storage Heat (£)	230	Exergoeconomics	D Cost Destruction Room Cold (£)

Table B - 3 cont. List of outputs provided by ExRET-Opt

Output id	Type	Output	Output id	Type	Output
231	Exergoeconomics	Z/(Z+D)Exergoeconomic factor room heating (-)	252	Exergoeconomics	D Cost Destruction Distribution and Use DHW (£)
232	Exergoeconomics	Z/(Z+D)Exergoeconomic factor room cooling (-)	253	Exergoeconomics	Z/(Z+D)Exergoeconomic factor DHW distribution(-)
233	Exergoeconomics	C Cost Product Room Heat (£/kWh)	254	Exergoeconomics	C Cost Product Distribution and Use DHW (£/kWh)
234	Exergoeconomics	C Cost Product Room Cold (£/kWh)	255	Exergoeconomics	RK Relative Cost Difference DHW Gen-Dist.(use) Heat ()
235	Exergoeconomics	rK Relative Cost Difference Emm-Room Heat ()	256	Exergoeconomics	rK Relative cost difference ALL DHW ()
236	Exergoeconomics	rK Relative Cost Difference Emm-Room Cold ()	257	Exergoeconomics	C Cost Product Electric Equip. (£/kWh)
237	Exergoeconomics	D Cost Destruction Envelope Heat (NON ACCOUNTABLE) (£)	258	Exergoeconomics	D Cost Destruction Electric Equip (£)
238	Exergoeconomics	D Cost Destruction Envelope Cold (NON ACCOUNTABLE) (£)	259	Exergoeconomics	Z/(Z+D)Exergoeconomic factor ELECTRIC EQUIP. (-)
239	Exergoeconomics	Z/(Z+D)Exergoeconomic factor envelope heating (-)	260	Exergoeconomics	C Cost Product Electric Equip. (£/kWh)
240	Exergoeconomics	Z/(Z+D)Exergoeconomic factor envelope cooling (-)	261	Exergoeconomics	rK Relative cost difference ELECTRIC EQUIP ()
241	Exergoeconomics	C Cost Product Envelope Heat (£/kWh)	262	Exergoeconomics	D TOTAL Cost Destruction HEAT (£)
242	Exergoeconomics	C Cost Product Envelope Cold (£/kWh)	263	Exergoeconomics	D TOTAL Cost Destruction COLD (£)
243	Exergoeconomics	rK Relative Cost Difference Room-Env Heat ()	264	Exergoeconomics	D TOTAL Cost Destruction DHW (£)
244	Exergoeconomics	rK Relative Cost Difference Room-Env Cold ()	265	Exergoeconomics	D TOTAL Cost Destruction Electric Appliances (£)
245	Exergoeconomics	rK Relative cost difference heating ()	266	Exergoeconomics	D TOTAL Cost Destruction (£)
246	Exergoeconomics	rK Relative cost difference cooling ()	267	Exergoeconomics	D TOTAL Cost Destruction incl ENVELOPE(£)
247	Exergoeconomics	C Cost Fuel Generation DHW (£/kWh)	268	Exergoeconomics	D/t Seasonal Cost per hour destroyed heating (£/h)
248	Exergoeconomics	D Cost Destruction Generation DHW (£)	269	Exergoeconomics	D/t Seasonal Cost per hour destroyed cooling (£/h)
249	Exergoeconomics	Z/(Z+D)Exergoeconomic factor DHW generation (-)	270	Exergoeconomics	D/t Annual Cost per hour destroyed heating (£/h)
250	Exergoeconomics	C Cost Product Generation DHW (£/kWh)	271	Exergoeconomics	D/t Annual Cost per hour destroyed cooling (£/h)
251	Exergoeconomics	rK Relative Cost Difference DHW Prim-Gen Heat ()	272	Exergoeconomics	D/t Annual Cost per hour destroyed exergy HVAC (£/h)

Table B - 3 cont. List of outputs provided by ExRET-Opt

Output id	Type	Output	Output id	Type	Output
273	Exergoeconomics	D/t Annual Cost per hour destroyed exergy DHW (£/h)	285	Exergoeconomics	(Z/t) Capital Cost per hour BUILDING(£/h)
274	Exergoeconomics	D/t Annual Cost per hour destroyed exergy Electricity (£/h)	286	Exergoeconomics	(E/t) Energy Cost per hour BUILDING(£/h)
275	Exergoeconomics	D/t Annual Cost per hour destroyed exergy TOTAL (£/h)	287	Exergoeconomics	(E+Z/t)/(Z/t) Energy and Capital against Capital RATIO
276	Exergoeconomics	(E+Z/t) Cost per hour HEATING Seasonal (£/h)	288	Exergoeconomics	(D/t)/(E/t) Exergy Destroyed against Energy RATIO
277	Exergoeconomics	(E+Z/t) Cost per hour COOLING Seasonal (£/h)	289	Exergoeconomics	(D/t)/(Z/t) Exergy Destroyed against Energy and Capital RATIO
278	Exergoeconomics	(E+Z/t) Cost per hour HEATING Annual(£/h)	290	Exergoeconomics	BUILDING Exergoeconomic factor Z/(Z+D) (-)
279	Exergoeconomics	(E+Z/t) Cost per hour COOLING Annual (£/h)	291	Exergoeconomics	Annual revenue (Income) per hour (%)
280	Exergoeconomics	(E+Z/t) Cost per hour HVAC Annual (£/h)	292	Exergoeconomics	Annual revenue (Income) per hour NO INCENTIVES(£)
281	Exergoeconomics	(E+Z/t) Cost per hour DHW (£/h)	293	Exergoeconomics	Expanded thermoeconomic (cost D - Annual Revenue + Annual cost) (£/h)
282	Exergoeconomics	(E+Z/t) Cost per hour ELECTRIC EQUIP(£/h)	294	Exergoeconomics	Expanded thermoeconomic (cost D - Annual Revenue + Annual cost) NO INCENTIVES (£/h)
283	Exergoeconomics	(E+Z/t) Cost per hour BUILDING(£/h)	295	Exergoeconomics	Improvement Expanded thermoeconomic indicator (%)
284	Exergoeconomics	(Z/t) Capital Cost per hour BUILDING(£/h)	296	Exergoeconomics	Improvement Expanded thermoeconomic indicator NO INCENTIVES (%)

B.4 BER measures description included in ExRET-Opt

C.4.1 Active systems' retrofits

a) HVAC primary systems

Some systems work with standard temperatures while others can work as low temperature heating and high temperature cooling, reducing temperature differences between the medium and the thermal zone in heat transfer and energy transport process. Within ExRET-Opt retrofit database, different HVAC primary systems and different energy sources were considered:

I. Condensing boilers

Building regulations that have come into force since 1st of April 2005 state that any replacement of new gas or oil boiler must be a condensing boiler. By condensing water vapour from the products of combustion (gases at 180 °C), condensing boilers typically use an additional heat exchanger to extract the latent heat that normally would be released to the ambient through the flue. As low temperature enters the condensing heat exchangers it cools the flue gases (55 °C), where the lower the temperature, the more condensation produced. This process allows the boilers to rise energy efficiency, from 0.75-0.80 for typical boilers to 0.90 for condensing boilers. However, it is only possible to get this efficiency if the temperature flow and return pipework is also kept below 55°C. This can come as a limitation if typical radiators which need around 82 °C are installed. Manufacturers claim that up to 0.98 thermal efficiency can be achieved; but a field trial, conducted by the Energy Saving Trust in the UK, found an average efficiency of 0.853. In this research different fuel options are considered for condensing boilers: natural gas, fuel oil, and biomass (wood pellets).

II. Electric boilers

Electric boilers heat the water for the heating system using only electricity. Electric boilers generally include a plurality of electrodes which are at least partially submerged in a quantity of water contained in the boiler. The flow of electric current through the water and between the electrodes heats the water for the production of steam. As the water evaporates, the concentration of salts and other impurities in the water tend to increase thereby affecting the conductivity of water.

III. Air source and ground source heat pumps

Heat pumps are devices that move energy from a 'heat source' to a 'heat sink', from one location to another through the input of high-grade low entropy energy (such as work or electricity). A heat source can be air, ground or a water body, where low-grade energy is available. The normal process in heating mode (Figure B - 2) is the following: 1) first the refrigerant (which is colder than the heat source) absorbs the low temperature heat obtained from the air, ground or water, making the refrigerant to evaporate. 2) Later, this vapour reaches a compression stage, increasing the pressure and the temperature of the medium. At this stage, work input for electricity is needed to run the compressor. 3) Later, this high pressure hot vapour flows through a condenser or a heat exchanger, transferring energy to a distribution system or directly to the room. This process condenses the vapour and reduces its temperature. 4) Finally, the condensed refrigerant flows through an expansion valve reducing its pressure closing the thermodynamic cycle. For cooling mode the cycle is reversed.

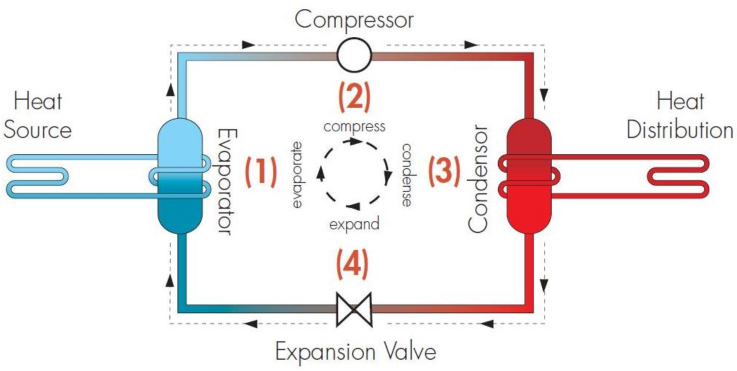


Figure B - 2 Heat pump cycle

It can be regraded that the heat transfer is larger than the work input as most of the energy for heating or cooling comes from the 'heat source' with a fraction coming from the electricity used in the compressor, thus producing high COP when operating at low temperature differentials. For the work two types of heat pumps were considered: air source heat pumps (ASHP) and ground source heat pumps (GSHP) with a closed loop borehole heat exchanger.

IV. Micro Combined heat and power (mCHP)

CHP or cogeneration involves generating electricity on site and using heat as a by-product produced in the generation process (Figure B - 3). This contrasts with the conventional ways of producing hot water through burning gas, where a vast amount of heat is wasted. The process results in a typical energy efficiency of around 0.65-0.85, larger than for typical off-site power stations. This system provides heat and power with less environmental impact. The common application of mCHP is in non-domestic buildings and large apartment blocks. Depending on the building and its demand, CHP can be more viable if it runs more than 5000 hours a year.

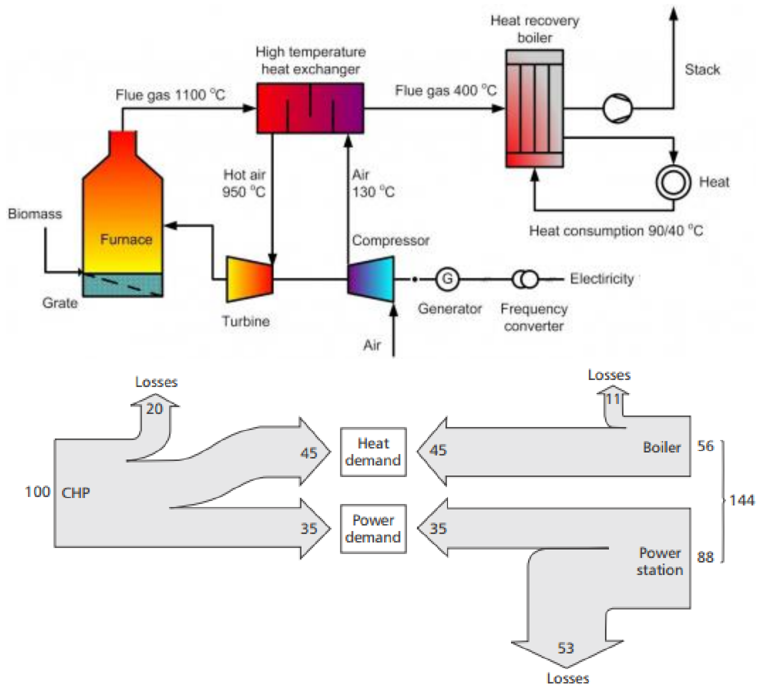


Figure B - 3 A typical cogeneration process for buildings (top) and energy efficiency comparison with traditional systems. Source: Cibse Guide F (2012)

The majority of mCHP installed in the UK are normally based on gas-fired reciprocating engines and in the form of packaged units, often in modular boiler arrangements with outputs between 50 kWe and 1MWe. The specific technologies that are employed, and the efficiencies they achieve will vary, but in every situation CHP offers the capability to make more efficient and effective use of valuable primary energy resources. In addition, absorption chillers can be used to deliver a Trigeneration solution by also providing chilled water for cooling. Nevertheless, this research considered a heating mode with configuration based natural gas sterling engine micro-CHP with a fuel cell system.

V. District systems (cooling/heating)

District energy systems produce steam, hot water or chilled water at a central plant. The energy stream is then commonly supplied through the underground pipes to premises, to cover for space conditioning demands or domestic hot water. The installation of centralised energy systems has multiple social benefits, compared to individual equipment, as it reduces investment costs, enables the utilisation of waste heat and reduces energy losses. In the last years, district systems have been evolving thanks to the introduction of new generation technologies and energy. It ranges from CHP plants, boilers, and heat pumps with potential of using waste heat from industrial sites (if possible and distance permits). The coupling of district systems with low-energy buildings has allowed district system designs to work with temperatures as low as 35° for heating and as high as 18°C for cooling. By reducing the temperature in supply, it reduces the energy use but can increase mass flow rates and therefore the pump's electric demand. For this research the district system was assumed to be run by Trigeneration process: a single-effect indirect-fired CHP with absorption chiller with a COP of 0.7.

b) HVAC secondary equipment and energy emission systems

To complement the proposed HVAC systems, different water-based and air-based energy emission subsystems were considered.

I. Air-based mechanical ventilation

An air based Fan-Coil (FC) is a terminal unit often composed of a fan and a heating and/or cooling coil located within the space they are serving. It can be wall-mounted, freestanding or ceiling-mounted and may be concealed in ceiling voids; however it can sometimes use ductwork. FCs are used to control the temperature in the space where it is installed, or serve multiple spaces. They may either just recirculate internal air, in which case a separate ventilation system is required, or may introduce a proportion of 'fresh' air that is mixed with the recirculated air. It is controlled either by a manual on/off switch or by a thermostat. Depending on the controls, three different systems are considered in the model:

Constant Air Volume (**CAV**)

It is a system designed to provide a constant air flow into a space. In a CAV system, the supply air flow rate is constant, but the supply air temperature is varied to meet the thermal loads of a space. CAV systems are still used in small and medium-sized premises with straightforward HVAC requirements, as they can be relatively simple to install, thus having lower capital cost.

Variable Air Volume (**VAV**)

Unlike CAV systems, VAV systems vary the airflow at a constant temperature. It has a stable supply-air temperature, and varies the air flow rate to meet the temperature requirements. The advantages of VAV systems include more precise temperature control, reduced compressor wear, lower energy consumption by system fans, and less fan noise. These systems conserve energy through lower fan speeds during the times of lower temperature control demand.

Variant Refrigerant Flow (VRF)

VRFs are typically installed with an inverter to the compressor in order to support variable motor speed and thus variable refrigerant flow. By operating at varying speeds and flows, VRF units supply energy at the needed rate allowing for substantial savings at partial-load conditions. In general, refrigerant is circulated between one or more fan coil units and is connected to an external heat exchanger.

II. Water-based low temperature systems

Underfloor and Wall heating/cooling

This type of system usually embeds hydronic pipes in concrete slabs or walls, where large surface areas are used for heating or cooling. Thus, these systems can work with lower temperatures and provide better thermal comfort by delivering more uniform space temperature. Underfloor and wall systems' outputs use infrared heat radiation rather than convection that is found in typical water-based systems. Moreover, to their advantage, these systems can be connected to any energy generation system, either boilers, heat pumps, or CHP.

According to the UK's National Calculation Method for Non-Domestic Buildings (BRE, 2013), Table B - 4 shows constant values for the most common emission system found in non-domestic buildings in the UK. These values were used in the system codification within ExRET-Opt.

Table B - 4 Energy efficiency values and auxiliary power requirements of different HVAC emission systems. (Rysanek and Choudhary, 2012)

Emission system	Heating η	Cooling η	Auxiliary energy (W/m²)
Single-duct VAV	0.7324	0.7218	14.82
Dual-duct VAV	0.6866	0.6380	14.82
Indoor packaged VAV	0.8316	0.9286	8.33
Fan coil systems	0.9216	0.7599	13.75
Induction systems	0.9673	0.7783	13.40
Constant volume (fixed fresh air)	0.9870	0.4715	37.02
Constant volume (variable fresh air)	0.9870	0.5425	37.02
Multi-zone (hot & cold deck)	0.7631	0.5352	37.02
Terminal reheat (constant volume)	0.6557	0.3097	37.02
Dual duct (constant volume)	0.6543	0.3101	37.02
Split or multi-split system	0.9318	0.9230	7.35
Single room HP/AC	0.9318	0.9230	7.35
Variable refrigerant flow (VRF)	0.9318	0.8447	7.35
Radiator	0.9500	0.9500	15.00
Slab and floor heating	0.9900	0.9900	15.00
Wall heating (LT 28/22)	0.9500	0.9500	15.00

c) ExRET-Opt HVAC systems configuration

From the aforementioned technologies, a number of different HVAC system configurations were assessed in this research. In total 33 different combinations were created.

Table B - 5 Possible HVAC systems designs in ExRET-Opt

HVAC ID	Primary system Description	Emission system
H1	*Condensing Gas Boiler + Chiller*	CAV
H2	*Condensing Gas Boiler + Chiller*	VAV
H3	*Condensing Gas Boiler + ASHP-VRF System*	FC
H4	*Condensing Oil Boiler + Chiller*	CAV
H5	*Condensing Oil Boiler + Chiller*	VAV
H6	*Condensing Oil Boiler + ASHP-VRF System*	FC
H7	*Electric Boiler + Chiller*	CAV
H8	*Electric Boiler + Chiller*	VAV
H9	*Electric Boiler + ASHP-VRF System*	FC
H10	*Condensing Biomass Boiler + Chiller*	CAV
H11	*Condensing Biomass Boiler + Chiller*	VAV
H12	*Condensing Biomass Boiler + ASHP-VRF System*	FC
H13	*District system*	CAV
H14	*District system*	VAV
H15	*District system*	Wall
H16	*District system*	Underfloor
H17	*District system*	Wall+Underfloor
H18	*Ground Source Heat Pump*	CAV
H19	*Ground Source Heat Pump*	VAV
H20	*Ground Source Heat Pump*	Wall
H21	*Ground Source Heat Pump*	Underfloor
H22	*Ground Source Heat Pump*	Wall+Underfloor
H23	*Air Source Heat Pump*	CAV
H24	*PVT-based system (50% roof) with supplemental Electric boiler + Old Chiller*	CAV
H25	*Condensing Gas Boiler + Chiller*	Wall
H26	*Condensing Gas Boiler + Chiller*	Underfloor
H27	*Condensing Gas Boiler + Chiller*	Wall+Underfloor
H28	*Condensing Biomass Boiler + Chiller*	Wall
H29	*Condensing Biomass Boiler + Chiller*	Underfloor
H30	*Condensing Biomass Boiler + Chiller*	Wall+Underfloor
H31	*Micro-CHP (natural gas) with Fuel Cell and Electric boiler + old Chiller*	CAV
H32	*Condensing Gas Boiler + old Chiller (Heat Recovery System included)*	CAV

d) Lighting measures

The existing database includes three different lighting technology options. It seeks the replacement of typically installed T-12 LFC Lamps with Low-wattage T-8 LFC Lamps, T-5 LFC Lamps or T-8 Led lamps.

T8 and T5 LFC are tri-phosphor low wattage lamps with low ballast factor electronic ballasts. Tri-phosphor low wattage T-8 lamps use less energy and produce better quality light than standard T-12 lighting systems. Electronic ballasts with low ballast factors (BF<0.85) can reduce lighting system energy use by as much as 40%. On the other hand, LED lamps are a solid-state lighting technology, therefore, instead of emitting light from gas (as in a CFL), they emit light from a semiconductor. In an effort to make T-8 LED lamps fit into existing linear fluorescent fixtures (for retrofit purposes), manufacturers have to include bypassing the existing ballast, or integrate it within the fixture.

e) Renewable electricity generation: wind turbines and PV panels

Wind turbines can be used to generate on-site electricity. Small scale wind turbines are defined as those that are capable of delivering energy at a rate of less than 50 kW. The performance of a micro wind turbine is influenced greatly by the availability of wind resources, including wind velocity and rate of occurrence. In the module, 20 kW stand-alone turbines capable to model a modular array are included.

Solar Photovoltaic (PV) modules generate electricity directly from sunlight via an electronic process that occurs naturally in certain types of material, called semiconductors. Different types exist, including monocrystalline silicon (c-Si), polycrystalline, amorphous solar cells, and hybrid solar cells. In this research monocrystalline silicon panels with module efficiency of 0.13-0.15 are included. For both technologies, electrons can be induced to travel through an electrical circuit, powering electrical devices or sending electricity to the grid.

C.4.2 Passive systems' retrofits

Among passive technologies that were considered in this research are the following:

a) Thermal envelope insulation

Insulation is a barrier that minimises the transfer of heat energy from one material to another by reducing the conduction, convection and/or radiation effects. Thermal insulation in buildings is one of the most effective energy-conservation measures where energy savings can be obtained by using an adequate thickness and technology. In the model, nine insulation technologies were included: Polyurethane, Extruded polystyrene, Expanded polystyrene, Cellular Glass, Glass Fibre Cork board, Phenolic foam board, Aerogel, and Phase Change Material (DuPont).

b) Glazing systems

Different energy-efficient glazing systems were included. Unlike the original single glazing, energy-efficient glazing incorporates coated (low-emissivity) glass and interlayer of a noble gas to prevent heat escaping through the windows, making the windows highly thermally insulated. The model includes a combination of double and triple glazing systems with different interlayer gases such as Air, Argon or Krypton. Argon and Krypton are denser than Air, reducing the amount of heat transfer through the glazing system. However, while Argon is relatively cheap, its production time can be large, increasing capital costs. On the other hand, even though Krypton has a better thermal performance, it can be 1,000 times more expensive than Argon.

c) Air infiltration improvements

Air leakage is the uncontrolled movement of air in and out of a building which is not for the specific and planned purpose of exhausting stale air and bringing in fresh air. Reducing unintentional air leakage (that is, air sealing) through the building envelope is also included as part of the measures. This should be the first priority in any building envelope retrofit because air leakage can reduce the effectiveness of some types of insulation. The reduction of unwanted infiltration rates includes measures such as air barriers, membrane sealing, and frame sealing. Although it is complicated to quantify the measures' implementation in a building modelling exercise, the chosen strategy was to reduce infiltration rate by percentage value, gathering data on approximate costs of doing so.

d) Thermostats set-point management (control)

Modifying set-point by just 1°C, either for heating or cooling, can potentially reduce the annual heating bill by up to 8% (CarbonTrust, 2011). As both, the thermostat set-point and the dead band range, impact energy use and occupants' thermal comfort, the tool can consider a parametric variation of heating and cooling set-point as part of retrofit measures, with the aim to find an optimal set-point value depending on the building's physical characteristics. Modifying a set-point can have a big impact on different areas in addition to the occupants' thermal comfort. For example, as airflow volume rates or water flow rates vary according to the set-point, this has direct implications on energy utilisation due to pumps and fans.

B.5 ExRET-Opt BER strategies techno-economic characteristics

Table B - 6 Characteristics and investment cost of lighting systems

Lights ID	Lighting technology	Cost per W/m²
L1	*T8 LFC*	£5.55
L2	*T5 LFC*	£7.55
L3	*T8 LED*	£11.87

Table B - 7 Characteristics and investment cost of renewable energy generation systems

Renewable	Technology	Cost
R1	*PV panels 25% roof*	PV: £1200/m²
R2	*PV panels 50% roof*	
R3	*PV panels 75% roof*	
R4	*Wind Turbine 20 kW*	Turbine: £4000/kW
R5	*Wind Turbine 40 kW*	

*For the Passivhaus case study PV panels roof area were applied in 10% steps (0-100%)

Table B - 8 Characteristics and investment cost of different insulation materials

Ins. ID	Insulation measure	Thickness (cm)	Total of measures	Cost per m² (lowest to highest)
I1	*Polyurethane*	2 to 15 in 1 cm steps	14	£6.67 to £23.32
I2	*Extruded polystyrene*	1 to 15 in 1 cm steps	15	£4.77 to £31.99
I3	*Expanded polystyrene*	2 to 15 in 1 cm steps	14	£4.35 to £9.95
I4	*Cellular Glass*	4 to 18 in 1 cm steps	15	£16.21 to £72.94
I5	*Glass Fibre*	6.7 7.5 8.5 and 10 cm	4	£5.65 to £7.75
I6	*Cork board*	2 to 6 in 1 cm steps 8 to 20 cm in 2 cm steps 28 and 30 cm	14	£5.57 to £85.80
I7	*Phenolic foam board*	2 to 10 in 1 cm steps	9	£5.58 to £21.89
I8	*Aerogel*	0.5 to 4 in 0.5 cm steps	8	£26.80 to £195.14
I9	*PCM (w/board)*	10 and 20 mm	2	£57.75 to £107.75

*For the Passivhaus case study, for insulation measures I1, I2, I3, I4, I5, I6, and I7, extra thicknesses (20, 25 and 30 cm) with its respective cost were added. This was done to achieve envelope U-values within the Passivhaus standard

Table B - 9 Characteristics and investment cost of glazing systems

Glazing ID	System Description (# panes – gap)	Gas Filling	Cost per m²
G1	*Double pane - 6mm*	Air	£261
G2	*Double pane - 13mm*	Air	£261
G3	*Double pane - 6mm*	Argon	£350
G4	*Double pane - 13mm*	Argon	£350
G5	*Double pane - 6mm*	Krypton	£370
G6	*Double pane - 13mm*	Krypton	£370
G7	*Triple pane - 6mm*	Air	£467
G8	*Triple pane - 13mm*	Air	£467
G9	*Triple pane - 6mm*	Argon	£613
G10	*Triple pane - 13mm*	Argon	£613
G11	*Triple pane - 6mm*	Krypton	£653
G12	*Triple pane - 13mm*	Krypton	£653

Table B - 10 Characteristics and investment cost for air tightness improvement considering baseline of 1 *ach* @50Pa

Sealing ID	ACH (1/h) @50Pa Improvement %	Cost per m² (opaque envelope)
S1	*10%*	£1.20
S2	*20%*	£3.31
S3	*30%*	£6.35
S4	*40%*	£10.30
S5	*50%*	£15.20
S6	*60%*	£20.98
S7	*70%*	£27.69
S8	*80%*	£35.33
S9	*90%*	£43.88

Table B - 11 Cooling and heating indoor set points variations

Set-point ID	Set-point Type	Value (°C)	Cost
SH18 SH19 SH20 SH21 SH22	*Heating*	18 19 20 21 22	(-)
SC23 SC24 SC25 SC26 SC27	*Cooling*	23 24 25 26 27	(-)

Appendix C: Case study 1: UK Archetype building models assumptions and input information

C.1 Primary School archetype

Table C - 1 Primary School baseline archetype main characteristics

General Description	Primary School	
Building Type	Non-domestic	
Configuration	Low Rise-Cellular Plan	
Location	London	
Coordinates	51° 33' 03'' N, 0° 04′ 57'' W	
Weather File	London Gatwick, UK	

Geometry				
Number of Floors	2	Total Floor Area	1,990m²	
Opaque Materials	**Construction**			**U-Value Wm²/K**
External Walls (GF/1^STF)	Cavity Wall-Brick walls 100 mm brick with 25mm air gap			1.66
Ground Floor	150 mm Concrete Slab			1.31
Roof	200mm Concrete Block			3.12
Transparent Materials	**Property**	**U-Value W/m²K**	**SHGC**	**VT**
Glazing Material	5mm Single Glazing	5.84	0.8	0.696
Glazing Area	28% of Total Wall Area			
Skylight Area	0% of Total Roof Area			
Shading	N/A			
Systems				
HVAC System Type	Boiler-based heating and natural ventilation			
Heating System	515 kW Gas Fired Boiler connected to high temperature radiators			
Energy efficiency	0.82			
Fuel Type	Natural Gas			
Heating System Controls	Main System Thermostat – Thermostatic Valves on Radiators			
Cooling System	N/A (Natural Ventilation and Night Cooling)			
Energy efficiency	N/A			
Fuel Type	N/A			
Ventilation	• Winter: Natural Ventilation • Summer: Natural Ventilation			
Specific Fan Power	N/A			
DHW				
Generator Type	Gas Fired Boiler + hot water tank			
Fuel Type	Natural Gas			
Lighting				
Type	T12 LFC			
Controls	manual-on-off			
Loads (classrooms only)				
Occupancy	2.1 person/m² - at average 130 watts			
Equipment	1.99 W/m²			
Lighting	12.2 W/m²			
Rates				
Infiltration Rate	1.0 ach			
Renewables (PV system)				
Available roof space	972 m²			
PV array	N/A			
Type	N/A			

Table C - 2 Occupancy profile (weekday) for each thermal zone. Primary School. Modified from Bull et. al, 2014.

Hour	7	8	9	10	11	12	13	14	15	16	17	18
Office	0.1	0.3	0.8	1.0	1.0	0.5	0.5	1.0	1.0	0.5	0.5	0.0
Classroom	0.1	0.3	0.8	1.0	1.0	0.5	0.5	1.0	1.0	0.5	0.5	0.0
Cafeteria	0.0	0.0	0.0	0.0	0.2	1.0	0.2	0.0	0.0	0.0	0.0	0.0
Kitchen	0.0	0.0	0.0	0.3	0.3	1.0	1.0	0.8	0.3	0.0	0.0	0.0
Teachers	0.1	0.5	0.1	0.1	0.1	0.1	0.3	0.1	0.1	0.1	0.1	0.1
Laboratory	0.1	0.3	0.8	1.0	1.0	0.5	0.5	1.0	1.0	0.5	0.5	0.0
Computer room	0.1	0.3	0.8	1.0	1.0	0.5	0.5	1.0	1.0	0.5	0.5	0.0
Library	0.3	0.5	0.2	0.2	0.2	0.2	0.2	0.2	0.4	0.4	0.0	0.0
Hall	0.1	0.1	0.1	0.1	0.3	0.3	0.3	0.1	0.1	0.1	0.1	0.1

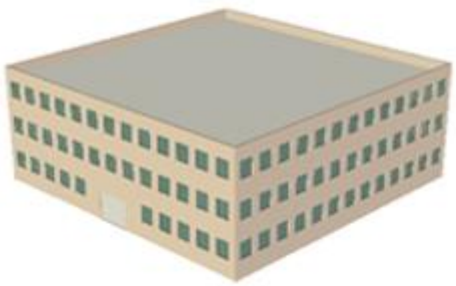
Table C - 3 Input assumptions for each thermal zone. Primary School. Modified from Bull et. al, 2014.

Zone category	Lighting (W/m^2)	Equipment (W/m^2)	Ventilation (l/s/pers.)	Heating setpoint (°C)	Occupancy (m^2/person)	Activity level (W/person)
Office	12.0	10.0	10	20	5.0	120
Classroom	12.2	2.0	5.5	20	2.1	113
Cafeteria	12.2	2.0	12	18	1.39	140
Kitchen	12.2	38.4	10	18	3.0	140
Teachers	7.5	1.0	10	20	20.0	140
Laboratory	12.2	49.5	25	18	4.0	130
Computer	12.2	15.0	10	18	3.3	113
Library	12.2	2.0	10	18	4.4	113
Hall	7.5	1.0	10	15	10.0	120

C.2 A/C Office archetype

Table C - 4 A/C Office baseline archetype main characteristics

General Description	A/C Office
Building Type	Non-domestic
Configuration	Low Rise-Open Plan
Location	London
Coordinates	51° 33’ 03’’ N, 0° 04′ 57’’ W
Weather File	London Gatwick, UK



Geometry			
Number of Floors	3	Total Floor Area	2,590m^2

Opaque Materials	**Construction**	**U-Value Wm^2/K**
External Walls	Cavity Wall-Brick walls 100 mm brick with 25mm air gap	1.61
Ground Floor	150 mm Concrete Slab	1.31
Roof	200mm Concrete Block	3.12

Transparent Materials	**Property**	**U-Value W/m^{2}K**	**SHGC**	**VT**
Glazing Material	5mm Single Glazing	5.84	0.8	0.696
Glazing Area	41% of Total Wall Area			
Skylight Area	0% of Total Roof Area			
Shading	N/A			

Systems	
HVAC System Type	Boiler-based heating and Chiller-based cooling
Heating System	750 kW Gas Fired Boiler connected to CAV system
Energy efficiency	0.70
Fuel Type	Natural Gas
Cooling System	272 kW Air-based Chiller
Energy efficiency	COP: 2.0
Fuel Type	Electricity
Ventilation	• Winter: Mechanical Ventilation • Summer: Mechanical Ventilation
Specific Fan Power (W-s/m3)	107.2
System Controls	Main System Dual set-point Thermostat
DHW	
Generator Type	Gas Fired Boiler + hot water tank
Fuel Type	Natural Gas
Lighting	
Type	T12 LFC
Controls	manual-on-off
Loads (offices only)	
Occupancy	8.2 person/m^2 - at average 130 watts
Equipment	16.4 W/m^2
Lighting	19.2 W/m^2
Rates	
Infiltration Rate	1.0 ach
Renewables (PV system)	
Available roof space	900 m^2
PV array	N/A
Type	N/A

Table C - 5 Occupancy profile (weekday) for each thermal zone. A/C Office

Hour	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Office areas	0.1	0.2	0.95	0.95	0.95	0.95	0.5	0.95	0.95	0.95	0.95	0.3	0.1	0.1	0.1
Common areas	0.1	0.1	0.5	0.1	0.1	0.1	0.8	0.1	0.1	0.1	0.1	0.5	0.3	0.1	0.1

Table C - 6 Input assumptions for each thermal zone. A/C Office

Zone category	Lighting (W/m^2)	Equipment (W/m^2)	Ventilation (l/s/pers.)	Heating setpoint (°C)	Occupancy (m^2/person)	Activity level (W/person)
Office areas	19.2	16.4	10	21	8.2	120
Common areas	7.5	8.0	5.5	18	20	130

Appendix D: Non-HVAC retrofits results

D.1 Primary School. Non-HVAC BER energy economic carbon emission and thermal comfort indicators

Table D - 1 Main energy and economic indicators related to Non-HVAC oriented BER measures for a Primary School.

BER Type	BER code	Total Cost Retrofit Project (£)	Total EUI (kWh/m²-year)	Annual Income (Savings + incentives) (£)	Annual Energy Bill (£)	Simple Payback (years)	Annual tCO2	Annual tCO2 Reduction	Life Cycle Cost (50 years) (£)	NPV (50 years) (£)	Thermal discomfort (hours)
--	**Base**	0.0	187.9	0.0	19449.3	0.0	214.8	0.0%	500425.4	0.0	1443.1
Set-point	**SH18**	0.0	170.3	1111.2	18338.1	0.0	199.5	7.1%	471833.7	28591.7	1448.9
Set-point	**SH19**	0.0	183.9	266.2	19183.1	0.0	211.3	1.7%	493577.4	6848.0	1445.2
Set-point	**SH20**	0.0	198.7	-722.0	20171.3	0.0	224.4	-4.5%	519002.3	-18576.9	1425.3
Set-point	**SH21**	0.0	214.4	-1784.1	21233.4	0.0	238.5	-11.1%	546330.4	-45905.0	1323.0
Set-point	**SH22**	0.0	231.1	-2909.2	22358.4	0.0	253.5	-18.0%	575277.1	-74851.7	1127.0
Glazing	**G1**	47324.5	186.3	116.3	19333.0	406.8	213.3	0.7%	543137.8	-42712.4	1449.2
Glazing	**G2**	67088.4	185.4	176.0	19273.3	381.1	212.5	1.1%	560689.3	-60263.9	1445.1
Glazing	**G3**	67088.4	185.1	197.3	19252.0	340.0	212.2	1.2%	560141.5	-59716.2	1443.3
Glazing	**G4**	84676.4	185.5	172.6	19276.7	490.6	212.6	1.0%	577763.6	-77338.2	1451.9
Glazing	**G5**	84676.4	184.9	217.7	19231.6	389.0	212.0	1.3%	576603.7	-76178.3	1447.9
Glazing	**G6**	111149.2	185.1	198.1	19251.2	561.1	212.3	1.2%	602674.6	-102249.3	1449.6
Glazing	**G7**	111149.2	184.6	235.4	19213.9	472.2	211.8	1.4%	601714.4	-101289.0	1446.3
Glazing	**G8**	122028.4	184.6	232.9	19216.4	524.0	211.8	1.4%	612287.0	-111861.6	1446.6
Glazing	**G9**	122028.4	184.3	253.7	19195.6	481.0	211.5	1.5%	611751.3	-111325.9	1444.7

Table D – 1 cont. Main energy and economic indicators related to Non-HVAC oriented BER measures for a Primary School.

BER Type	BER code	Total Cost Retrofit Project (£)	Total EUI (kWh/m²-year)	Annual Income (Savings + incentives) (£)	Annual Energy Bill (£)	Simple Payback (years)	Annual tCO2	Annual tCO2 Reduction	Life Cycle Cost (50 years) (£)	NPV (50 years) (£)	Thermal discomfort (hours)
Glazing	**G10**	47324.5	185.6	160.7	19288.5	294.4	212.7	1.0%	541994.8	-41569.5	1446.2
Glazing	**G11**	63462.0	185.9	141.0	19308.3	450.1	213.0	0.8%	558088.3	-57662.9	1447.2
Glazing	**G12**	63462.0	185.4	178.7	19270.6	355.2	212.5	1.1%	557118.6	-56693.2	1445.0
Sealing	**S1**	2187.7	185.5	166.8	19282.5	13.1	212.6	1.0%	498247.5	2177.9	1435.9
Sealing	**S2**	6465.3	183.2	331.0	19118.3	19.5	210.5	2.0%	498152.2	2273.2	1428.7
Sealing	**S3**	12403.3	180.8	482.7	18966.6	25.7	208.4	3.0%	499984.8	440.6	1421.7
Sealing	**S4**	20118.7	178.5	635.2	18814.0	31.7	206.4	3.9%	503511.1	-3085.7	1414.9
Sealing	**S5**	29650.6	176.1	788.9	18660.4	37.6	204.3	4.9%	508764.1	-8338.7	1406.4
Sealing	**S6**	40979.6	173.7	945.0	18504.3	43.4	202.2	5.9%	515689.2	-15263.8	1396.3
Sealing	**S7**	54086.0	171.2	1102.7	18346.5	49.0	200.0	6.9%	524287.6	-23862.2	1385.9
Sealing	**S8**	69009.0	168.8	1263.3	18186.0	54.6	197.9	7.9%	534568.0	-34142.6	1372.1
Sealing	**S9**	85709.5	166.3	1426.5	18022.8	60.1	195.7	8.9%	546499.5	-46074.1	1358.7
Insulation	**I1.02**	19435.8	172.4	1042.2	18407.1	18.6	200.9	6.5%	492381.1	8044.3	1349.6
Insulation	**I1.03**	71830.5	168.2	1319.1	18130.1	54.5	197.2	8.2%	535857.0	-35431.6	1343.7
Insulation	**I1.04**	76055.7	165.7	1475.2	17974.1	51.6	195.1	9.2%	535922.4	-35497.1	1327.8
Insulation	**I1.05**	96010.4	165.0	1521.2	17928.0	63.1	194.5	9.5%	554009.5	-53584.1	1323.6
Insulation	**I1.06**	102391.8	163.5	1621.3	17828.0	63.2	193.1	10.1%	557597.6	-57172.2	1308.9
Insulation	**I1.07**	111234.1	162.9	1657.6	17791.7	67.1	192.6	10.3%	565205.2	-64779.8	1303.9
Insulation	**I1.08**	115838.1	162.0	1718.2	17731.1	67.4	191.8	10.7%	568090.8	-67665.5	1293.7
Insulation	**I1.09**	136952.0	162.3	1699.8	17749.4	80.6	192.1	10.6%	588954.9	-88529.5	1312.8
Insulation	**I1.10**	140069.9	161.0	1785.0	17664.3	78.5	190.9	11.1%	589776.0	-89350.6	1298.3

Table D – 1 cont. Main energy and economic indicators related to Non-HVAC oriented BER measures for a Primary School.

BER Type	BER code	Total Cost Retrofit Project (£)	Total EUI (kWh/m²-year)	Annual Income (Savings + incentives) (£)	Annual Energy Bill (£)	Simple Payback (years)	Annual tCO2	Annual tCO2 Reduction	Life Cycle Cost (50 years) (£)	NPV (50 years) (£)	Thermal discomfort (hours)
Insulation	**I1.11**	169777.0	161.1	1777.0	17672.3	95.5	191.0	11.1%	618671.0	-118245.6	1300.4
Insulation	**I1.12**	171612.8	160.1	1845.2	17604.1	93.0	190.1	11.5%	618690.5	-118265.1	1289.1
Insulation	**I1.13**	186338.4	159.9	1854.3	17595.0	100.5	189.9	11.6%	632677.5	-132252.1	1288.2
Insulation	**I1.14**	186746.3	159.3	1896.1	17553.2	98.5	189.4	11.8%	631995.2	-131569.9	1279.9
Insulation	**I1.15**	67952.4	164.3	1574.3	17875.0	43.2	193.8	9.8%	525545.6	-25120.2	1289.9
Insulation	**I2.01**	13899.4	178.7	633.4	18815.9	21.9	206.5	3.9%	497553.0	2872.4	1387.7
Insulation	**I2.02**	22553.7	174.5	904.3	18544.9	24.9	202.8	5.6%	498938.9	1486.5	1362.7
Insulation	**I2.03**	32227.8	172.0	1068.0	18381.3	30.2	200.6	6.6%	504071.4	-3646.0	1345.9
Insulation	**I2.04**	38376.2	170.5	1169.8	18279.5	32.8	199.2	7.3%	507390.1	-6964.7	1336.4
Insulation	**I2.05**	46797.4	169.3	1246.3	18203.0	37.5	198.2	7.7%	513555.3	-13129.9	1329.0
Insulation	**I2.06**	54723.2	168.4	1303.8	18145.5	42.0	197.4	8.1%	519729.2	-19303.8	1321.8
Insulation	**I2.07**	60026.5	167.7	1348.3	18101.0	44.5	196.8	8.4%	523707.1	-23281.7	1317.5
Insulation	**I2.08**	68768.3	167.2	1384.3	18065.0	49.7	196.3	8.6%	531224.3	-30798.9	1313.4
Insulation	**I2.09**	73080.9	166.7	1413.7	18035.6	51.7	195.9	8.8%	534631.0	-34205.6	1310.2
Insulation	**I2.10**	77801.4	166.3	1438.5	18010.8	54.1	195.6	8.9%	538553.7	-38128.4	1307.8
Insulation	**I2.11**	81647.8	166.0	1459.4	17989.9	55.9	195.3	9.1%	541730.7	-41305.4	1305.0
Insulation	**I2.12**	84561.7	165.8	1477.6	17971.7	57.2	195.1	9.2%	544074.9	-43649.5	1302.7
Insulation	**I2.13**	86455.7	165.5	1496.0	17953.3	57.8	194.8	9.3%	545431.2	-45005.8	1300.9
Insulation	**I2.14**	87213.3	165.3	1506.4	17942.9	57.9	194.7	9.4%	545895.8	-45470.4	1299.6
Insulation	**I2.15**	93216.0	165.1	1518.7	17930.6	61.4	194.5	9.4%	551377.4	-50952.0	1297.6
Insulation	**I3.02**	12675.5	174.5	904.8	18544.5	14.0	202.8	5.6%	489387.9	11037.5	1362.6

Table D – 1 cont. Main energy and economic indicators related to Non-HVAC oriented BER measures for a Primary School.

BER Type	BER code	Total Cost Retrofit Project (£)	Total EUI (kWh/m²-year)	Annual Income (Savings + incentives) (£)	Annual Energy Bill (£)	Simple Payback (years)	Annual tCO2	Annual tCO2 Reduction	Life Cycle Cost (50 years) (£)	NPV (50 years) (£)	Thermal discomfort (hours)
Insulation	**I3.03**	13928.5	172.0	1068.1	18381.2	13.0	200.6	6.6%	486396.1	14029.3	1345.9
Insulation	**I3.04**	15181.5	170.5	1169.9	18279.3	13.0	199.2	7.3%	484985.1	15440.3	1336.1
Insulation	**I3.05**	16434.5	169.3	1247.0	18202.3	13.2	198.2	7.7%	484213.8	16211.6	1329.0
Insulation	**I3.06**	17687.4	168.4	1304.1	18145.2	13.6	197.4	8.1%	483952.9	16472.5	1321.6
Insulation	**I3.07**	18940.4	167.7	1348.9	18100.4	14.0	196.8	8.4%	484010.3	16415.0	1317.4
Insulation	**I3.08**	20193.4	167.2	1384.9	18064.4	14.6	196.3	8.6%	484295.7	16129.7	1313.1
Insulation	**I3.09**	21475.5	166.7	1414.4	18034.9	15.2	195.9	8.8%	484774.9	15650.4	1310.1
Insulation	**I3.10**	22728.5	166.3	1439.2	18010.1	15.8	195.6	8.9%	485347.2	15078.2	1307.5
Insulation	**I3.11**	23981.5	166.0	1460.1	17989.2	16.4	195.3	9.1%	486019.3	14406.1	1304.7
Insulation	**I3.12**	25234.5	165.7	1478.4	17970.9	17.1	195.1	9.2%	486756.8	13668.6	1303.1
Insulation	**I3.13**	26487.4	165.5	1493.7	17955.6	17.7	194.8	9.3%	487575.0	12850.4	1301.2
Insulation	**I3.14**	27740.4	165.3	1507.4	17941.9	18.4	194.7	9.4%	488432.6	11992.8	1299.2
Insulation	**I3.15**	28993.4	165.1	1522.0	17927.3	19.1	194.5	9.5%	489267.3	11158.0	1297.0
Insulation	**I4.04**	47234.5	171.4	1108.7	18340.6	42.6	200.0	6.9%	517517.1	-17091.7	1343.1
Insulation	**I4.05**	59880.9	170.2	1190.1	18259.2	50.3	199.0	7.4%	527636.6	-27211.2	1334.8
Insulation	**I4.06**	70837.2	169.2	1250.9	18198.4	56.6	198.1	7.8%	536654.4	-36229.1	1328.4
Insulation	**I4.07**	82667.6	168.5	1298.3	18151.0	63.7	197.5	8.1%	546859.8	-46434.4	1323.7
Insulation	**I4.08**	94469.0	167.9	1336.8	18112.5	70.7	197.0	8.3%	557267.7	-56842.3	1319.9
Insulation	**I4.09**	106241.2	167.4	1368.8	18080.5	77.6	196.5	8.5%	567813.5	-67388.1	1316.4
Insulation	**I4.10**	118100.8	167.0	1395.4	18053.9	84.6	196.2	8.7%	578581.4	-78156.0	1313.3
Insulation	**I4.11**	129931.2	166.6	1420.5	18028.8	91.5	195.8	8.8%	589361.0	-88935.6	1311.0

Table D – 1 cont. Main energy and economic indicators related to Non-HVAC oriented BER measures for a Primary School.

BER Type	BER code	Total Cost Retrofit Project (£)	Total EUI (kWh/m²-year)	Annual Income (Savings + incentives) (£)	Annual Energy Bill (£)	Simple Payback (years)	Annual tCO_2	Annual tCO_2 Reduction	Life Cycle Cost (50 years) (£)	NPV (50 years) (£)	Thermal discomfort (hours)
Insulation	**I4.12**	141674.3	166.4	1439.0	18010.3	98.5	195.6	8.9%	600227.8	-99802.4	1308.9
Insulation	**I4.13**	153533.9	166.1	1456.6	17992.7	105.4	195.4	9.1%	611228.5	-110803.1	1307.4
Insulation	**I4.14**	165335.3	165.9	1471.5	17977.8	112.4	195.2	9.1%	622241.7	-121816.3	1306.0
Insulation	**I4.15**	177136.6	165.7	1484.6	17964.7	119.3	195.0	9.2%	633303.7	-132878.3	1304.3
Insulation	**I4.16**	188967.1	165.5	1495.4	17953.9	126.4	194.8	9.3%	644451.2	-144025.8	1302.7
Insulation	**I4.17**	200739.3	165.4	1505.7	17943.6	133.3	194.7	9.4%	655555.1	-155129.7	1301.8
Insulation	**I4.18**	212540.6	165.2	1515.7	17933.6	140.2	194.6	9.4%	666696.4	-166271.0	1300.4
Insulation	**I5.065**	14773.5	165.8	1465.5	17983.8	10.1	195.2	9.1%	476986.2	23439.2	1303.9
Insulation	**I5.075**	18503.3	165.3	1502.9	17946.4	12.3	194.7	9.4%	479626.9	20798.5	1298.2
Insulation	**I5.085**	20106.0	164.8	1532.6	17916.7	13.1	194.3	9.6%	480409.5	20015.9	1294.3
Insulation	**I5.100**	22582.8	164.2	1567.7	17881.6	14.4	193.8	9.8%	481898.2	18527.2	1290.2
Insulation	**I6.02**	16230.5	175.1	863.0	18586.3	18.8	203.4	5.3%	493896.5	6528.9	1367.0
Insulation	**I6.03**	24360.3	172.7	1024.7	18424.6	23.8	201.2	6.3%	497586.6	2838.8	1352.2
Insulation	**I6.04**	32053.0	171.0	1134.0	18315.3	28.3	199.7	7.0%	502205.1	-1779.8	1341.7
Insulation	**I6.05**	42717.9	169.8	1212.5	18236.8	35.2	198.7	7.5%	510484.1	-10058.7	1334.1
Insulation	**I6.06**	48720.6	168.9	1271.1	18178.2	38.3	197.9	7.9%	514774.1	-14348.7	1327.3
Insulation	**I6.08**	64106.0	167.6	1355.3	18094.0	47.3	196.7	8.4%	527466.9	-27041.5	1320.5
Insulation	**I6.10**	81210.7	166.8	1410.0	18039.3	57.6	196.0	8.8%	542577.6	-42152.2	1314.3
Insulation	**I6.12**	96159.0	166.2	1449.7	17999.5	66.3	195.5	9.0%	555992.8	-55567.4	1309.9
Insulation	**I6.14**	112185.5	165.8	1481.0	17968.3	75.7	195.0	9.2%	570666.1	-70240.7	1306.9
Insulation	**I6.16**	121931.3	165.3	1512.9	17936.4	80.6	194.6	9.4%	579258.6	-78833.2	1302.0

Table D – 1 cont. Main energy and economic indicators related to Non-HVAC oriented BER measures for a Primary School.

BER Type	BER code	Total Cost Retrofit Project (£)	Total EUI (kWh/m²-year)	Annual Income (Savings + incentives) (£)	Annual Energy Bill (£)	Simple Payback (years)	Annual tCO_2	Annual tCO_2 Reduction	Life Cycle Cost (50 years) (£)	NPV (50 years) (£)	Thermal discomfort (hours)
Insulation	**I6.18**	133626.1	164.9	1538.3	17911.0	86.9	194.3	9.6%	589899.5	-89474.1	1298.2
Insulation	**I6.20**	141422.7	164.6	1556.2	17893.1	90.9	194.0	9.7%	596968.0	-96542.6	1295.9
Insulation	**I6.28**	192100.5	163.8	1612.5	17836.8	119.1	193.3	10.0%	644464.5	-144039.1	1289.0
Insulation	**I6.30**	195998.8	163.6	1622.3	17827.0	120.8	193.2	10.1%	647977.5	-147552.1	1287.4
Insulation	**I7.02**	16259.6	171.5	1102.6	18346.7	14.7	200.1	6.8%	487760.1	12665.3	1342.8
Insulation	**I7.03**	18619.9	169.3	1246.9	18202.4	14.9	198.2	7.7%	486326.0	14099.4	1328.2
Insulation	**I7.04**	26982.8	167.9	1335.0	18114.3	20.2	197.0	8.3%	492136.7	8288.6	1318.6
Insulation	**I7.05**	32315.3	167.0	1395.1	18054.2	23.2	196.2	8.7%	495738.8	4686.5	1311.8
Insulation	**I7.06**	38667.6	166.3	1438.7	18010.6	26.9	195.6	8.9%	500752.8	-327.4	1307.3
Insulation	**I7.07**	48050.4	165.8	1472.1	17977.2	32.6	195.1	9.2%	508955.9	-8530.5	1303.4
Insulation	**I7.08**	52858.3	165.4	1501.1	17948.2	35.2	194.7	9.3%	512853.4	-12428.1	1300.1
Insulation	**I7.09**	56529.9	165.1	1519.0	17930.3	37.2	194.5	9.4%	515938.3	-15512.9	1297.4
Insulation	**I7.10**	63785.5	164.9	1536.0	17913.3	41.5	194.3	9.6%	522508.0	-22082.6	1294.5
Insulation	**I8.005**	78092.8	176.9	747.9	18701.4	104.4	204.9	4.6%	556602.9	-56177.5	1372.9
Insulation	**I8.010**	129406.7	172.7	1021.0	18428.2	126.7	201.2	6.3%	599133.2	-98707.8	1349.9
Insulation	**I8.015**	221748.6	170.4	1173.1	18276.2	189.0	199.2	7.3%	684403.2	-183977.9	1334.9
Insulation	**I8.020**	282882.4	168.9	1269.0	18180.3	222.9	197.9	7.9%	740978.3	-240553.0	1324.6
Insulation	**I8.025**	364530.1	167.9	1335.0	18114.2	273.0	197.0	8.3%	818132.5	-317707.1	1318.2
Insulation	**I8.030**	421351.4	167.2	1384.0	18065.3	304.5	196.3	8.6%	871750.6	-371325.2	1313.4
Insulation	**I8.035**	507340.9	166.6	1420.9	18028.4	357.1	195.8	8.8%	953847.6	-453422.2	1309.1
Insulation	**I8.040**	568620.4	166.2	1451.8	17997.5	391.7	195.4	9.0%	1012235.6	-511810.2	1306.3

Table D – 1 cont. Main energy and economic indicators related to Non-HVAC oriented BER measures for a Primary School.

BER Type	BER code	Total Cost Retrofit Project (£)	Total EUI (kWh/m²-year)	Annual Income (Savings + incentives) (£)	Annual Energy Bill (£)	Simple Payback (years)	Annual tCO_2	Annual tCO_2 Reduction	Life Cycle Cost (50 years) (£)	NPV (50 years) (£)	Thermal discomfort (hours)
Insulation	**I9.010**	168278.3	164.2	1542.3	17907.0	109.1	193.9	9.7%	623262.1	-122836.7	1305.4
Insulation	**I9.020**	313973.8	165.5	1467.4	17981.9	214.0	195.0	9.2%	765901.4	-265476.0	1332.3
Lighting	**L1**	111145.6	186.1	473.5	18975.8	234.7	210.8	1.9%	595584.2	-95158.8	1444.2
Lighting	**L2**	108522.8	182.6	1835.9	17613.4	59.1	200.0	6.9%	557998.7	-57573.3	1461.6
Lighting	**L3**	128829.5	180.5	2684.0	16765.3	48.0	193.2	10.0%	555787.4	-55362.0	1474.3
Ren. solar	**R1**	342588.0	160.9	9307.1	10142.2	36.8	166.1	22.7%	591822.9	-91397.5	1443.0
Ren. solar	**R2**	685176.0	140.2	15951.0	3498.3	43.0	147.3	31.4%	751743.2	-251317.8	1443.1
Ren. solar	**R3**	1027764.0	117.5	22081.8	-2632.5	46.5	138.4	35.6%	924864.6	-424439.2	1443.1
Ren. Wind	**R4**	80000.0	181.1	3110.6	16338.7	25.7	207.2	3.5%	497653.4	2772.0	1443.1
Ren. Wind	**R5**	160000.0	180.4	3387.6	16061.7	47.2	206.8	3.7%	567788.9	-67363.5	1443.1

D.2 Primary School. Non-HVAC BER exergy and exergoeconomic indicators

Table D - 2 Main exergy and exergoeconomic indicators related to Non-HVAC oriented BER measures for a Primary School.

BER Type	BER code	Primary exergy input (kWhex/ m²-year)	Exergy dest. (kWhex/ m²-year)	Exergy efficiency Ψ Building (-)	Exergy dest. Cost Stream: heat (£)	Exergy dest. Cost Stream: cold (£)	Price Fuel Stream: heat (£/kWh)	Price Fuel Stream: cold (£/kWh)	Price Product Stream: heat (£/kWh)	Price Product Stream: cold (£/kWh)	Exergy dest. cost rate (£/h)	BER Capital Cost rate (£/h)	Annual revenue rate (£/h)	$Exec_{CB}$
	Base	267.4	241.9	0.095	9844.1	n/a	0.03	n/a	1.79	n/a	2.72	0.00	0.00	2.72
Set-point	**SH18**	248.7	223.8	0.100	8456.9	n/a	0.03	n/a	1.84	n/a	2.45	0.00	0.13	2.32
Set-point	**SH19**	263.1	237.8	0.096	9315.5	n/a	0.03	n/a	1.80	n/a	2.63	0.00	0.03	2.60
Set-point	**SH20**	279.3	253.2	0.093	10617.7	n/a	0.03	n/a	1.74	n/a	2.87	0.00	-0.08	2.95
Set-point	**SH21**	296.6	269.6	0.091	11824.3	n/a	0.03	n/a	1.68	n/a	3.11	0.00	-0.20	3.31
Set-point	**SH22**	315.0	287.0	0.089	13084.5	n/a	0.03	n/a	1.61	n/a	3.36	0.00	-0.33	3.69
Glazing	**G1**	265.6	240.2	0.095	9702.9	n/a	0.03	n/a	1.83	n/a	2.69	0.20	0.01	2.88
Glazing	**G2**	264.6	239.3	0.096	9639.2	n/a	0.03	n/a	1.85	n/a	2.68	0.29	0.02	2.94
Glazing	**G3**	264.3	239.0	0.096	9606.1	n/a	0.03	n/a	1.86	n/a	2.67	0.29	0.02	2.94
Glazing	**G4**	264.7	239.4	0.095	9641.5	n/a	0.03	n/a	1.85	n/a	2.68	0.36	0.02	3.02
Glazing	**G5**	264.0	238.8	0.096	9588.0	n/a	0.03	n/a	1.87	n/a	2.67	0.36	0.02	3.01
Glazing	**G6**	264.3	239.1	0.096	9616.7	n/a	0.03	n/a	1.86	n/a	2.67	0.48	0.02	3.13
Glazing	**G7**	263.7	238.5	0.096	9500.0	n/a	0.03	n/a	1.87	n/a	2.66	0.48	0.03	3.11
Glazing	**G8**	263.8	238.5	0.096	9509.8	n/a	0.03	n/a	1.87	n/a	2.66	0.52	0.03	3.15
Glazing	**G9**	263.4	238.2	0.096	9489.3	n/a	0.03	n/a	1.88	n/a	2.65	0.52	0.03	3.15
Glazing	**G10**	264.9	239.6	0.096	9651.0	n/a	0.03	n/a	1.85	n/a	2.68	0.20	0.02	2.86
Glazing	**G11**	265.2	239.9	0.096	9673.9	n/a	0.03	n/a	1.84	n/a	2.68	0.27	0.02	2.94
Glazing	**G12**	264.6	239.3	0.096	9633.3	n/a	0.03	n/a	1.85	n/a	2.68	0.27	0.02	2.93
Sealing	**S1**	264.8	239.5	0.096	9661.1	n/a	0.03	n/a	1.84	n/a	2.68	0.01	0.02	2.67

Table D – 2 cont. Main exergy and exergoeconomic indicators related to Non-HVAC oriented BER measures for a Primary School.

BER Type	BER code	Primary exergy input (kWhex / m²-year)	Exergy dest. (kWhex / m²-year)	Exergy efficiency Ψ Building (-)	Exergy dest. Cost Stream : heat (£)	Exergy dest. Cost Stream : cold (£)	Price Fuel Stream : heat (£/kWh)	Price Fuel Stream : cold (£/kWh)	Price Product Stream : heat (£/kWh)	Price Product Stream : cold (£/kWh)	Exergy dest. cost rate (£/h)	BER Capital Cost rate (£/h)	Annual revenue rate (£/h)	$Exec_{CB}$
Sealing	**S2**	262.1	237.0	0.096	9390.1	n/a	0.03	n/a	1.89	n/a	2.63	0.03	0.04	2.62
Sealing	**S3**	259.6	234.6	0.096	8934.0	n/a	0.03	n/a	1.94	n/a	2.57	0.05	0.06	2.57
Sealing	**S4**	257.1	232.2	0.097	8980.2	n/a	0.03	n/a	2.00	n/a	2.56	0.09	0.07	2.57
Sealing	**S5**	254.5	229.8	0.097	8741.2	n/a	0.03	n/a	2.07	n/a	2.51	0.13	0.09	2.55
Sealing	**S6**	251.9	227.3	0.098	8501.7	n/a	0.03	n/a	2.13	n/a	2.47	0.18	0.11	2.54
Sealing	**S7**	249.3	224.8	0.098	8277.6	n/a	0.03	n/a	2.21	n/a	2.43	0.23	0.13	2.54
Sealing	**S8**	246.6	222.3	0.099	8016.8	n/a	0.03	n/a	2.29	n/a	2.39	0.30	0.14	2.54
Sealing	**S9**	244.0	219.7	0.099	7787.4	n/a	0.03	n/a	2.38	n/a	2.34	0.37	0.16	2.55
Insulation	**I1.02**	250.5	226.0	0.098	8586.0	n/a	0.03	n/a	2.20	n/a	2.47	0.08	0.12	2.44
Insulation	**I1.03**	245.9	221.7	0.099	7953.6	n/a	0.03	n/a	2.40	n/a	2.38	0.31	0.15	2.53
Insulation	**I1.04**	243.3	219.2	0.099	7959.4	n/a	0.03	n/a	2.49	n/a	2.36	0.33	0.17	2.52
Insulation	**I1.05**	242.6	218.5	0.099	7807.2	n/a	0.03	n/a	2.50	n/a	2.34	0.41	0.17	2.58
Insulation	**I1.06**	240.9	216.9	0.100	7679.0	n/a	0.03	n/a	2.57	n/a	2.31	0.44	0.19	2.57
Insulation	**I1.07**	240.3	216.3	0.100	7606.6	n/a	0.03	n/a	2.60	n/a	2.30	0.48	0.19	2.59
Insulation	**I1.08**	239.3	215.4	0.100	7489.7	n/a	0.03	n/a	2.65	n/a	2.28	0.50	0.20	2.58
Insulation	**I1.09**	239.6	215.7	0.100	7532.4	n/a	0.03	n/a	2.67	n/a	2.29	0.59	0.19	2.68
Insulation	**I1.10**	238.2	214.3	0.100	7379.4	n/a	0.03	n/a	2.75	n/a	2.26	0.60	0.20	2.66
Insulation	**I1.11**	238.3	214.4	0.100	7190.1	n/a	0.03	n/a	2.74	n/a	2.24	0.73	0.20	2.77
Insulation	**I1.12**	237.2	213.4	0.100	7290.3	n/a	0.03	n/a	2.81	n/a	2.25	0.74	0.21	2.77

Table D – 2 cont. Main exergy and exergoeconomic indicators related to Non-HVAC oriented BER measures for a Primary School.

BER Type	BER code	Primary exergy input (kWhex / m²-year)	Exergy dest. (kWhex / m²-year)	Exergy efficiency Ψ Building (-)	Exergy dest. Cost Stream : heat (£)	Exergy dest. Cost Stream : cold (£)	Price Fuel Stream : heat (£/kWh)	Price Fuel Stream : cold (£/kWh)	Price Product Stream : heat (£/kWh)	Price Product Stream : cold (£/kWh)	Exergy dest. cost rate (£/h)	BER Capital Cost rate (£/h)	Annual revenue rate (£/h)	$Exec_{CB}$
Insulation	**I1.13**	237.0	213.2	0.100	7274.0	n/a	0.03	n/a	2.82	n/a	2.24	0.80	0.21	2.83
Insulation	**I1.14**	236.3	212.5	0.101	7180.9	n/a	0.03	n/a	2.86	n/a	2.23	0.80	0.22	2.81
Insulation	**I1.15**	241.7	217.6	0.100	7612.9	n/a	0.03	n/a	2.46	n/a	2.31	0.29	0.18	2.42
Insulation	**I2.01**	257.3	232.4	0.097	8856.7	n/a	0.03	n/a	2.01	n/a	2.55	0.06	0.07	2.53
Insulation	**I2.02**	252.8	228.2	0.097	8792.1	n/a	0.03	n/a	2.14	n/a	2.51	0.10	0.10	2.50
Insulation	**I2.03**	250.1	225.6	0.098	8353.4	n/a	0.03	n/a	2.21	n/a	2.45	0.14	0.12	2.46
Insulation	**I2.04**	248.4	224.0	0.098	8409.1	n/a	0.03	n/a	2.25	n/a	2.44	0.16	0.13	2.47
Insulation	**I2.05**	247.1	222.8	0.098	8289.8	n/a	0.03	n/a	2.27	n/a	2.42	0.20	0.14	2.48
Insulation	**I2.06**	246.2	221.9	0.099	8217.0	n/a	0.03	n/a	2.30	n/a	2.41	0.23	0.15	2.49
Insulation	**I2.07**	245.4	221.2	0.099	7994.8	n/a	0.03	n/a	2.32	n/a	2.38	0.26	0.15	2.48
Insulation	**I2.08**	244.8	220.6	0.099	7924.5	n/a	0.03	n/a	2.33	n/a	2.37	0.29	0.16	2.50
Insulation	**I2.09**	244.4	220.2	0.099	7867.8	n/a	0.03	n/a	2.35	n/a	2.36	0.31	0.16	2.51
Insulation	**I2.10**	243.9	219.8	0.099	7816.4	n/a	0.03	n/a	2.37	n/a	2.35	0.33	0.16	2.52
Insulation	**I2.11**	243.6	219.4	0.099	7806.7	n/a	0.03	n/a	2.38	n/a	2.34	0.35	0.17	2.53
Insulation	**I2.12**	243.3	219.2	0.099	7775.1	n/a	0.03	n/a	2.39	n/a	2.34	0.36	0.17	2.53
Insulation	**I2.13**	243.0	218.9	0.099	7747.1	n/a	0.03	n/a	2.40	n/a	2.33	0.37	0.17	2.53
Insulation	**I2.14**	242.8	218.7	0.099	7736.4	n/a	0.03	n/a	2.41	n/a	2.33	0.37	0.17	2.53
Insulation	**I2.15**	242.6	218.5	0.099	7722.8	n/a	0.03	n/a	2.42	n/a	2.33	0.40	0.17	2.56
Insulation	**I3.02**	252.8	228.2	0.097	8789.9	n/a	0.03	n/a	2.14	n/a	2.51	0.05	0.10	2.46

Table D – 2 cont. Main exergy and exergoeconomic indicators related to Non-HVAC oriented BER measures for a Primary School.

BER Type	BER code	Primary exergy input (kWhex/ m²-year)	Exergy dest. (kWhex/ m²-year)	Exergy efficiency Ψ Building (-)	Exergy dest. Cost Stream: heat (£)	Exergy dest. Cost Stream: cold (£)	Price Fuel Stream: heat (£/kWh)	Price Fuel Stream: cold (£/kWh)	Price Product Stream: heat (£/kWh)	Price Product Stream: cold (£/kWh)	Exergy dest. cost rate (£/h)	BER Capital Cost rate (£/h)	Annual revenue rate (£/h)	$Exec_{CB}$
Insulation	**I3.03**	250.1	225.6	0.098	8206.1	n/a	0.03	n/a	2.21	n/a	2.43	0.06	0.12	2.37
Insulation	**I3.04**	248.4	224.0	0.098	8412.2	n/a	0.03	n/a	2.25	n/a	2.44	0.07	0.13	2.37
Insulation	**I3.05**	247.1	222.8	0.098	8295.5	n/a	0.03	n/a	2.27	n/a	2.42	0.07	0.14	2.35
Insulation	**I3.06**	246.2	221.9	0.099	8215.7	n/a	0.03	n/a	2.29	n/a	2.41	0.08	0.15	2.33
Insulation	**I3.07**	245.4	221.2	0.099	8002.7	n/a	0.03	n/a	2.31	n/a	2.38	0.08	0.15	2.30
Insulation	**I3.08**	244.8	220.6	0.099	7919.5	n/a	0.03	n/a	2.33	n/a	2.36	0.09	0.16	2.29
Insulation	**I3.09**	244.3	220.1	0.099	7865.2	n/a	0.03	n/a	2.35	n/a	2.36	0.09	0.16	2.29
Insulation	**I3.10**	243.9	219.8	0.099	7575.5	n/a	0.03	n/a	2.36	n/a	2.32	0.10	0.16	2.25
Insulation	**I3.11**	243.6	219.4	0.099	7801.8	n/a	0.03	n/a	2.38	n/a	2.34	0.10	0.17	2.28
Insulation	**I3.12**	243.3	219.1	0.099	7777.2	n/a	0.03	n/a	2.39	n/a	2.34	0.11	0.17	2.28
Insulation	**I3.13**	243.0	218.9	0.099	7746.6	n/a	0.03	n/a	2.40	n/a	2.33	0.11	0.17	2.28
Insulation	**I3.14**	242.8	218.7	0.099	7733.7	n/a	0.03	n/a	2.41	n/a	2.33	0.12	0.17	2.28
Insulation	**I3.15**	242.6	218.5	0.099	7660.5	n/a	0.03	n/a	2.42	n/a	2.32	0.12	0.17	2.27
Insulation	**I4.04**	249.4	225.0	0.098	8495.3	n/a	0.03	n/a	2.22	n/a	2.46	0.20	0.13	2.53
Insulation	**I4.05**	248.1	223.7	0.098	8375.0	n/a	0.03	n/a	2.25	n/a	2.44	0.26	0.14	2.56
Insulation	**I4.06**	247.1	222.7	0.098	8287.6	n/a	0.03	n/a	2.28	n/a	2.42	0.30	0.14	2.58
Insulation	**I4.07**	246.3	222.0	0.099	8212.6	n/a	0.03	n/a	2.30	n/a	2.41	0.35	0.15	2.61
Insulation	**I4.08**	245.6	221.4	0.099	8004.7	n/a	0.03	n/a	2.32	n/a	2.38	0.40	0.15	2.63
Insulation	**I4.09**	245.1	220.9	0.099	7938.6	n/a	0.03	n/a	2.33	n/a	2.37	0.46	0.16	2.67

Table D – 2 cont. Main exergy and exergoeconomic indicators related to Non-HVAC oriented BER measures for a Primary School.

BER Type	BER code	Primary exergy input (kWhex/ m²-year)	Exergy dest. (kWhex/ m²-year)	Exergy efficiency Ψ Building (-)	Exergy dest. Cost Stream: heat (£)	Exergy dest. Cost Stream: cold (£)	Price Fuel Stream: heat (£/kWh)	Price Fuel Stream: cold (£/kWh)	Price Product Stream: heat (£/kWh)	Price Product Stream: cold (£/kWh)	Exergy dest. cost rate (£/h)	BER Capital Cost rate (£/h)	Annual revenue rate (£/h)	$Exec_{CB}$
Insulation	**I4.10**	244.7	220.5	0.099	7888.2	n/a	0.03	n/a	2.35	n/a	2.36	0.51	0.16	2.71
Insulation	**I4.11**	244.3	220.1	0.099	7837.8	n/a	0.03	n/a	2.36	n/a	2.35	0.56	0.16	2.75
Insulation	**I4.12**	244.0	219.8	0.099	7823.0	n/a	0.03	n/a	2.38	n/a	2.35	0.61	0.16	2.79
Insulation	**I4.13**	243.7	219.5	0.099	7798.6	n/a	0.03	n/a	2.39	n/a	2.34	0.66	0.17	2.84
Insulation	**I4.14**	243.4	219.3	0.099	7781.9	n/a	0.03	n/a	2.40	n/a	2.34	0.71	0.17	2.88
Insulation	**I4.15**	243.2	219.1	0.099	7762.6	n/a	0.03	n/a	2.41	n/a	2.34	0.76	0.17	2.93
Insulation	**I4.16**	243.0	218.9	0.099	7745.0	n/a	0.03	n/a	2.42	n/a	2.33	0.81	0.17	2.97
Insulation	**I4.17**	242.9	218.7	0.099	7712.0	n/a	0.03	n/a	2.43	n/a	2.33	0.86	0.17	3.02
Insulation	**I4.18**	242.7	218.6	0.099	7702.0	n/a	0.03	n/a	2.44	n/a	2.33	0.91	0.17	3.07
Insulation	**I5.065**	243.4	219.2	0.099	8054.6	n/a	0.03	n/a	2.33	n/a	2.37	0.06	0.17	2.27
Insulation	**I5.075**	242.8	218.6	0.100	8002.7	n/a	0.03	n/a	2.34	n/a	2.36	0.08	0.17	2.27
Insulation	**I5.085**	242.3	218.2	0.100	7784.6	n/a	0.03	n/a	2.35	n/a	2.33	0.09	0.17	2.25
Insulation	**I5.100**	241.7	217.6	0.100	7898.6	n/a	0.03	n/a	2.36	n/a	2.34	0.10	0.18	2.26
Insulation	**I6.02**	253.5	228.8	0.097	8849.9	n/a	0.03	n/a	2.12	n/a	2.52	0.07	0.10	2.49
Insulation	**I6.03**	250.8	226.3	0.098	8370.5	n/a	0.03	n/a	2.19	n/a	2.45	0.10	0.12	2.44
Insulation	**I6.04**	249.0	224.6	0.098	8449.7	n/a	0.03	n/a	2.24	n/a	2.45	0.14	0.13	2.46
Insulation	**I6.05**	247.7	223.4	0.098	8137.5	n/a	0.03	n/a	2.27	n/a	2.41	0.18	0.14	2.45
Insulation	**I6.06**	246.7	222.4	0.098	8259.3	n/a	0.03	n/a	2.29	n/a	2.41	0.21	0.15	2.48
Insulation	**I6.08**	245.3	221.1	0.099	7966.2	n/a	0.03	n/a	2.33	n/a	2.37	0.27	0.15	2.49
Insulation	**I6.10**	244.4	220.3	0.099	7870.4	n/a	0.03	n/a	2.37	n/a	2.36	0.35	0.16	2.54

Table D – 2 cont. Main exergy and exergoeconomic indicators related to Non-HVAC oriented BER measures for a Primary School.

BER Type	BER code	Primary exergy input (kWhex/ m²-year)	Exergy dest. (kWhex/ m²-year)	Exergy efficiency Ψ Building (-)	Exergy dest. Cost Stream: heat (£)	Exergy dest. Cost Stream: cold (£)	Price Fuel Stream: heat (£/kWh)	Price Fuel Stream: cold (£/kWh)	Price Product Stream: heat (£/kWh)	Price Product Stream: cold (£/kWh)	Exergy dest. cost rate (£/h)	BER Capital Cost rate (£/h)	Annual revenue rate (£/h)	$Exec_{CB}$
Insulation	**I6.12**	243.8	219.6	0.099	7803.9	n/a	0.03	n/a	2.40	n/a	2.35	0.41	0.17	2.59
Insulation	**I6.14**	243.3	219.2	0.099	7768.9	n/a	0.03	n/a	2.43	n/a	2.34	0.48	0.17	2.65
Insulation	**I6.16**	242.8	218.7	0.099	7690.8	n/a	0.03	n/a	2.45	n/a	2.33	0.52	0.17	2.68
Insulation	**I6.18**	242.3	218.3	0.099	7658.8	n/a	0.03	n/a	2.47	n/a	2.32	0.57	0.18	2.72
Insulation	**I6.20**	242.0	218.0	0.099	7635.9	n/a	0.03	n/a	2.49	n/a	2.32	0.61	0.18	2.74
Insulation	**I6.28**	241.1	217.1	0.099	7528.1	n/a	0.03	n/a	2.54	n/a	2.30	0.82	0.18	2.94
Insulation	**I6.30**	241.0	217.0	0.100	7493.5	n/a	0.03	n/a	2.55	n/a	2.29	0.84	0.19	2.95
Insulation	**I7.02**	249.5	225.1	0.098	8502.1	n/a	0.03	n/a	2.22	n/a	2.46	0.07	0.13	2.40
Insulation	**I7.03**	247.1	222.8	0.098	8291.0	n/a	0.03	n/a	2.27	n/a	2.42	0.08	0.14	2.36
Insulation	**I7.04**	245.7	221.4	0.099	8021.7	n/a	0.03	n/a	2.31	n/a	2.38	0.12	0.15	2.34
Insulation	**I7.05**	244.7	220.4	0.099	7900.1	n/a	0.03	n/a	2.34	n/a	2.36	0.14	0.16	2.34
Insulation	**I7.06**	243.9	219.8	0.099	7826.1	n/a	0.03	n/a	2.37	n/a	2.35	0.17	0.16	2.35
Insulation	**I7.07**	243.4	219.2	0.099	7783.2	n/a	0.03	n/a	2.39	n/a	2.34	0.21	0.17	2.38
Insulation	**I7.08**	242.9	218.8	0.099	7749.4	n/a	0.03	n/a	2.41	n/a	2.33	0.23	0.17	2.39
Insulation	**I7.09**	242.6	218.5	0.099	7723.3	n/a	0.03	n/a	2.42	n/a	2.33	0.24	0.17	2.40
Insulation	**I7.10**	242.3	218.2	0.099	7670.2	n/a	0.03	n/a	2.43	n/a	2.32	0.27	0.18	2.42
Insulation	**I8.005**	255.4	230.6	0.097	8913.2	n/a	0.03	n/a	2.07	n/a	2.54	0.33	0.09	2.79
Insulation	**I8.010**	250.9	226.4	0.098	8620.6	n/a	0.03	n/a	2.19	n/a	2.48	0.55	0.12	2.92
Insulation	**I8.015**	248.4	224.0	0.098	8408.0	n/a	0.03	n/a	2.25	n/a	2.44	0.95	0.13	3.26
Insulation	**I8.020**	246.8	222.4	0.099	8268.2	n/a	0.03	n/a	2.28	n/a	2.42	1.21	0.14	3.48

Table D – 2 cont. Main exergy and exergoeconomic indicators related to Non-HVAC oriented BER measures for a Primary School.

BER Type	BER code	Primary exergy input (kWhex/ m²-year)	Exergy dest. (kWhex/ m²-year)	Exergy efficiency Ψ Building (-)	Exergy dest. Cost Stream: heat (£)	Exergy dest. Cost Stream: cold (£)	Price Fuel Stream: heat (£/kWh)	Price Fuel Stream: cold (£/kWh)	Price Product Stream: heat (£/kWh)	Price Product Stream: cold (£/kWh)	Exergy dest. cost rate (£/h)	BER Capital Cost rate (£/h)	Annual revenue rate (£/h)	$Exec_{CB}$
Insulation	**I8.025**	245.7	221.4	0.099	8013.3	n/a	0.03	n/a	2.31	n/a	2.38	1.56	0.15	3.79
Insulation	**I8.030**	244.8	220.6	0.099	7921.6	n/a	0.03	n/a	2.34	n/a	2.37	1.81	0.16	4.01
Insulation	**I8.035**	244.2	220.1	0.099	7850.0	n/a	0.03	n/a	2.36	n/a	2.35	2.17	0.16	4.37
Insulation	**I8.040**	243.7	219.6	0.099	7808.2	n/a	0.03	n/a	2.38	n/a	2.35	2.44	0.17	4.62
Insulation	**I9.010**	241.9	217.6	0.100	7857.4	n/a	0.03	n/a	2.29	n/a	2.34	0.72	0.18	2.88
Insulation	**I9.020**	243.2	219.0	0.100	7976.5	n/a	0.03	n/a	2.36	n/a	2.36	1.35	0.17	3.54
Lighting	**L1**	262.5	237.4	0.096	9882.6	n/a	0.03	n/a	1.79	n/a	2.68	0.48	0.05	3.10
Lighting	**L2**	249.2	225.3	0.096	10153.2	n/a	0.03	n/a	1.75	n/a	2.59	0.47	0.21	2.84
Lighting	**L3**	241.0	217.8	0.096	10343.3	n/a	0.03	n/a	1.73	n/a	2.53	0.55	0.31	2.78
Ren. solar	**R1**	267.4	241.9	0.095	9769.2	n/a	0.03	n/a	1.78	n/a	2.71	1.47	1.06	3.11
Ren. solar	**R2**	267.4	241.9	0.096	9926.8	n/a	0.03	n/a	1.77	n/a	2.73	2.94	1.82	3.84
Ren. solar	**R3**	267.4	241.9	0.096	9962.0	n/a	0.03	n/a	1.76	n/a	2.73	4.40	2.52	4.61
Ren. Wind	**R4**	267.4	241.9	0.095	9844.4	n/a	0.03	n/a	1.79	n/a	2.72	0.34	0.36	2.70
Ren. Wind	**R5**	267.4	241.9	0.095	9844.8	n/a	0.03	n/a	1.79	n/a	2.72	0.69	0.39	3.02

D.3 A/C Office Non-HVAC BER energy economic carbon emission and thermal comfort indicators

Table D - 3 Main energy and economic indicators related to Non-HVAC oriented BER measures for an A/C Office.

BER Type	BER code	Total Cost Retrofit Project (£)	Total EUI (kWh/m²-year)	Annual Income (Savings + incentives) (£)	Annual Energy Bill (£)	Simple Payback (years)	Annual tCO_2	Annual tCO_2 Reduction	Life Cycle Cost (50 years) (£)	NPV (50 years) (£)	Thermal discomfort (hours)
--	**Base**	0.0	288.5	0.0	59625.3	0.0	285.6	0.0%	1534145.9	0.0	1413.8
Set-point	**SH18**	0.0	288.5	-59.8	59685.2	0.0	285.8	-0.1%	1535685.6	-1539.7	1413.8
Set-point	**SH19**	0.0	288.5	-58.1	59683.5	0.0	285.8	-0.1%	1535641.3	-1495.4	1413.8
Set-point	**SH20**	0.0	288.5	-56.8	59682.2	0.0	285.8	-0.1%	1535607.6	-1461.7	1413.8
Set-point	**SH21**	0.0	288.5	-56.7	59682.0	0.0	285.8	-0.1%	1535603.5	-1457.6	1413.8
Set-point	**SH22**	0.0	288.5	1.8	59623.6	0.0	285.6	0.0%	1534100.4	45.5	1413.8
Set-point	**SC23**	0.0	292.6	-751.3	60376.6	0.0	289.3	-1.3%	1553475.4	-19329.5	1351.4
Set-point	**SC24**	0.0	288.5	1.8	59623.6	0.0	285.6	0.0%	1534100.4	45.5	1413.8
Set-point	**SC25**	0.0	284.4	709.6	58915.8	0.0	282.0	1.3%	1515888.3	18257.6	1463.9
Set-point	**SC26**	0.0	280.2	1399.0	58226.3	0.0	278.4	2.5%	1498149.7	35996.2	1492.3
Set-point	**SC27**	0.0	276.1	2037.6	57587.8	0.0	275.1	3.7%	1481719.2	52426.7	1509.1
Glazing	**G1**	141201.0	277.8	1487.2	58138.1	94.9	277.4	2.9%	1632250.3	-98104.4	1374.0
Glazing	**G2**	200170.0	272.3	1865.1	57760.2	107.3	274.6	3.8%	1679477.3	-145331.4	1372.3
Glazing	**G3**	200170.0	270.4	1992.3	57633.0	100.5	273.6	4.2%	1676205.0	-142059.0	1372.2
Glazing	**G4**	252647.0	272.5	2158.9	57466.4	117.0	273.7	4.2%	1722600.4	-188454.4	1352.4
Glazing	**G5**	252647.0	268.2	2448.0	57177.4	103.2	271.5	4.9%	1715163.2	-181017.2	1352.8
Glazing	**G6**	331633.0	270.0	2321.6	57303.7	142.8	272.4	4.6%	1794697.5	-260551.6	1350.8
Glazing	**G7**	331633.0	266.6	2562.4	57063.0	129.4	270.6	5.2%	1788502.3	-254356.4	1350.7

Table D- 3 cont. Main energy and economic indicators related to Non-HVAC oriented BER measures for an A/C Office.

BER Type	BER code	Total Cost Retrofit Project (£)	Total EUI (kWh/m^2-year)	Annual Income (Savings + incentives) (£)	Annual Energy Bill (£)	Simple Payback (years)	Annual tCO_2	Annual tCO_2 Reduction	Life Cycle Cost (50 years) (£)	NPV (50 years) (£)	Thermal discomfort (hours)
Glazing	**G8**	353273.0	266.8	2544.1	57081.3	138.9	270.7	5.2%	1809872.7	-275726.8	1351.1
Glazing	**G9**	353273.0	264.9	2679.7	56945.6	131.8	269.7	5.6%	1806383.3	-272237.3	1348.5
Glazing	**G10**	141201.0	273.9	1747.2	57878.2	80.8	275.5	3.5%	1625560.8	-91414.9	1369.5
Glazing	**G11**	189350.0	275.3	1654.3	57971.1	114.5	276.2	3.3%	1674452.9	-140307.0	1370.9
Glazing	**G12**	189350.0	272.0	1879.3	57746.0	100.8	274.5	3.9%	1668662.9	-134517.0	1372.2
Sealing	**S1**	3097.6	279.7	683.8	58941.6	4.5	280.7	1.7%	1519544.6	14601.3	1408.4
Sealing	**S2**	8578.0	270.9	1359.7	58265.6	6.3	275.9	3.4%	1507445.1	26700.8	1405.7
Sealing	**S3**	16441.0	261.9	2072.6	57552.8	7.9	271.0	5.1%	1496697.1	37448.8	1397.8
Sealing	**S4**	26687.0	253.4	2756.5	56868.9	9.7	266.2	6.8%	1488996.7	45149.2	1389.7
Sealing	**S5**	39316.0	244.5	3505.4	56120.0	11.2	261.1	8.6%	1481924.3	52221.6	1393.8
Sealing	**S6**	54327.0	236.6	4095.6	55529.8	13.3	256.9	10.1%	1481236.3	52909.6	1392.3
Sealing	**S7**	71722.0	229.0	4658.9	54966.4	15.4	252.8	11.5%	1483540.7	50605.2	1382.8
Sealing	**S8**	91499.0	221.6	5185.2	54440.1	17.6	248.9	12.8%	1489100.2	45045.7	1362.9
Sealing	**S9**	113659.0	215.1	5636.8	53988.5	20.2	245.5	14.0%	1498881.9	35264.0	1328.7
Insulation	**I1.02**	20005.9	268.9	1361.8	58263.6	14.7	275.4	3.6%	1518429.5	15716.4	1347.4
Insulation	**I1.03**	25233.0	266.0	1539.5	58085.8	16.4	273.9	4.1%	1518904.6	15241.3	1343.1
Insulation	**I1.04**	29587.6	264.4	1638.0	57987.3	18.1	273.1	4.4%	1520574.8	13571.2	1344.6
Insulation	**I1.05**	33522.4	263.3	1694.7	57930.6	19.8	272.6	4.5%	1522916.3	11229.7	1347.5
Insulation	**I1.06**	40092.4	262.4	1744.2	57881.1	23.0	272.2	4.7%	1527988.6	6157.3	1349.0
Insulation	**I1.07**	45450.5	261.9	1777.4	57848.0	25.6	272.0	4.8%	1532309.7	1836.2	1350.9

Table D - 3 cont. Main energy and economic indicators related to Non-HVAC oriented BER measures for an A/C Office.

BER Type	BER code	Total Cost Retrofit Project (£)	Total EUI (kWh/m²-year)	Annual Income (Savings + incentives) (£)	Annual Energy Bill (£)	Simple Payback (years)	Annual tCO_2	Annual tCO_2 Reduction	Life Cycle Cost (50 years) (£)	NPV (50 years) (£)	Thermal discomfort (hours)
Insulation	**I1.08**	50201.7	261.1	1833.5	57791.9	27.4	271.5	4.9%	1535455.7	-1309.8	1352.7
Insulation	**I1.09**	53827.1	260.5	1872.9	57752.5	28.7	271.2	5.0%	1537942.3	-3796.3	1353.5
Insulation	**I1.10**	57027.9	260.2	1891.8	57733.6	30.1	271.1	5.1%	1540547.8	-6401.8	1351.8
Insulation	**I1.11**	60357.5	260.0	1891.2	57734.2	31.9	271.0	5.1%	1543778.6	-9632.7	1353.6
Insulation	**I1.12**	62237.2	259.8	1891.4	57733.9	32.9	271.0	5.1%	1545587.6	-11441.6	1355.8
Insulation	**I1.13**	66214.7	259.4	1904.1	57721.3	34.8	270.8	5.2%	1549104.0	-14958.1	1357.3
Insulation	**I1.14**	66637.8	259.0	1938.5	57686.8	34.4	270.6	5.3%	1548625.5	-14479.5	1357.8
Insulation	**I1.15**	69960.1	258.6	1968.3	57657.0	35.5	270.4	5.3%	1551067.3	-16921.4	1357.5
Insulation	**I2.01**	14317.8	275.3	981.8	58643.6	14.6	278.5	2.5%	1522712.9	11433.1	1357.0
Insulation	**I2.02**	23232.2	271.1	1235.0	58390.4	18.8	276.4	3.2%	1524807.7	9338.2	1350.8
Insulation	**I2.03**	33183.6	268.5	1387.4	58238.0	23.9	275.2	3.6%	1530497.2	3648.8	1347.4
Insulation	**I2.04**	39503.0	266.7	1503.7	58121.6	26.3	274.2	4.0%	1533607.2	538.7	1344.5
Insulation	**I2.05**	48170.0	265.2	1589.0	58036.3	30.3	273.5	4.2%	1539782.4	-5636.4	1342.6
Insulation	**I2.06**	56341.0	264.1	1660.6	57964.7	33.9	273.0	4.4%	1545831.5	-11685.6	1345.5
Insulation	**I2.07**	61790.0	263.4	1697.7	57927.6	36.4	272.6	4.5%	1550139.3	-15993.3	1347.8
Insulation	**I2.08**	70789.0	262.7	1739.3	57886.0	40.7	272.3	4.6%	1557760.3	-23614.3	1349.0
Insulation	**I2.09**	75225.0	262.3	1755.0	57870.4	42.9	272.2	4.7%	1561642.6	-27496.6	1349.3
Insulation	**I2.10**	80091.0	261.9	1772.0	57853.4	45.2	272.0	4.8%	1565903.9	-31758.0	1351.2
Insulation	**I2.11**	84065.0	261.3	1816.2	57809.1	46.3	271.7	4.9%	1568603.9	-34458.0	1351.3
Insulation	**I2.12**	87063.0	261.0	1837.6	57787.7	47.4	271.5	4.9%	1570948.4	-36802.5	1353.7

Table D - 3 cont. Main energy and economic indicators related to Non-HVAC oriented BER measures for an A/C Office.

BER Type	BER code	Total Cost Retrofit Project (£)	Total EUI (kWh/m²-year)	Annual Income (Savings + incentives) (£)	Annual Energy Bill (£)	Simple Payback (years)	Annual tCO_2	Annual tCO_2 Reduction	Life Cycle Cost (50 years) (£)	NPV (50 years) (£)	Thermal discomfort (hours)
Insulation	**I2.13**	89004.0	260.5	1871.4	57753.9	47.6	271.2	5.0%	1571953.1	-37807.2	1354.7
Insulation	**I2.14**	89802.0	260.1	1903.2	57722.2	47.2	271.0	5.1%	1571906.9	-37761.0	1352.7
Insulation	**I2.15**	95972.0	259.9	1910.4	57715.0	50.2	271.0	5.1%	1577680.3	-43534.3	1353.0
Insulation	**I3.02**	13057.1	271.1	1235.1	58390.3	10.6	276.4	3.2%	1514978.5	19167.5	1350.5
Insulation	**I3.03**	14348.7	268.6	1384.7	58240.7	10.4	275.2	3.6%	1512375.9	21770.0	1347.3
Insulation	**I3.04**	15640.2	266.6	1508.8	58116.6	10.4	274.2	4.0%	1510430.9	23715.0	1344.3
Insulation	**I3.05**	16931.8	265.3	1576.4	58048.9	10.7	273.6	4.2%	1509937.7	24208.2	1342.8
Insulation	**I3.06**	18223.3	264.2	1647.5	57977.9	11.1	273.1	4.4%	1509357.2	24788.7	1345.7
Insulation	**I3.07**	19514.6	263.2	1715.1	57910.2	11.4	272.5	4.6%	1508863.2	25282.7	1347.3
Insulation	**I3.08**	20806.2	262.8	1722.9	57902.4	12.1	272.4	4.6%	1509910.2	24235.8	1349.3
Insulation	**I3.09**	22097.7	262.4	1750.8	57874.6	12.6	272.2	4.7%	1510441.1	23704.8	1349.6
Insulation	**I3.10**	23389.2	261.9	1781.2	57844.2	13.1	271.9	4.8%	1510906.0	23239.9	1350.8
Insulation	**I3.11**	24680.6	261.3	1818.9	57806.4	13.6	271.6	4.9%	1511181.9	22964.0	1351.3
Insulation	**I3.12**	25972.4	260.9	1846.8	57778.6	14.1	271.4	5.0%	1511713.2	22432.7	1353.5
Insulation	**I3.13**	27264.0	260.4	1880.7	57744.7	14.5	271.2	5.0%	1512087.9	22058.1	1353.4
Insulation	**I3.14**	28554.8	260.2	1894.5	57730.8	15.1	271.1	5.1%	1512977.9	21168.0	1352.1
Insulation	**I3.15**	29846.6	260.1	1892.5	57732.9	15.8	271.1	5.1%	1514278.2	19867.7	1352.8
Insulation	**I4.04**	48645.0	267.8	1423.7	58201.6	34.2	274.8	3.8%	1544494.0	-10348.1	1348.7
Insulation	**I4.05**	60769.0	265.9	1563.0	58062.4	38.9	273.8	4.1%	1552620.8	-18474.9	1344.8
Insulation	**I4.06**	72936.0	265.1	1602.2	58023.1	45.5	273.5	4.2%	1563361.6	-29215.7	1344.8

Table D -3 cont. Main energy and economic indicators related to Non-HVAC oriented BER measures for an A/C Office.

BER Type	BER code	Total Cost Retrofit Project (£)	Total EUI (kWh/m²-year)	Annual Income (Savings + incentives) (£)	Annual Energy Bill (£)	Simple Payback (years)	Annual tCO_2	Annual tCO_2 Reduction	Life Cycle Cost (50 years) (£)	NPV (50 years) (£)	Thermal discomfort (hours)
Insulation	**I4.07**	85120.0	264.1	1659.7	57965.7	51.3	273.0	4.4%	1573650.8	-39504.9	1348.5
Insulation	**I4.08**	97290.0	263.2	1728.5	57896.8	56.3	272.5	4.6%	1583633.1	-49487.2	1349.9
Insulation	**I4.09**	109409.0	262.6	1761.4	57864.0	62.1	272.2	4.7%	1594491.5	-60345.6	1351.6
Insulation	**I4.10**	121586.0	262.3	1772.9	57852.4	68.6	272.1	4.7%	1605954.7	-71808.7	1352.6
Insulation	**I4.11**	133759.0	261.8	1810.6	57814.7	73.9	271.8	4.8%	1616741.9	-82596.0	1356.0
Insulation	**I4.12**	145873.0	261.8	1800.3	57825.1	81.0	271.9	4.8%	1628707.7	-94561.8	1355.8
Insulation	**I4.13**	158064.0	261.4	1824.6	57800.7	86.6	271.6	4.9%	1639855.1	-105709.1	1356.5
Insulation	**I4.14**	170226.0	261.0	1834.2	57791.1	92.8	271.5	4.9%	1651353.2	-117207.2	1358.5
Insulation	**I4.15**	182355.0	260.6	1868.1	57757.3	97.6	271.3	5.0%	1662197.0	-128051.0	1359.9
Insulation	**I4.16**	194538.0	260.3	1896.3	57729.0	102.6	271.1	5.1%	1673235.5	-139089.6	1359.7
Insulation	**I4.17**	206678.0	260.1	1910.5	57714.9	108.2	271.0	5.1%	1684595.8	-150449.8	1361.5
Insulation	**I4.18**	218819.0	260.0	1913.7	57711.6	114.3	271.0	5.1%	1696238.5	-162092.6	1362.6
Insulation	**I5.065**	16893.6	264.9	1499.4	58125.9	11.3	273.8	4.1%	1511882.0	22263.9	1349.8
Insulation	**I5.075**	18986.6	264.2	1547.0	58078.3	12.3	273.4	4.3%	1512678.4	21467.5	1353.7
Insulation	**I5.085**	20631.0	263.4	1597.1	58028.3	12.9	273.0	4.4%	1512979.3	21166.6	1354.5
Insulation	**I5.100**	23172.6	262.6	1656.1	57969.2	14.0	272.6	4.6%	1513914.3	20231.6	1354.3
Insulation	**I6.02**	16719.9	271.8	1185.5	58439.9	14.1	276.8	3.1%	1519791.4	14354.6	1353.5
Insulation	**I6.03**	25079.8	269.3	1332.3	58293.1	18.8	275.6	3.5%	1524088.6	10057.3	1349.8
Insulation	**I6.04**	33000.0	267.0	1491.8	58133.6	22.1	274.4	3.9%	1527634.2	6511.8	1348.4
Insulation	**I6.05**	43988.0	265.6	1596.1	58029.3	27.6	273.6	4.2%	1535561.8	-1415.9	1345.0

Table D -3 cont. Main energy and economic indicators related to Non-HVAC oriented BER measures for an A/C Office.

BER Type	BER code	Total Cost Retrofit Project (£)	Total EUI (kWh/m²-year)	Annual Income (Savings + incentives) (£)	Annual Energy Bill (£)	Simple Payback (years)	Annual tCO_2	Annual tCO_2 Reduction	Life Cycle Cost (50 years) (£)	NPV (50 years) (£)	Thermal discomfort (hours)
Insulation	**I6.06**	50160.0	264.4	1657.7	57967.6	30.3	273.1	4.4%	1539936.9	-5791.0	1349.1
Insulation	**I6.08**	66000.0	262.7	1772.2	57853.2	37.2	272.2	4.7%	1552289.9	-18144.0	1353.4
Insulation	**I6.10**	83601.0	261.8	1825.9	57799.5	45.8	271.8	4.8%	1567907.0	-33761.0	1357.5
Insulation	**I6.12**	99000.0	261.1	1866.1	57759.3	53.1	271.4	5.0%	1581745.5	-47599.6	1362.1
Insulation	**I6.14**	115501.0	260.3	1922.4	57702.9	60.1	271.0	5.1%	1596231.8	-62085.9	1363.7
Insulation	**I6.16**	127243.0	259.9	1949.4	57675.9	65.3	270.8	5.2%	1606877.6	-72731.6	1362.6
Insulation	**I6.18**	141334.0	259.5	1988.6	57636.7	71.1	270.5	5.3%	1619477.8	-85331.9	1363.4
Insulation	**I6.20**	150728.0	259.0	2011.7	57613.7	74.9	270.3	5.3%	1627956.6	-93810.6	1363.7
Insulation	**I6.28**	211789.0	257.7	2112.4	57513.0	100.3	269.6	5.6%	1684337.0	-150191.1	1365.8
Insulation	**I6.30**	216486.0	257.6	2123.3	57502.1	102.0	269.5	5.6%	1688593.7	-154447.7	1365.0
Insulation	**I7.02**	16740.0	267.9	1418.1	58207.3	11.8	274.9	3.7%	1513826.8	20319.1	1348.3
Insulation	**I7.03**	19170.1	265.3	1581.9	58043.4	12.1	273.6	4.2%	1511957.4	22188.5	1343.8
Insulation	**I7.04**	27779.8	263.6	1685.2	57940.2	16.5	272.8	4.5%	1517615.9	16530.0	1347.5
Insulation	**I7.05**	33269.8	262.7	1723.8	57901.5	19.3	272.4	4.6%	1521923.9	12222.0	1349.3
Insulation	**I7.06**	39811.0	261.9	1775.8	57849.5	22.4	272.0	4.8%	1526903.3	7242.6	1352.5
Insulation	**I7.07**	49470.0	261.1	1830.3	57795.0	27.0	271.5	4.9%	1534829.6	-683.6	1354.3
Insulation	**I7.08**	54420.0	260.3	1888.1	57737.3	28.8	271.1	5.1%	1538124.8	-3978.9	1353.0
Insulation	**I7.09**	58200.0	260.0	1898.6	57726.8	30.7	271.0	5.1%	1541504.5	-7358.6	1353.7
Insulation	**I7.10**	65670.0	259.8	1905.4	57720.0	34.5	270.9	5.1%	1548544.0	-14398.1	1356.3
Insulation	**I8.005**	80392.0	273.9	1022.6	58602.7	78.6	277.9	2.7%	1585475.2	-51329.3	1360.3

Table D -3 cont. Main energy and economic indicators related to Non-HVAC oriented BER measures for an A/C Office.

BER Type	BER code	Total Cost Retrofit Project (£)	Total EUI (kWh/m²-year)	Annual Income (Savings + incentives) (£)	Annual Energy Bill (£)	Simple Payback (years)	Annual tCO_2	Annual tCO_2 Reduction	Life Cycle Cost (50 years) (£)	NPV (50 years) (£)	Thermal discomfort (hours)
Insulation	**I8.010**	146552.0	269.1	1343.9	58281.4	109.0	275.5	3.5%	1641104.2	-106958.3	1352.7
Insulation	**I8.015**	228295.0	266.4	1515.4	58110.0	150.7	274.1	4.0%	1715638.9	-181493.0	1347.6
Insulation	**I8.020**	291247.0	264.6	1616.5	58008.9	180.2	273.3	4.3%	1773836.0	-239690.0	1349.7
Insulation	**I8.025**	375306.0	263.6	1683.8	57941.6	222.9	272.8	4.5%	1853287.9	-319142.0	1351.3
Insulation	**I8.030**	433766.0	262.7	1722.9	57902.5	251.8	272.4	4.6%	1908740.9	-374594.9	1353.0
Insulation	**I8.035**	522340.0	262.1	1769.4	57856.0	295.2	272.0	4.7%	1993088.3	-458942.4	1355.3
Insulation	**I8.040**	585430.0	261.4	1815.7	57809.6	322.4	271.7	4.9%	2052826.5	-518680.6	1356.3
Insulation	**I9.010**	173251.0	280.7	190.4	59434.9	909.7	282.7	1.0%	1696569.0	-162423.1	1392.6
Insulation	**I9.020**	323251.0	278.7	506.0	59119.3	638.8	281.1	1.6%	1833317.0	-299171.1	1398.6
Lighting	**L1**	152998.1	276.3	5959.9	53665.5	25.7	261.7	8.4%	1528563.5	5582.4	1414.6
Lighting	**L2**	149314.2	270.9	8779.7	50845.7	17.0	250.6	12.3%	1452452.3	81693.6	1411.1
Lighting	**L3**	177343.8	267.2	10554.1	49071.3	16.8	243.5	14.8%	1433868.2	100277.7	1412.3
Ren. solar	**R1**	259200.0	269.1	8388.5	51236.8	30.9	262.6	8.0%	1568642.7	-34496.8	1414.3
Ren. solar	**R2**	495600.0	254.9	15216.3	44409.1	32.6	246.9	13.5%	1621277.4	-87131.5	1415.6
Ren. solar	**R3**	754800.0	240.4	21781.2	37844.2	34.7	232.9	18.5%	1702695.8	-168549.9	1417.8
Ren. Wind	**R4**	80000.0	283.3	3480.2	56145.2	23.0	280.0	2.0%	1521864.2	12281.8	1413.8
Ren. Wind	**R5**	160000.0	282.8	3793.3	55832.0	42.2	279.6	2.1%	1591070.1	-56924.2	1413.8

D.4 A/C Office. Non-HVAC BER exergy and exergoeconomic indicators

Table D - 4 Main exergy and exergoeconomic indicators related to Non-HVAC oriented BER measures for an A/C Office

BER Type	BER code	Primary exergy input (kWhex/ m²-year)	Exergy dest. (kWhex/ m²-year)	Exergy efficiency Ψ Building (-)	Exergy dest. Cost Stream: heat (£)	Exergy dest. Cost Stream: cold (£)	Price Fuel Stream: heat (£/kWh)	Price Fuel Stream: cold (£/kWh)	Price Product Stream: heat (£/kWh)	Price Product Stream: cold (£/kWh)	Exergy dest. cost rate (£/h)	BER Capital Cost rate (£/h)	Annual revenue rate (£/h)	$Exec_{CB}$
-	**Base**	550.0	465.5	0.154	11624.8	6383.5	0.03	0.12	0.43	6.28	6.25	0.00	0.00	6.25
Set-point	**SH18**	550.3	467.8	0.150	14433.8	6384.2	0.03	0.12	0.60	6.28	6.57	0.00	-0.01	6.58
Set-point	**SH19**	550.3	467.4	0.151	14038.4	6384.1	0.03	0.12	0.55	6.28	6.53	0.00	-0.01	6.53
Set-point	**SH20**	550.4	466.9	0.152	13377.9	6384.1	0.03	0.12	0.51	6.28	6.45	0.00	-0.01	6.46
Set-point	**SH21**	550.4	466.3	0.153	12405.3	6384.2	0.03	0.12	0.46	6.28	6.34	0.00	-0.01	6.35
Set-point	**SH22**	550.0	465.5	0.154	11578.8	6383.5	0.03	0.12	0.43	6.28	6.25	0.00	0.00	6.24
Set-point	**SC23**	556.9	471.6	0.153	12351.1	6550.4	0.03	0.12	0.45	5.96	6.39	0.00	-0.09	6.48
Set-point	**SC24**	550.0	465.5	0.154	11623.8	6382.8	0.03	0.12	0.43	6.28	6.25	0.00	0.00	6.25
Set-point	**SC25**	543.4	459.5	0.154	11013.1	6141.8	0.03	0.12	0.41	6.49	6.11	0.00	0.08	6.03
Set-point	**SC26**	536.7	453.4	0.155	10633.2	5896.0	0.03	0.12	0.39	6.96	5.99	0.00	0.16	5.83
Set-point	**SC27**	530.5	447.6	0.156	10269.7	5696.5	0.03	0.12	0.37	7.79	5.88	0.00	0.23	5.65
Glazing	**G1**	534.8	451.9	0.155	11142.6	5391.0	0.03	0.12	0.43	5.77	5.96	0.61	0.17	6.39
Glazing	**G2**	529.3	446.7	0.156	10388.1	5530.8	0.03	0.12	0.42	5.66	5.85	0.86	0.21	6.49
Glazing	**G3**	527.5	444.9	0.157	10140.6	5591.0	0.03	0.12	0.41	5.62	5.81	0.86	0.23	6.44
Glazing	**G4**	527.6	445.5	0.156	10826.5	4985.3	0.03	0.12	0.43	5.47	5.82	1.08	0.25	6.65
Glazing	**G5**	523.5	441.5	0.157	10243.3	5106.2	0.03	0.12	0.42	5.39	5.73	1.08	0.28	6.54

Table D - 4 cont. Main exergy and exergoeconomic indicators related to Non-HVAC oriented BER measures for an A/C Office

BER Type	BER code	Primary exergy input (kWhex/ m²-year)	Exergy dest. (kWhex/ m²-year)	Exergy efficiency Ψ Building (-)	Exergy dest. Cost Stream: heat (£)	Exergy dest. Cost Stream: cold (£)	Price Fuel Stream: heat (£/kWh)	Price Fuel Stream: cold (£/kWh)	Price Product Stream: heat (£/kWh)	Price Product Stream: cold (£/kWh)	Price Product Stream: cold (£/kWh)	Exergy dest. cost rate (£/h)	Annual revenue rate (£/h)	$Exec_{CB}$
Glazing	**G6**	525.2	443.2	0.156	10490.8	5075.7	0.03	0.12	0.43	5.43	5.77	1.42	0.27	6.93
Glazing	**G7**	521.8	439.9	0.157	10024.1	5139.3	0.03	0.12	0.42	5.34	5.70	1.42	0.29	6.83
Glazing	**G8**	522.1	440.2	0.157	10056.9	5137.5	0.03	0.12	0.42	5.36	5.71	1.51	0.29	6.93
Glazing	**G9**	520.2	438.3	0.157	9811.7	5173.2	0.03	0.12	0.41	5.31	5.67	1.51	0.31	6.88
Glazing	**G10**	531.0	448.3	0.156	10633.1	5510.5	0.03	0.12	0.43	5.69	5.88	0.61	0.20	6.29
Glazing	**G11**	532.4	449.6	0.155	10812.9	5451.0	0.03	0.12	0.43	5.72	5.91	0.81	0.19	6.53
Glazing	**G12**	529.1	446.5	0.156	10356.7	5538.3	0.03	0.12	0.42	5.65	5.84	0.81	0.21	6.44
Sealing	**S1**	540.8	456.8	0.155	10608.8	6448.2	0.03	0.12	0.42	5.98	6.07	0.01	0.08	6.01
Sealing	**S2**	531.8	448.3	0.157	9604.8	6507.1	0.03	0.12	0.40	5.68	5.90	0.04	0.16	5.78
Sealing	**S3**	522.3	439.3	0.159	8579.0	6534.0	0.03	0.12	0.39	5.37	5.71	0.07	0.24	5.54
Sealing	**S4**	513.2	430.9	0.161	7686.7	6513.6	0.03	0.12	0.37	5.02	5.54	0.11	0.31	5.33
Sealing	**S5**	503.6	421.8	0.162	6725.3	6381.0	0.03	0.12	0.36	4.59	5.33	0.17	0.40	5.10
Sealing	**S6**	495.4	414.1	0.164	5927.6	6425.2	0.03	0.12	0.34	4.36	5.19	0.23	0.47	4.95
Sealing	**S7**	487.6	406.8	0.166	5152.7	6478.4	0.03	0.12	0.32	4.13	5.04	0.31	0.53	4.82
Sealing	**S8**	480.2	399.9	0.167	4401.9	6554.8	0.03	0.12	0.31	3.92	4.91	0.39	0.59	4.71
Sealing	**S9**	473.6	393.8	0.169	3769.2	6683.1	0.03	0.12	0.29	3.76	4.80	0.49	0.64	4.65
Insulation	**I1.02**	530.7	447.3	0.157	9092.1	7034.4	0.03	0.12	0.40	5.87	5.90	0.09	0.16	5.83
Insulation	**I1.03**	528.0	444.8	0.158	8791.0	7096.2	0.03	0.12	0.39	5.67	5.85	0.11	0.18	5.78
Insulation	**I1.04**	526.5	443.4	0.158	8663.8	7141.4	0.03	0.12	0.40	5.55	5.83	0.13	0.19	5.77

Table D - 4 cont. Main exergy and exergoeconomic indicators related to Non-HVAC oriented BER measures for an A/C Office

BER Type	BER code	Primary exergy input (kWhex/ m²-year)	Exergy dest. (kWhex/ m²-year)	Exergy efficiency Ψ Building (-)	Exergy dest. Cost Stream: heat (£)	Exergy dest. Cost Stream: cold (£)	Price Fuel Stream: heat (£/kWh)	Price Fuel Stream: cold (£/kWh)	Price Product Stream: heat (£/kWh)	Price Product Stream: cold (£/kWh)	Price Product Stream: cold (£/kWh)	Exergy dest. cost rate (£/h)	Annual revenue rate (£/h)	$Exec_{CB}$
Insulation	**I1.05**	525.5	442.5	0.158	8554.0	7183.3	0.03	0.12	0.40	5.46	5.82	0.14	0.19	5.77
Insulation	**I1.06**	524.7	441.8	0.158	8469.1	7214.1	0.03	0.12	0.40	5.40	5.81	0.17	0.20	5.78
Insulation	**I1.07**	524.2	441.4	0.158	8459.8	7214.2	0.03	0.12	0.40	5.35	5.80	0.19	0.20	5.79
Insulation	**I1.08**	523.4	440.6	0.158	8346.7	7212.1	0.03	0.12	0.40	5.30	5.78	0.22	0.21	5.79
Insulation	**I1.09**	522.8	440.1	0.158	8293.1	7212.4	0.03	0.12	0.40	5.27	5.77	0.23	0.21	5.79
Insulation	**I1.10**	522.5	439.9	0.158	8270.4	7222.6	0.03	0.12	0.40	5.24	5.77	0.24	0.22	5.80
Insulation	**I1.11**	522.4	439.8	0.158	8262.0	7252.5	0.03	0.12	0.40	5.23	5.77	0.26	0.22	5.81
Insulation	**I1.12**	522.3	439.7	0.158	8250.6	7276.1	0.03	0.12	0.40	5.22	5.77	0.27	0.22	5.82
Insulation	**I1.13**	522.0	439.4	0.158	8192.5	7276.1	0.03	0.12	0.40	5.20	5.76	0.28	0.22	5.83
Insulation	**I1.14**	521.6	438.9	0.158	8141.3	7263.2	0.03	0.12	0.40	5.17	5.75	0.29	0.22	5.82
Insulation	**I1.15**	521.2	438.6	0.158	8100.6	7252.5	0.03	0.12	0.40	5.15	5.74	0.30	0.22	5.82
Insulation	**I2.01**	536.7	452.7	0.156	9769.3	6712.4	0.03	0.12	0.40	6.26	5.98	0.06	0.11	5.93
Insulation	**I2.02**	532.7	449.1	0.157	9298.2	6938.1	0.03	0.12	0.39	6.03	5.92	0.10	0.14	5.88
Insulation	**I2.03**	530.3	446.9	0.157	9037.7	7050.4	0.03	0.12	0.39	5.85	5.89	0.14	0.16	5.88
Insulation	**I2.04**	528.6	445.3	0.158	8877.9	7083.8	0.03	0.12	0.40	5.70	5.86	0.17	0.17	5.86
Insulation	**I2.05**	527.2	444.1	0.158	8746.1	7119.5	0.03	0.12	0.40	5.61	5.84	0.21	0.18	5.87
Insulation	**I2.06**	526.1	443.1	0.158	8624.6	7143.1	0.03	0.12	0.40	5.53	5.83	0.24	0.19	5.88
Insulation	**I2.07**	525.5	442.5	0.158	8559.6	7168.3	0.03	0.12	0.40	5.47	5.82	0.26	0.19	5.89
Insulation	**I2.08**	524.9	442.0	0.158	8501.6	7171.1	0.03	0.12	0.40	5.41	5.81	0.30	0.20	5.91

Table D - 4 cont. Main exergy and exergoeconomic indicators related to Non-HVAC oriented BER measures for an A/C Office

BER Type	BER code	Primary exergy input (kWhex/ m²-year)	Exergy dest. (kWhex/ m²-year)	Exergy efficiency Ψ Building (-)	Exergy dest. Cost Stream: heat (£)	Exergy dest. Cost Stream: cold (£)	Price Fuel Stream: heat (£/kWh)	Price Fuel Stream: cold (£/kWh)	Price Product Stream: heat (£/kWh)	Price Product Stream: cold (£/kWh)	Price Product Stream: cold (£/kWh)	Exergy dest. cost rate (£/h)	Annual revenue rate (£/h)	$Exec_{CB}$
Insulation	**I2.09**	524.6	441.7	0.158	8473.6	7213.2	0.03	0.12	0.40	5.38	5.81	0.32	0.20	5.93
Insulation	**I2.10**	524.3	441.5	0.158	8462.7	7228.8	0.03	0.12	0.40	5.35	5.80	0.34	0.20	5.95
Insulation	**I2.11**	523.6	440.9	0.158	8381.7	7215.9	0.03	0.12	0.40	5.32	5.79	0.36	0.21	5.94
Insulation	**I2.12**	523.3	440.6	0.158	8354.0	7221.1	0.03	0.12	0.40	5.29	5.78	0.37	0.21	5.95
Insulation	**I2.13**	522.8	440.1	0.158	8298.1	7222.2	0.03	0.12	0.40	5.27	5.77	0.38	0.21	5.94
Insulation	**I2.14**	522.4	439.8	0.158	8257.1	7211.7	0.03	0.12	0.40	5.24	5.76	0.38	0.22	5.93
Insulation	**I2.15**	522.3	439.6	0.158	8241.5	7221.7	0.03	0.12	0.40	5.23	5.76	0.41	0.22	5.96
Insulation	**I3.02**	532.7	449.1	0.157	9297.9	6938.4	0.03	0.12	0.39	6.03	5.92	0.06	0.14	5.84
Insulation	**I3.03**	530.4	446.9	0.157	9040.5	7048.5	0.03	0.12	0.39	5.85	5.89	0.06	0.16	5.80
Insulation	**I3.04**	528.5	445.2	0.158	8864.6	7084.5	0.03	0.12	0.40	5.69	5.86	0.07	0.17	5.76
Insulation	**I3.05**	527.4	444.2	0.158	8753.4	7141.2	0.03	0.12	0.40	5.62	5.85	0.07	0.18	5.74
Insulation	**I3.06**	526.3	443.3	0.158	8647.0	7146.8	0.03	0.12	0.40	5.52	5.83	0.08	0.19	5.72
Insulation	**I3.07**	525.3	442.4	0.158	8541.4	7147.9	0.03	0.12	0.40	5.46	5.81	0.08	0.20	5.70
Insulation	**I3.08**	525.1	442.1	0.158	8511.2	7194.6	0.03	0.12	0.40	5.42	5.81	0.09	0.20	5.70
Insulation	**I3.09**	524.6	441.8	0.158	8487.1	7211.6	0.03	0.12	0.40	5.38	5.81	0.09	0.20	5.70
Insulation	**I3.10**	524.2	441.4	0.158	8454.8	7212.4	0.03	0.12	0.40	5.35	5.80	0.10	0.20	5.70
Insulation	**I3.11**	523.6	440.8	0.158	8372.8	7212.3	0.03	0.12	0.40	5.32	5.79	0.11	0.21	5.69
Insulation	**I3.12**	523.2	440.5	0.158	8334.2	7212.3	0.03	0.12	0.40	5.29	5.78	0.11	0.21	5.68
Insulation	**I3.13**	522.7	440.0	0.158	8285.9	7206.6	0.03	0.12	0.40	5.26	5.77	0.12	0.21	5.67

Table D - 4 cont. Main exergy and exergoeconomic indicators related to Non-HVAC oriented BER measures for an A/C Office

BER Type	BER code	Primary exergy input (kWhex/m²-year)	Exergy dest. (kWhex/m²-year)	Exergy efficiency Ψ Building (-)	Exergy dest. Cost Stream: heat (£)	Exergy dest. Cost Stream: cold (£)	Price Fuel Stream: heat (£/kWh)	Price Fuel Stream: cold (£/kWh)	Price Product Stream: heat (£/kWh)	Price Product Stream: cold (£/kWh)	Price Product Stream: cold (£/kWh)	Exergy dest. cost rate (£/h)	Annual revenue rate (£/h)	$Exec_{CB}$
Insulation	**I3.14**	522.5	439.8	0.158	8266.3	7215.5	0.03	0.12	0.40	5.24	5.77	0.12	0.22	5.67
Insulation	**I3.15**	522.5	439.8	0.158	8260.5	7237.4	0.03	0.12	0.40	5.23	5.77	0.13	0.22	5.68
Insulation	**I4.04**	529.7	446.4	0.157	8985.5	7102.3	0.03	0.12	0.40	5.80	5.89	0.21	0.16	5.93
Insulation	**I4.05**	527.8	444.6	0.158	8776.8	7090.6	0.03	0.12	0.39	5.66	5.85	0.26	0.18	5.93
Insulation	**I4.06**	527.1	444.0	0.158	8735.1	7141.3	0.03	0.12	0.40	5.59	5.85	0.31	0.18	5.97
Insulation	**I4.07**	526.2	443.2	0.158	8650.5	7171.5	0.03	0.12	0.40	5.54	5.83	0.36	0.19	6.01
Insulation	**I4.08**	525.2	442.3	0.158	8535.0	7172.3	0.03	0.12	0.40	5.48	5.81	0.42	0.20	6.03
Insulation	**I4.09**	524.7	441.8	0.158	8485.8	7177.7	0.03	0.12	0.40	5.42	5.80	0.47	0.20	6.07
Insulation	**I4.10**	524.5	441.7	0.158	8479.2	7193.0	0.03	0.12	0.40	5.39	5.80	0.52	0.20	6.12
Insulation	**I4.11**	523.9	441.2	0.158	8425.4	7198.8	0.03	0.12	0.40	5.36	5.79	0.57	0.21	6.16
Insulation	**I4.12**	524.0	441.3	0.158	8475.4	7215.9	0.03	0.12	0.40	5.35	5.80	0.63	0.21	6.22
Insulation	**I4.13**	523.6	440.9	0.158	8414.7	7252.5	0.03	0.12	0.40	5.34	5.80	0.68	0.21	6.27
Insulation	**I4.14**	523.4	440.7	0.158	8373.2	7278.2	0.03	0.12	0.40	5.33	5.79	0.73	0.21	6.31
Insulation	**I4.15**	522.9	440.3	0.158	8332.3	7276.2	0.03	0.12	0.40	5.31	5.79	0.78	0.21	6.35
Insulation	**I4.16**	522.6	439.9	0.158	8281.7	7265.6	0.03	0.12	0.40	5.28	5.78	0.83	0.22	6.39
Insulation	**I4.17**	522.3	439.7	0.158	8267.6	7268.4	0.03	0.12	0.40	5.27	5.77	0.89	0.22	6.44
Insulation	**I4.18**	522.3	439.7	0.158	8272.8	7273.6	0.03	0.12	0.40	5.26	5.77	0.94	0.22	6.49
Insulation	**I5.065**	527.6	444.3	0.158	8653.7	7167.1	0.03	0.12	0.39	5.36	5.84	0.07	0.17	5.74
Insulation	**I5.075**	526.9	443.7	0.158	8586.1	7178.8	0.03	0.12	0.39	5.31	5.83	0.08	0.18	5.74

Table D - 4 cont. Main exergy and exergoeconomic indicators related to Non-HVAC oriented BER measures for an A/C Office

BER Type	BER code	Primary exergy input (kWhex/ m^2-year)	Exergy dest. (kWhex/ m^2-year)	Exergy efficiency Ψ Building (-)	Exergy dest. Cost Stream: heat (£)	Exergy dest. Cost Stream: cold (£)	Price Fuel Stream: heat (£/kWh)	Price Fuel Stream: cold (£/kWh)	Price Product Stream: heat (£/kWh)	Price Product Stream: cold (£/kWh)	Price Product Stream: cold (£/kWh)	Exergy dest. cost rate (£/h)	Annual revenue rate (£/h)	$Exec_{CB}$
Insulation	**I5.085**	526.1	443.0	0.158	8483.7	7203.4	0.03	0.12	0.39	5.27	5.82	0.09	0.18	5.72
Insulation	**I5.100**	525.3	442.3	0.158	8439.5	7209.6	0.03	0.12	0.40	5.23	5.81	0.10	0.19	5.72
Insulation	**I6.02**	533.4	449.7	0.157	9382.1	6944.7	0.03	0.12	0.40	6.07	5.94	0.07	0.14	5.88
Insulation	**I6.03**	531.1	447.6	0.157	9131.9	7068.0	0.03	0.12	0.40	5.90	5.91	0.11	0.15	5.87
Insulation	**I6.04**	528.9	445.6	0.157	8900.9	7079.4	0.03	0.12	0.40	5.74	5.87	0.14	0.17	5.84
Insulation	**I6.05**	527.4	444.2	0.158	8759.6	7089.1	0.03	0.12	0.40	5.63	5.84	0.19	0.18	5.85
Insulation	**I6.06**	526.4	443.3	0.158	8666.8	7155.7	0.03	0.12	0.40	5.57	5.83	0.21	0.19	5.86
Insulation	**I6.08**	524.7	441.8	0.158	8502.5	7181.4	0.03	0.12	0.40	5.46	5.81	0.28	0.20	5.89
Insulation	**I6.10**	523.9	441.1	0.158	8438.8	7211.0	0.03	0.12	0.40	5.39	5.80	0.36	0.21	5.95
Insulation	**I6.12**	523.2	440.6	0.158	8430.3	7236.2	0.03	0.12	0.40	5.34	5.79	0.42	0.21	6.01
Insulation	**I6.14**	522.4	439.9	0.158	8330.3	7250.1	0.03	0.12	0.40	5.31	5.78	0.49	0.22	6.05
Insulation	**I6.16**	522.0	439.5	0.158	8287.6	7266.2	0.03	0.12	0.41	5.29	5.77	0.55	0.22	6.10
Insulation	**I6.18**	521.5	439.1	0.158	8284.5	7255.0	0.03	0.12	0.41	5.26	5.77	0.61	0.23	6.15
Insulation	**I6.20**	521.1	438.7	0.158	8235.5	7247.0	0.03	0.12	0.41	5.23	5.76	0.65	0.23	6.17
Insulation	**I6.28**	519.8	437.4	0.158	8123.5	7231.5	0.03	0.12	0.41	5.18	5.73	0.91	0.24	6.40
Insulation	**I6.30**	519.6	437.3	0.158	8117.1	7227.1	0.03	0.12	0.41	5.16	5.73	0.93	0.24	6.42
Insulation	**I7.02**	529.8	446.4	0.157	8983.3	7085.6	0.03	0.12	0.40	5.80	5.89	0.07	0.16	5.80
Insulation	**I7.03**	527.3	444.2	0.158	8754.2	7121.8	0.03	0.12	0.40	5.60	5.85	0.08	0.18	5.75
Insulation	**I7.04**	525.7	442.8	0.158	8600.4	7149.1	0.03	0.12	0.40	5.49	5.82	0.12	0.19	5.75

Table D - 4 cont. Main exergy and exergoeconomic indicators related to Non-HVAC oriented BER measures for an A/C Office

BER Type	BER code	Primary exergy input (kWhex/ m²-year)	Exergy dest. (kWhex/ m²-year)	Exergy efficiency Ψ Building (-)	Exergy dest. Cost Stream: heat (£)	Exergy dest. Cost Stream: cold (£)	Price Fuel Stream: heat (£/kWh)	Price Fuel Stream: cold (£/kWh)	Price Product Stream: heat (£/kWh)	Price Product Stream: cold (£/kWh)	Price Product Stream: cold (£/kWh)	Exergy dest. cost rate (£/h)	Annual revenue rate (£/h)	$Exec_{CB}$
Insulation	**I7.05**	525.0	442.1	0.158	8512.6	7208.1	0.03	0.12	0.40	5.41	5.81	0.14	0.20	5.76
Insulation	**I7.06**	524.2	441.4	0.158	8454.8	7223.3	0.03	0.12	0.40	5.35	5.80	0.17	0.20	5.77
Insulation	**I7.07**	523.4	440.7	0.158	8355.2	7223.2	0.03	0.12	0.40	5.30	5.79	0.21	0.21	5.79
Insulation	**I7.08**	522.6	439.9	0.158	8274.7	7208.0	0.03	0.12	0.40	5.25	5.77	0.23	0.22	5.79
Insulation	**I7.09**	522.4	439.8	0.158	8256.6	7232.7	0.03	0.12	0.40	5.23	5.77	0.25	0.22	5.80
Insulation	**I7.10**	522.2	439.6	0.158	8236.5	7261.5	0.03	0.12	0.40	5.21	5.77	0.28	0.22	5.83
Insulation	**I8.005**	535.6	451.7	0.157	9606.2	6871.2	0.03	0.12	0.40	6.15	5.97	0.34	0.12	6.20
Insulation	**I8.010**	530.9	447.4	0.157	9092.7	7024.8	0.03	0.12	0.40	5.86	5.90	0.63	0.15	6.37
Insulation	**I8.015**	528.4	445.1	0.158	8831.5	7085.9	0.03	0.12	0.40	5.67	5.86	0.98	0.17	6.66
Insulation	**I8.020**	526.7	443.6	0.158	8664.7	7160.4	0.03	0.12	0.40	5.57	5.84	1.25	0.18	6.90
Insulation	**I8.025**	525.7	442.7	0.158	8585.5	7169.8	0.03	0.12	0.40	5.47	5.82	1.61	0.19	7.24
Insulation	**I8.030**	525.0	442.1	0.158	8498.2	7224.2	0.03	0.12	0.40	5.42	5.81	1.86	0.20	7.48
Insulation	**I8.035**	524.4	441.6	0.158	8471.4	7229.8	0.03	0.12	0.40	5.37	5.81	2.24	0.20	7.84
Insulation	**I8.040**	523.7	440.9	0.158	8398.0	7220.6	0.03	0.12	0.40	5.32	5.79	2.51	0.21	8.09
Insulation	**I9.010**	543.5	449.2	0.173	7682.8	5538.0	0.03	0.12	0.17	2.35	5.65	0.74	0.02	6.38
Insulation	**I9.020**	540.5	446.7	0.174	7580.0	5407.7	0.03	0.12	0.17	2.40	5.60	1.39	0.06	6.93
Lighting	**L1**	505.1	424.5	0.160	12613.6	5813.7	0.03	0.12	0.44	7.29	5.77	0.66	0.68	5.74
Lighting	**L2**	484.1	405.3	0.163	13163.6	5548.9	0.03	0.12	0.45	7.65	5.55	0.64	1.00	5.19
Lighting	**L3**	470.7	393.0	0.165	13468.9	5253.3	0.03	0.12	0.45	7.70	5.40	0.76	1.20	4.95

Table D - 4 cont. Main exergy and exergoeconomic indicators related to Non-HVAC oriented BER measures for an A/C Office

BER Type	BER code	Primary exergy input (kWhex/ m²-year)	Exergy dest. (kWhex/ m²-year)	Exergy efficiency Ψ Building (-)	Exergy dest. Cost Stream: heat (£)	Exergy dest. Cost Stream: cold (£)	Price Fuel Stream: heat (£/kWh)	Price Fuel Stream: cold (£/kWh)	Price Product Stream: heat (£/kWh)	Price Product Stream: cold (£/kWh)	Price Product Stream: cold (£/kWh)	Exergy dest. cost rate (£/h)	Annual revenue rate (£/h)	$Exec_{CB}$
Ren. Solar	**R1**	551.4	466.6	0.154	11669.7	6677.1	0.03	0.12	0.43	6.42	6.30	1.11	0.96	6.45
Ren. solar	**R2**	552.2	467.4	0.154	11714.3	6725.9	0.03	0.12	0.43	6.41	6.32	2.12	1.74	6.70
Ren. solar	**R3**	552.4	467.5	0.154	11699.4	6720.7	0.03	0.12	0.43	6.36	6.32	3.23	2.49	7.07
Ren. Wind	**R4**	550.0	465.5	0.154	11625.1	6384.3	0.03	0.12	0.43	6.28	6.25	0.34	0.40	6.20
Ren. Wind	**R5**	550.0	465.5	0.154	11625.3	6385.2	0.03	0.12	0.43	6.28	6.25	0.69	0.43	6.50

Appendix E: List of Pareto solutions for the archetypes case studies

This appendix presents the database for all Pareto solutions obtained from the MOO study presented in Chapter 7.

Note: The tables show its corresponding design variables in a coded format which can be reviewed checking the retrofit database presented in Appendix B.5. For example a value of 3.08 in the wall insulation column corresponds to insulation I3: Expanded polystyrene (EPS) and the .08 corresponds to the thickness (.08m).

E.1 Pareto solutions for the School case

Table E - 1 Pareto optimal solutions with design variables and objectives outputs from the Primary School MOO study

Solution	X^{HVAC}	X^{wall} Wall Insulation (m)	X^{roof} Roof Insulation (m)	X^{ground} Ground Insulation (m)	X^{seal} Infiltration reduction % (ach)	X^{glaz} (glass-gap-glass in mm)	X^{light} Light techn.	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)	X^{cool} (°C)	$Ex_{destbui}$ (kWh/m^2-year)	*Discomfort* (hours)	$NPV_{50years}$ (£)
1	28	6.03	5.085	3.15	0.6	0	0	0	20	18	---	159.9	1116	141029
2	28	3.02	4.05	4.12	0.7	1	3	0	20	19	---	122.8	960	2069
3	31	4.06	3.08	4.07	0.9	6	2	0	0	18	---	135.9	1261	164677
4	28	5.075	3.12	6.02	0.9	7	2	0	0	19	---	132.3	794	43779
5	2	1.14	1.11	8.005	0.5	1	0	0	0	19	---	126.6	886	13855
6	31	1.05	1.09	3.02	0.7	9	0	0	20	18	---	140.9	1251	178867
7	31	1.09	3.09	3.07	0.7	7	0	0	0	18	---	141.5	1276	227243
8	31	2.11	1.08	1.08	0.7	8	0	0	20	18	---	139.1	1266	181051
9	31	6.2	2.08	3.04	0.7	8	0	0	0	19	---	143.3	1236	185158
10	31	4.18	3.15	1.08	0.4	2	0	0	0	20	---	129.0	1373	186819

Table E - 1 cont. Pareto optimal solutions with design variables and objectives outputs from the Primary School MOO study

Solution	X^{HVAC}	X^{wall} Wall Insulation (m)	X^{roof} Roof Insulation (m)	X^{ground} Ground Insulation (m)	X^{seal} Infiltration reduction % (ach)	X^{glaz} (glass-gap-glass in mm)	X^{light} Light techn.	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)	X^{cool} (°C)	$Ex_{destbui}$ (kWh/m[2]-year)	*Discomfort* (hours)	$NPV_{50years}$ (£)
11	31	3.05	1.15	2.03	0.4	7	2	0	0	20	---	120.6	1371	126903
12	31	7.06	6.3	7.03	0.8	4	2	0	20	18	---	126.4	1246	90745
13	31	3.14	3.15	1.11	0.4	0	0	0	0	20	---	134.0	1417	263272
14	31	1.05	5.085	5.065	0.6	5	2	0	0	19	---	126.6	1345	183746
15	31	3.14	3.15	1.11	0.6	0	1	0	0	20	---	139.2	1350	185221
16	28	3.11	7.04	2.02	0.3	2	3	0	0	20	---	119.4	1369	23493
17	31	6.28	1.1	5.065	0.7	2	2	0	0	18	---	122.5	1290	156119
18	31	1.13	5.085	3.08	0.6	11	0	0	0	19	---	136.2	1280	180524
19	31	6.12	1.05	7.09	0.9	8	2	0	0	21	---	146.2	1172	133013
20	31	1.11	1.06	1.04	0.8	1	0	0	0	21	---	157.4	1200	241033
21	31	1.11	7.07	1.1	0.8	1	0	0	20	21	---	155.8	1205	209101
22	31	8.005	1.09	3.02	0.6	0	0	0	0	20	---	154.1	1389	276182
23	31	6.05	3.1	0	0.8	1	0	0	0	21	---	160.8	1220	260385
24	30	3.07	1.12	3.15	0.8	2	3	0	20	18	---	125.5	901	4937
25	29	1.05	1.05	1.08	0.9	0	2	0	20	21	---	151.0	817	59348
26	31	2.04	7.04	3.07	0.9	6	0	0	20	18	---	152.8	1244	229874
27	31	7.08	7.03	1.15	0.9	10	0	0	0	21	---	161.7	1162	174967
28	28	2.02	7.04	4.17	0.9	0	0	0	20	18	---	156.4	834	96798
29	31	3.08	3.03	0	0.5	2	2	0	0	21	---	139.6	1403	195289
30	28	4.09	6.04	1.02	0.8	0	0	0	20	20	---	156.4	903	135828
31	28	4.09	6.04	1.02	0.8	0	0	0	20	18	---	155.3	908	138872

Table E - 1 cont. Pareto optimal solutions with design variables and objectives outputs from the Primary School MOO study

Solution	X^{HVAC}	X^{wall} Wall Insulation (m)	X^{roof} Roof Insulation (m)	X^{ground} Ground Insulation (m)	X^{seal} Infiltration reduction % (ach)	X^{glaz} (glass-gap-glass in mm)	X^{light} Light techn.	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)	X^{cool} (°C)	$Ex_{destbui}$ (kWh/m^2-year)	*Discomfort* (hours)	$NPV_{50years}$ (£)
32	28	6.16	7.05	4.06	0.5	0	3	0	20	19	---	124.4	1168	37824
33	28	6.05	6.04	8.03	1	0	0	0	0	20	---	160.8	745	21169
34	10	1.08	3.07	1.11	0.8	2	0	0	0	21	---	250.2	507	64293
35	28	2.1	7.05	2.15	0.7	0	3	0	20	19	---	126.5	982	58968
36	31	2.07	5.1	0	0.9	6	2	0	20	19	---	136.4	1210	175355
37	28	3.02	7.04	8.005	0.8	1	0	0	20	19	---	148.8	888	92370
38	10	4.13	3.15	5.065	0.6	6	0	0	0	19	---	228.4	355	19333
39	26	1.02	1.06	2.03	0.9	0	2	0	0	21	---	144.1	798	55699
40	10	6.12	7.06	2.01	0.8	1	0	0	0	21	---	239.7	681	62246
41	28	0	8.01	7.03	0.9	8	0	0	0	21	---	190.6	805	68175
42	28	6.2	2.01	1.02	0.8	0	2	0	0	18	---	137.3	900	99788
43	10	3.08	3.11	6.05	0.3	5	0	0	0	18	---	209.1	409	7548
44	29	2.03	6.1	1.03	1	5	0	0	0	19	---	170.8	750	58593
45	31	2.07	7.09	2.08	0.4	7	2	0	0	20	---	119.5	1384	107147
46	10	1.12	2.1	1.02	0.1	0	0	0	0	20	---	196.5	640	18516
47	2	1.12	2.1	1.02	0.1	0	0	0	0	20	---	125.4	908	22940
48	31	6.06	3.08	7.02	0.4	1	2	0	0	20	---	125.8	1419	177040
49	2	1.12	2.1	1.02	0.1	0	0	0	0	21	---	127.8	849	17335
50	31	1.08	1.09	5.1	0.7	10	2	0	20	19	---	127.0	1277	107853
51	2	1.12	2.1	1.02	0.6	2	0	0	0	20	---	131.7	914	26856
52	31	3.12	2.03	7.04	0.8	1	2	0	20	18	---	138.4	1344	183030

Table E- 1 cont. Pareto optimal solutions with design variables and objectives outputs from the Primary School MOO study

Solution	X^{HVAC}	X^{wall} Wall Insulation (m)	X^{roof} Roof Insulation (m)	X^{ground} Ground Insulation (m)	X^{seal} Infiltration reduction % (ach)	X^{glaz} (glass-gap-glass in mm)	X^{light} Light techn.	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)	X^{cool} (°C)	$Ex_{destbui}$ (kWh/m^2-year)	*Discomfort* (hours)	$NPV_{50years}$ (£)
53	31	2.07	3.11	4.18	0.7	8	3	0	20	18	---	120.8	1348	73081
54	31	1.06	1.07	7.04	0.8	10	0	0	0	18	---	144.3	1220	197686
55	10	2.03	3.04	7.06	0.8	1	0	0	0	18	---	260.1	812	78246
56	2	3.06	5.075	3.12	0.8	0	0	0	0	18	---	132.3	1120	115518
57	31	2.11	7.08	8.005	0.8	9	2	0	0	18	---	128.4	1229	110563
58	10	6.1	3.15	6.02	0.4	0	0	0	20	19	---	219.3	599	61663
59	2	6.16	7.06	1.06	0.3	0	0	0	20	18	---	124.7	1027	31516
60	2	1.08	7.06	7.02	0.9	0	0	0	20	19	---	136.3	1094	85548
61	30	2.05	1.04	8.005	1	2	0	0	20	20	---	158.5	746	44883
62	31	1.1	1.11	1.07	0.9	6	2	0	20	18	---	130.7	1217	148289
63	30	7.06	7.04	1.12	0.9	0	2	0	20	19	---	139.1	804	46385
64	31	5.075	5.1	3.11	0.5	5	2	0	0	19	---	120.3	1382	175127
65	31	5.075	5.1	8.015	0.8	0	0	0	0	18	---	148.6	1291	240018
66	31	2.01	5.085	4.04	1	2	2	0	0	18	---	143.9	1262	207173
67	28	1.06	1.02	8.01	0.9	1	2	0	20	18	---	132.2	782	23243
68	31	5.075	5.1	3.11	0.5	5	2	0	20	19	---	120.3	1382	153104
69	28	7.02	6.02	2.11	0.7	2	2	0	0	20	---	131.9	982	49543
70	28	8.015	7.04	1.12	1	3	3	0	0	20	---	127.4	701	13964

E.2 Pareto solutions for the A/C Office case

Table E - 2 Pareto optimal solutions with design variables and objectives outputs from the A/C Office MOO study

Solution	X^{HVAC}	X^{wall} Wall Insulation (m)	X^{roof} Roof Insulation (m)	X^{ground} Ground Insulation (m)	X^{seal} Infiltration reduction % (ach)	X^{glaz} (glass-gap-glass in mm)	X^{light} Light techn.	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)	X^{cool} (°C)	$Ex_{destbui}$ (kWh/m^2-year)	*Discomfort* (hours)	$NPV_{50years}$ (£)
1	21	3.06	3.14	4.08	0.7	0	3	0	0	19	25	276.9	658	13172
2	21	3.06	1.09	5.1	0.7	0	3	0	20	20	24	275.9	660	24753
3	32	3.1	1.12	5.085	0.9	0	3	0	0	20	26	251.1	1389	318385
4	32	3.12	7.09	5.085	0.9	0	3	0	0	20	26	251.1	1391	318382
5	31	2.07	7.09	2.04	0.4	0	3	0	20	19	25	316.4	837	246699
6	29	1.04	3.14	6.03	0.7	0	3	0	20	19	24	343.5	215	56918
7	31	3.06	3.08	4.04	0.6	2	3	0	0	19	24	317.4	499	177622
8	31	2.07	2.14	2.04	0.4	0	3	25	0	18	25	313.6	855	239981
9	31	3.04	2.08	3.02	0.4	1	3	0	0	18	25	302.3	656	169676
10	31	3.07	3.15	5.075	0.6	1	3	0	0	20	24	320.4	484	177285
11	31	3.09	3.11	6.04	0.6	8	3	0	0	19	24	307.6	434	83438
12	29	2.14	4.06	4.1	1	0	3	0	20	19	24	361.6	111	28663
13	32	3.08	5.1	1.07	0.8	2	3	0	20	22	26	247.3	979	184760
14	32	1.04	3.14	6.03	0.7	0	3	0	20	19	24	248.4	1398	310700
15	32	2.07	2.14	2.04	0.9	1	3	0	0	22	24	252.2	875	151415
16	31	3.12	6.08	0	0.4	0	3	25	0	21	24	326.9	528	247134
17	29	3.08	1.09	4.12	0.7	0	3	0	0	21	26	334.8	215	41261
18	32	4.14	2.14	6.02	0.7	7	3	0	20	22	24	243.5	938	5542
19	16	1.04	3.15	3.1	0.6	0	3	0	0	19	24	309.2	319	25171

Table E - 2 cont. Pareto optimal solutions with design variables and objectives outputs from the A/C Office MOO study

Solution	X^{HVAC}	X^{wall} Wall Insulation (m)	X^{roof} Roof Insulation (m)	X^{ground} Ground Insulation (m)	X^{seal} Infiltration reduction % (ach)	X^{glaz} (glass-gap-glass in mm)	X^{light} Light techn.	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)	X^{cool} (°C)	$Ex_{destbui}$ (kWh/m^2-year)	*Discomfort* (hours)	$NPV_{50years}$ (£)
20	29	1.04	7.09	2.04	1	0	3	0	20	22	24	352.3	114	83972
21	23	4.13	7.09	3.02	0.4	0	3	0	20	19	24	278.3	653	43077
22	31	3.14	3.13	5.085	0.4	2	3	0	20	20	25	300.2	745	154505
23	31	3.14	3.05	3.06	0.5	2	3	0	0	18	25	304.7	694	189058
24	32	3.08	5.1	1.07	1	2	3	0	20	22	26	252.1	883	186058
25	29	2.01	3.11	3.05	1	0	3	0	20	19	24	365.6	111	111630
26	23	3.06	1.12	5.085	0.5	0	3	0	0	20	24	290.5	671	85859
27	32	3.08	5.1	5.1	0.9	2	3	0	0	22	25	250.6	915	194193
28	21	3.08	3.11	1.07	0.8	0	3	0	20	19	25	278.1	615	18587
29	31	3.14	2.14	6.02	0.4	2	3	0	20	20	25	299.1	677	143984
30	32	3.1	3.14	3.02	0.5	0	3	0	20	19	24	245.9	1405	303612
31	32	3.06	2.14	5.065	0.8	0	3	0	0	20	26	249.8	1392	310734
32	29	3.14	3.05	3.06	1	2	3	0	0	18	25	338.6	112	3930
33	21	1.03	3.12	6.02	0.7	0	3	0	0	20	25	275.8	660	33818
34	32	1.07	1.12	5.085	0.9	0	3	0	0	22	24	254.0	1004	297778
35	31	3.13	5.085	6.02	0.5	2	3	0	20	20	25	307.3	622	182597
36	31	3.08	3.05	4.05	0.5	7	3	0	0	18	24	305.4	482	67085
37	31	3.05	2.14	2.05	0.5	7	3	0	0	19	24	305.6	451	48880
38	32	3.06	7.09	5.085	0.7	0	3	0	20	20	26	248.7	1394	308961
39	32	5.075	3.07	2.06	0.9	2	3	0	20	18	25	245.3	1344	194586
40	29	3.15	4.05	2.11	1	0	3	0	20	19	24	362.6	111	65681

Table E - 2 cont. Pareto optimal solutions with design variables and objectives outputs from the A/C Office MOO study

Solution	X^{HVAC}	X^{wall} Wall Insulation (m)	X^{roof} Roof Insulation (m)	X^{ground} Ground Insulation (m)	X^{seal} Infiltration reduction % (ach)	X^{glaz} (glass-gap-glass in mm)	X^{light} Light techn.	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)	X^{cool} (°C)	$Ex_{destbui}$ (kWh/m^2-year)	***Discomfort*** (hours)	$NPV_{50years}$ (£)
41	32	1.04	3.14	2.01	0.6	5	3	0	20	19	25	240.3	1301	131034
42	31	3.08	6.14	3.14	0.6	2	3	25	20	22	24	326.3	360	116072
43	32	3.08	5.1	5.1	0.9	2	3	0	0	22	23	251.0	907	189702
44	29	5.085	1.12	2.05	0.9	0	3	0	0	19	25	349.4	141	84678
45	21	5.075	3.12	6.02	0.7	0	3	0	0	20	25	275.5	667	39627
46	31	3.1	1.12	3.06	0.4	1	3	0	20	19	25	300.4	699	152218
47	29	1.04	3.14	6.03	1	0	3	0	20	22	24	352.9	111	97390
48	31	3.12	3.09	0	0.6	7	3	25	0	21	24	313.9	370	90296
49	31	3.14	3.13	5.085	0.4	1	3	25	0	20	25	301.6	715	158322
50	29	2.07	1.12	7.1	0.8	0	3	0	0	22	25	339.1	170	52329
51	32	3.08	2.08	3.02	0.4	1	3	0	0	22	25	242.3	1227	154931
52	32	7.02	5.1	1.03	0.9	2	3	0	20	22	25	251.9	896	188930
53	31	3.14	2.06	6.03	0.4	0	3	25	0	18	25	313.9	854	269921
54	32	2.07	1.12	2.02	0.4	0	3	0	0	22	24	247.9	1227	261177
55	29	3.12	4.15	6.02	1	0	3	0	20	22	24	351.0	112	56570
56	32	1.07	1.09	2.05	0.9	2	3	0	0	22	25	250.2	897	170530
57	31	4.12	2.07	0	0.5	1	3	25	0	19	25	305.2	583	142961
58	32	3.08	3.14	6.03	0.6	0	3	0	20	19	24	247.0	1398	309075
59	29	1.04	2.12	6.03	1	0	3	0	0	20	24	357.1	111	85158
60	32	5.085	1.09	2.06	0.6	7	3	0	20	22	24	242.9	1060	58998
61	23	3.06	1.12	5.085	0.4	0	3	0	0	20	24	282.9	676	84226

Table E - 2 cont. Pareto optimal solutions with design variables and objectives outputs from the A/C Office MOO study

Solution	X^{HVAC}	X^{wall} Wall Insulation (m)	X^{roof} Roof Insulation (m)	X^{ground} Ground Insulation (m)	X^{seal} Infiltration reduction % (ach)	X^{glaz} (glass-gap-glass in mm)	X^{light} Light techn.	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)	X^{cool} (°C)	$Ex_{destbui}$ (kWh/m^2-year)	*Discomfort* (hours)	$NPV_{50years}$ (£)
62	32	4.04	7.09	4.04	0.7	7	3	0	20	22	24	245.1	926	51121
63	31	3.08	4.09	6.02	0.4	0	3	25	0	19	25	317.0	823	259294
64	32	2.07	1.12	2.02	0.7	1	3	0	0	22	24	246.1	956	161086
65	32	3.11	5.065	5.085	0.7	7	3	0	20	22	24	245.6	984	79166
66	31	3.13	3.11	0	0.5	2	3	0	20	21	24	312.0	394	169805
67	32	4.14	2.14	6.02	1	7	3	0	20	22	24	252.4	750	6478
68	31	4.07	1.1	3.14	0.4	2	3	25	0	18	25	298.0	770	123073
69	32	3.08	5.065	4.04	0.7	2	3	0	0	21	24	246.0	1225	184372
70	31	3.06	3.05	3.06	0.5	2	3	0	0	19	25	308.8	677	193479
71	32	4.14	2.14	6.02	0.5	7	3	0	0	20	26	238.4	1294	4671
72	31	3.13	3.12	3.02	0.4	1	3	0	0	20	24	306.6	469	151186
73	31	3.13	3.13	5.085	0.5	1	3	0	20	18	24	308.2	500	160504
74	31	3.08	2.14	6.03	0.4	7	3	0	0	21	24	302.3	461	34427
75	32	5.085	3.07	2.05	0.6	8	3	0	20	22	24	243.2	1096	70342
76	31	3.1	1.12	3.08	0.4	4	3	0	0	19	25	297.4	766	105241
77	23	1.04	3.14	5.085	0.4	0	3	0	0	19	24	279.4	711	97357
78	31	3.06	3.11	2.04	0.5	8	3	0	0	18	25	297.8	586	85485
79	32	3.06	1.15	3.1	0.6	7	3	0	0	22	24	242.9	1063	69591
80	32	3.06	3.14	5.1	0.7	0	3	0	20	20	24	250.3	1387	311394
81	31	3.1	3.05	5.085	0.5	2	3	0	0	19	25	307.6	691	188789
82	32	5.075	7.09	2.06	1	8	3	0	20	22	24	251.5	805	66459

Table E - 2 cont. Pareto optimal solutions with design variables and objectives outputs from the A/C Office MOO study

Solution	X^{HVAC}	X^{wall} Wall Insulation (m)	X^{roof} Roof Insulation (m)	X^{ground} Ground Insulation (m)	X^{seal} Infiltration reduction % (ach)	X^{glaz} (glass-gap-glass in mm)	X^{light} Light techn.	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)	X^{cool} (°C)	$Ex_{destbui}$ (kWh/m^2-year)	*Discomfort* (hours)	$NPV_{50years}$ (£)
83	32	3.1	7.09	6.03	1	0	3	0	0	20	26	253.5	1388	318825
84	31	4.14	7.09	2.04	0.4	0	3	25	0	19	25	314.3	843	202535
85	32	3.1	1.1	3.14	0.9	0	3	0	0	22	24	254.1	1013	305399
86	32	3.12	4.09	3.03	1	2	3	0	20	22	26	252.7	863	168885
87	32	1.14	3.07	6.06	0.7	2	3	0	0	22	24	246.4	1025	163356
88	32	3.06	4.14	6.02	0.9	8	3	0	20	22	23	249.7	816	45707
89	31	2.07	7.09	2.04	0.4	0	3	0	20	18	25	314.0	851	248885
90	23	3.12	5.065	6.02	0.6	1	3	0	20	20	24	283.1	536	11083
91	32	1.07	1.12	5.085	0.9	1	3	0	0	22	23	251.4	884	169933
92	32	2.07	7.09	3.02	0.5	0	3	0	0	20	26	245.1	1386	284769
93	32	5.075	3.14	2.04	0.8	1	3	0	0	20	25	246.1	1268	194461
94	31	2.07	7.09	2.04	0.4	1	3	0	20	19	25	301.3	672	134753
95	32	4.13	7.09	3.02	0.6	1	3	0	0	22	24	244.3	1035	121410
96	23	3.15	3.13	3.08	0.6	1	3	0	20	20	24	280.7	533	6590
97	32	3.06	1.12	2.02	0.7	0	3	0	0	22	24	251.2	1044	301836
98	31	3.1	2.11	3.11	0.7	2	3	0	0	19	25	317.4	675	190996
99	23	3.08	7.1	6.02	0.5	0	3	0	0	21	24	294.7	567	79829
100	31	5.085	2.14	2.05	0.5	0	3	0	20	19	25	322.5	828	265785
101	16	3.12	7.09	2.04	0.9	0	3	0	20	19	24	315.4	151	3843
102	32	3.1	3.11	0	0.5	0	3	25	0	20	26	243.2	1365	272846
103	31	2.07	1.15	6.02	0.6	7	3	0	20	22	24	318.7	296	45071

Table E - 2 cont. Pareto optimal solutions with design variables and objectives outputs from the A/C Office MOO study

Solution	X^{HVAC}	X^{wall} Wall Insulation (m)	X^{roof} Roof Insulation (m)	X^{ground} Ground Insulation (m)	X^{seal} Infiltration reduction % (ach)	X^{glaz} (glass-gap-glass in mm)	X^{light} Light techn.	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)	X^{cool} (°C)	$Ex_{destbui}$ (kWh/m^2-year)	*Discomfort* (hours)	$NPV_{50years}$ (£)
104	16	2.07	7.09	3.1	0.6	0	3	0	0	18	25	308.1	318	4984
105	32	3.09	3.15	3.05	0.5	0	3	0	0	20	26	246.0	1400	307130
106	23	3.12	3.05	3.06	0.4	0	3	0	20	19	24	279.5	728	98872
107	31	3.08	5.1	5.1	0.7	2	3	0	0	22	23	341.9	370	128831
108	32	5.075	3.07	3.11	0.7	2	3	0	0	22	25	246.7	1029	189368
109	32	3.06	3.15	3.11	0.7	2	3	0	0	21	24	245.5	1238	190572
110	31	3.1	2.1	3.02	0.6	0	3	0	0	22	24	347.0	451	238771
111	32	3.06	3.15	3.1	1	8	3	0	20	22	24	251.8	815	83021
112	31	2.07	3.09	2.04	0.4	7	3	25	0	20	24	301.3	486	28309
113	32	3.12	7.09	4.04	0.6	2	3	0	0	20	26	240.8	1305	175842
114	32	3.08	7.09	5.085	0.7	7	3	0	20	22	24	244.4	975	72412
115	31	3.04	1.1	3.02	0.4	1	3	0	20	18	24	305.4	506	145957
116	31	3.1	3.11	3.14	0.6	0	3	0	0	19	24	336.0	638	265798
117	16	5.075	3.12	6.02	0.6	0	3	0	0	20	25	310.9	325	31628
118	32	3.09	3.15	4.04	0.6	2	3	0	0	19	26	240.4	1323	187239
119	32	5.085	3.07	2.05	0.6	2	3	25	0	22	25	244.7	1099	134423
120	32	4.08	3.12	2.04	0.9	2	3	0	0	22	25	250.9	891	158559
121	29	2.07	3.07	4.17	1	0	3	0	0	21	25	355.5	111	45333
122	21	5.075	3.15	2.05	1	0	3	0	0	19	24	279.4	550	4701
123	32	7.02	5.1	1.03	1	2	3	0	20	22	24	254.4	851	185566
124	23	3.1	1.12	3.06	0.4	0	3	0	0	19	24	278.5	691	95083

Table E - 2 cont. Pareto optimal solutions with design variables and objectives outputs from the A/C Office MOO study

Solution	X^{HVAC}	X^{wall} Wall Insulation (m)	X^{roof} Roof Insulation (m)	X^{ground} Ground Insulation (m)	X^{seal} Infiltration reduction % (ach)	X^{glaz} (glass-gap-glass in mm)	X^{light} Light techn.	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)	X^{cool} (°C)	$Ex_{destbui}$ (kWh/m^2-year)	***Discomfort*** (hours)	$NPV_{50years}$ (£)
125	31	2.07	2.14	4.04	0.4	8	3	25	0	18	24	296.2	531	6112
126	31	3.06	3.08	3.05	0.5	0	3	0	0	19	25	325.8	844	294332
127	32	3.11	5.085	3.15	0.8	1	3	0	0	20	26	245.7	1293	197718
128	16	3.12	3.11	3.03	0.8	0	3	0	20	19	24	313.5	186	24118
129	32	3.1	7.09	3.03	0.9	8	3	0	0	22	24	248.3	841	83974
130	32	3.08	5.1	5.1	0.7	2	3	0	0	22	23	247.6	1025	186570
131	32	3.12	7.09	5.085	0.9	0	3	0	0	22	26	253.2	1016	312527
132	31	3.1	3.11	3.14	0.7	0	3	0	0	19	26	330.2	1213	323170
133	32	3.09	3.15	2.04	0.7	1	3	0	0	18	24	242.8	1315	193270
134	31	2.06	1.15	3.1	0.4	1	3	25	0	20	24	306.5	495	115598
135	32	5.075	6.16	3.05	0.6	3	3	0	20	20	26	241.5	1299	114118
136	31	5.075	6.16	3.05	0.5	8	3	0	20	20	24	303.7	442	35398
137	31	2.07	2.14	6.03	0.5	7	3	25	0	20	24	305.9	414	31435
138	16	3.13	7.09	3.12	0.7	0	3	0	20	20	24	310.7	239	18916
139	23	3.04	3.1	3.06	0.3	1	3	0	0	19	24	268.4	668	2990
140	31	2.07	1.12	2.04	0.4	0	3	0	20	22	23	337.0	451	178479
141	31	3.03	2.05	3.05	0.5	1	3	0	0	20	25	316.6	647	184781
142	16	3.1	1.12	1.06	0.7	0	3	0	0	18	24	309.2	239	18144
143	32	1.14	2.14	6.02	0.7	7	3	0	0	22	24	243.2	948	53660
144	23	3.12	3.13	2.06	0.6	2	3	0	20	19	24	275.2	552	10617
145	31	3.08	3.12	3.02	0.4	7	3	0	0	18	24	297.6	492	58569

Table E - 2 cont. Pareto optimal solutions with design variables and objectives outputs from the A/C Office MOO study

Solution	X^{HVAC}	X^{wall} Wall Insulation (m)	X^{roof} Roof Insulation (m)	X^{ground} Ground Insulation (m)	X^{seal} Infiltration reduction % (ach)	X^{glaz} (glass-gap-glass in mm)	X^{light} Light techn.	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)	X^{cool} (°C)	$Ex_{destbui}$ (kWh/m^2-year)	*Discomfort* (hours)	$NPV_{50years}$ (£)
146	31	3.1	1.12	2.02	0.4	1	3	0	20	18	24	301.8	496	138369
147	32	4.14	7.09	3.02	0.8	7	3	0	0	22	24	246.3	867	22615
148	32	2.07	3.13	2.05	0.8	4	3	0	0	22	24	247.5	951	121238
149	32	3.12	3.15	5.085	0.9	0	3	0	0	20	26	251.1	1391	326306
150	31	3.15	3.15	3.05	0.7	8	3	0	20	22	24	322.8	328	72269
151	29	3.1	5.065	3.1	0.7	0	3	0	0	21	26	340.4	219	74042
152	32	3.1	3.14	3.02	0.5	2	3	0	20	22	24	242.9	1168	173982
153	32	1.14	3.14	2.01	0.6	5	3	0	20	20	24	241.3	1287	114083
154	32	3.06	3.07	6.04	0.5	0	3	0	0	20	26	246.5	1389	304801
155	32	3.1	1.12	3.06	0.9	0	3	0	0	20	24	252.0	1376	313474
156	31	2.06	3.14	3.02	0.4	1	3	25	0	20	25	302.1	640	156904
157	29	3.12	7.09	6.03	0.9	0	3	0	20	22	24	345.2	142	79765
158	32	3.1	2.14	4.04	1	8	3	0	0	22	24	251.3	790	63685
159	32	2.07	7.09	6.03	0.4	0	3	0	0	22	26	246.5	1232	263928
160	21	3.07	3.15	5.075	0.7	0	3	0	20	20	24	275.6	662	32903
161	32	3.1	1.12	2.02	0.7	1	3	0	20	21	24	244.7	1193	176157
162	31	6.08	1.12	6.03	0.4	7	3	0	0	18	24	297.2	496	25461
163	23	3.09	3.08	3.04	0.3	1	3	0	0	19	24	267.6	669	4260
164	16	3.1	1.12	5.085	1	0	3	0	0	19	24	317.9	120	5149
165	23	5.075	3.15	2.05	0.3	0	3	0	0	19	24	275.9	726	88429
166	31	3.07	2.11	6.02	0.5	4	3	0	0	19	24	308.4	461	108763

Table E - 2 cont. Pareto optimal solutions with design variables and objectives outputs from the A/C Office MOO study

Solution	X^{HVAC}	X^{wall} Wall Insulation (m)	X^{roof} Roof Insulation (m)	X^{ground} Ground Insulation (m)	X^{seal} Infiltration reduction % (ach)	X^{glaz} (glass-gap-glass in mm)	X^{light} Light techn.	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)	X^{cool} (°C)	$Ex_{destbui}$ (kWh/m²-year)	*Discomfort* (hours)	$NPV_{50years}$ (£)
167	31	3.12	7.09	6.03	0.5	0	3	0	0	19	24	325.8	579	263126
168	29	3.09	3.08	3.04	0.7	0	3	0	0	19	26	340.5	219	85459
169	32	4.14	7.09	2.04	0.5	7	3	0	0	20	26	239.1	1318	6234
170	29	3.1	4.15	3.14	1	0	3	0	0	22	24	351.1	111	57695
171	32	3.08	7.09	5.085	1	7	3	0	20	22	24	252.5	797	73895
172	31	5.075	2.14	6.03	0.5	8	3	0	20	20	24	303.8	426	46434
173	32	3.12	1.1	6.02	0.9	0	3	0	20	22	24	254.7	979	304209
174	31	3.03	2.14	4.04	0.5	1	3	0	0	22	24	325.6	382	131295
175	32	3.1	3.14	2.01	0.7	8	3	0	0	20	26	239.3	1217	100524
176	32	3.06	3.15	1.06	0.9	8	3	0	0	22	24	248.9	863	84841
177	32	3.11	3.08	3.13	0.7	1	3	0	0	20	25	244.7	1299	192260
178	31	3.11	3.13	4.05	0.5	0	3	0	20	18	24	323.9	602	259239
179	31	3.15	2.1	2.04	0.4	1	3	0	0	19	25	300.6	686	146370
180	32	3.1	7.09	3.1	0.7	7	3	0	20	22	24	244.3	988	71031
181	32	3.06	3.08	2.06	0.5	7	3	0	0	22	24	242.7	1146	63972
182	32	2.15	2.11	3.02	0.8	2	3	0	0	22	24	247.6	924	148594
183	31	3.06	5.1	2.04	0.6	1	3	0	0	20	25	319.0	633	192090
184	29	1.04	3.14	3.05	1	0	3	0	20	22	24	352.4	111	99521
185	31	3.15	3.07	2.05	0.5	8	3	0	20	20	24	304.9	459	52250
186	29	2.01	3.11	6.03	1	0	3	0	20	19	24	366.1	111	108976
187	23	3.1	1.11	1.07	0.5	1	3	0	0	20	25	272.0	772	11615

Table E - 2 cont. Pareto optimal solutions with design variables and objectives outputs from the A/C Office MOO study

Solution	X^{HVAC}	X^{wall} Wall Insulation (m)	X^{roof} Roof Insulation (m)	X^{ground} Ground Insulation (m)	X^{seal} Infiltration reduction % (ach)	X^{glaz} (glass-gap-glass in mm)	X^{light} Light techn.	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)	X^{cool} (°C)	$Ex_{destbui}$ (kWh/m²-year)	*Discomfort* (hours)	$NPV_{50years}$ (£)
188	32	3.1	7.09	3.1	0.9	0	3	0	20	22	24	254.1	1009	301923
189	23	5.075	1.1	2.05	0.3	0	3	0	0	22	24	284.0	614	53522
190	31	3.1	1.12	3.07	0.4	2	3	0	0	19	25	298.5	745	152979
191	31	1.04	3.09	2.04	0.4	0	3	0	20	19	24	323.6	608	246662
192	32	7.09	7.04	3.02	0.9	7	3	0	20	22	26	249.6	833	75876
193	31	2.07	2.07	0	0.5	1	3	0	0	19	25	307.2	580	182532
194	32	3.08	1.12	2.02	0.7	0	3	0	20	20	26	247.5	1375	308197
195	29	3.1	2.1	3.02	1	0	3	0	20	22	24	352.3	111	86870
196	31	5.085	1.12	2.05	0.4	0	3	25	20	22	24	331.4	471	206384
197	31	5.075	3.07	2.06	0.5	2	3	0	20	18	25	304.7	688	177581
198	32	5.085	7.09	4.04	1	8	3	0	20	22	26	250.0	808	75264
199	32	4.14	3.06	2.02	0.8	8	3	0	20	22	24	246.8	899	24108
200	31	1.14	2.14	6.03	0.4	7	3	0	0	21	24	300.4	487	14558
201	16	3.12	7.09	3.06	0.9	0	3	0	20	19	24	315.3	151	10149
202	32	3.06	1.12	5.085	0.7	8	3	0	0	22	24	243.9	1001	78786
203	32	1.14	2.14	8.005	0.7	8	3	0	0	22	26	240.9	994	42270
204	31	3.03	2.14	3.05	0.5	8	3	0	20	22	24	313.8	351	42892
205	32	3.1	1.12	3.14	1	0	3	0	0	22	24	255.7	990	304602
206	29	3.08	1.12	2.02	0.7	0	3	0	0	22	26	332.4	215	73383
207	32	3.1	1.12	6.02	0.9	7	3	25	0	22	23	249.0	805	36750
208	31	5.065	2.14	3.03	0.5	4	3	0	0	18	24	306.1	482	107956

Table E - 2 cont. Pareto optimal solutions with design variables and objectives outputs from the A/C Office MOO study

Solution	X^{HVAC}	X^{wall} Wall Insulation (m)	X^{roof} Roof Insulation (m)	X^{ground} Ground Insulation (m)	X^{seal} Infiltration reduction % (ach)	X^{glaz} (glass-gap-glass in mm)	X^{light} Light techn.	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)	X^{cool} (°C)	$Ex_{destbui}$ (kWh/m^2-year)	*Discomfort* (hours)	$NPV_{50years}$ (£)
209	31	3.12	4.11	0	0.6	7	3	25	20	21	24	314.1	369	46974
210	32	3.1	3.14	2.01	0.6	0	3	0	0	22	24	249.2	1079	307082
211	23	2.07	7.09	2.04	0.5	0	3	0	20	22	24	301.8	481	32920
212	32	4.14	7.09	2.02	0.9	8	3	0	20	22	24	248.1	831	17280
213	31	3.1	7.09	3.03	0.5	8	3	0	0	22	24	308.2	373	54919
214	32	3.1	3.11	0	1	0	3	0	20	22	24	257.4	936	319917
215	32	1.04	3.15	2.01	0.6	5	3	0	20	22	24	243.6	1039	121066
216	31	4.12	3.07	0	0.5	8	3	25	0	20	24	303.0	389	30605
217	32	1.04	3.14	3.05	1	2	3	0	20	22	24	253.6	854	183390
218	32	3.1	1.12	5.085	1	0	3	0	0	22	26	254.7	992	313157
219	32	3.06	7.09	6.03	0.7	8	3	0	0	20	24	241.6	1213	85090
220	31	3.15	2.07	2.05	0.5	1	3	0	20	19	25	307.0	654	165367
221	32	3.1	2.1	3.02	0.8	6	3	25	0	22	24	246.8	950	80096
222	32	3.07	3.15	5.075	0.9	8	3	0	20	22	25	248.3	868	88598
223	16	3.13	3.12	3.02	1	0	3	0	0	20	24	319.7	121	13459
224	16	3.12	3.13	3.03	1	0	3	0	0	19	24	318.7	121	13340
225	32	3.1	3.05	6.02	0.9	2	3	0	0	18	25	245.7	1333	209741
226	32	3.13	3.13	3.02	0.7	1	3	0	20	20	24	243.7	1251	190134
227	32	3.1	5.1	1.07	1	2	3	0	0	22	24	253.1	869	183874
228	31	3.1	3.14	3.02	0.5	2	3	0	0	20	24	310.2	438	167692
229	31	3.12	1.12	5.085	0.5	4	3	0	0	18	24	304.7	492	105170
230	31	3.08	3.06	6.02	0.4	1	3	25	0	19	24	306.6	490	154852

Appendix F: Passivhaus and its differences with the 'LowEx' approach

Since the 'LowEx' approach was developed, researchers have been discussing its similarities and differences with the Passivhaus approach. Passivhaus is a well-established standard, focusing on providing high level of occupant thermal comfort with low levels of energy use. The standard was developed by the German Passivhaus Institute (PHI, 2015) aiming for new construction, although it also provides certification for low energy retrofit projects (EnerPHit standard). The three elements which consist the Passivhaus Standard are: a) energy limit for heating and cooling, b) minimum requirements in terms of thermal comfort, and c) a defined set of passive systems capable to provide the aforementioned requirements in a cost-effective way. In order to achieve a Passivhaus/EnerPHit certification the criteria indicated in Table F - 1 have to be met. The requirements for the EnerPHit standard are less strict than those for the new buildings. For the purpose of calculating these energy values, the Passive House Planning Package (PHPP, 2012) with the appropriate regional climatic dataset is required.

Table F - 1 Passivhaus Standard/EnerPHit Standard Requirements. Source: PHI, 2015

	Passivhaus Standard	**EnerPHit Standard**
Requirement	**Criteria**	
*Specific heating demand**	≤ 15 kWh/m^2-year	≤ 25 kWh/m^2-year
*Specific Heating Load**	≤ 10 W/m^2	≤ 10 W/m^2
Specific Cooling Demand,***	≤ 15 kWh/m^2-year	≤ 25 kWh/m^2-year
*Specific Primary Energy Demand****	≤120 kWh/m^2-year	≤120 kWh/m^2-year + ((SHD -15 kWh/m^2) * 1.2)
Air changes per hour	≤ 0.6 @50	≤ 1.0@50
Thermal comfort	≤ 10% overheating hours/year	≤ 10% overheating hours/year

*Treated Floor Area = Net Living Space calculated from the PHPP
**Climates were active cooling is needed
***Primary energy demand includes space heating, DHW, and electric-based equipment

Typical measures to achieve these values are based on high levels of insulation (U-values of 0.15 W/m²K or lower), high performance glazing systems (U values < 0.80 W/m²K), airtight building fabric (<0.6 *ach* or <1.0 *ach* for retrofits), mechanical ventilation and heat recovery system (η =75% or greater), and absence of thermal bridging. A limitation of the standard is that it is not an embodied carbon standard, where materials, used for insulation, generally have intrinsic high CO_2 embodied emissions.

Shukuya and Hammache (2002) described the exergy-entropy process of passive systems. The authors consider bioclimatic or passive design to be a strategy to control the exergy available in the building's surroundings. The authors conceive passive strategies as a prerequisite to the efficient use of low exergy devices. Strategies such as daylighting, passive ventilation, and shading manage and consume solar exergy to illuminate indoor spaces, provide heating and cooling energy, or block the access of exergy excess, respectively. On the other hand, Meggers et al. (2012) considers 'Passivhaus' designs restrictive, showing that smart integration of low exergy active systems results in better environmental performance. The author demonstrates that an efficient building design finds a balance between the active and passive components, criticising the common practice of maximizing thermal insulation and air tightening of the building envelope. Less dependency on passive components can create higher design flexibility and less construction material demands. Later, Meggers et al. (2013) showed that the LowEx was the most appropriate technique for tropical climates by using high temperature cooling systems.

As seen in the literature review, design based on exergy leads to slightly different system configurations. The 'LowEx' standard, based on Second Law calculations, promotes a rational use of resources while also providing comfortable internal conditions for the occupant. For the space heating and cooling demand, the approach focuses on low exergy active systems, meaning it employs technologies with low temperature heating and high temperature cooling systems, therefore having lower ΔT between the source and the room air conditions. These technologies also have the capability of using low quality energy sources. For emission systems, it advocates the use of large surface areas, such as underfloor, wall, and ceiling systems. Lowering temperatures for heat distribution systems, apart from reducing transmission losses, helps improve indoor thermal comfort by reducing the temperature gradient, radiant heat asymmetry, and temperature fluctuations.

However, Hepbasli (2012) emphasized that either 'LowEx' or 'Passivhaus' are not individual techniques but rather a group of technical methods that could work best together, with both methods still with room for further development. Next table shows an extensive but not exhaustive list of characteristics for each method.

Table F - 2 Similarities and differences of LowEx and Passivhaus approaches

Characteristics	Passivhaus	LowEx
Comfort and interior climate control	x	x
Air quality control	x	
Energy efficiency	x	
Thermodynamic efficiency		x
Use of low grade heat	x	x
Integration of storage systems and PCM		x
Emission reduction during operation	x	x
Embodied emission during life cycle		x
Construction cost		x
Design adaptation to different climates		x
Space efficiency		x
Performance Gap reduction	x	
Esthetical	x	
Design flexibility		x
Heritage conservation		x
Use of renewable energy	x	x

Appendix G: Case Study 2: Mayville Community Centre model assumptions and input information

G.1 Pre-retrofit Mayville Community Centre

Table G - 1 Pre-retrofit Mayville Community Centre main characteristics

General Description	Three Storey Community Centre - Offices	  
Building Type	Commercial	
Configuration	Low Rise-Shallow Plan	
Location	London	
Coordinates	51° 33' 03'' N, 0° 04′ 57'' W Decimal 51.550833^0, -0.082489^0	
Weather File	London Heathrow, UK	

Geometry				
Number of Floors	3	Total Floor Area	612m^2	
Opaque Materials	**Construction**		**U-Value Wm^2/K**	
External Walls (GF/1STF)	400mm Solid Wall		1.777	
External Walls (Basement)	400mm Solid Wall		1.877	
Basement Floor	300 mm Concrete Floor Slab		0.539	
Ground Floor	300 mm Concrete Floor Slab		0.539	
Pitched Roof	20mm Asbestos		5.463	
Flat Roof	200 mm Concrete Slab		3.121	
Transparent Materials	**Property**	**U-Value W/m^{2}K**	**SHGC**	**VT**
Glazing Material	5mm Single Glazing	5.84	0.8	0.696
Glazing Area	29% of Total Wall Area			
Skylight Area	5% of Total Roof Area			
Shading	N/A			
Systems				
HVAC System Type	Boiler-based heating and natural ventilation			
Heating System	145 kW Gas Fired Boiler connected to high temperature radiators			
Energy efficiency	0.80			
Fuel Type	Natural Gas			
Heating System Controls	Main System Thermostat – Thermostatic Valves on Radiators			
Cooling System	N/A (Natural Ventilation and Night Cooling)			
Energy efficiency	N/A			
Fuel Type	N/A			
Ventilation	Winter: Natural Ventilation Summer: Natural Ventilation			
Specific Fan Power	N/A			
DHW				
Generator Type	Gas Fired Boiler + hot water tank			
Fuel Type	Natural Gas			
Lighting				
Type	T12 LFC			
Controls	manual-on-off			
Loads				
Occupancy	1 person/16m^2 - at average 140 watts= 8.75 W/m^2			
Equipment	73.4 W/m^2			
Lighting	10.6 W/m^2			
Rates				
Infiltration Rate	1.0 ach			
Renewables (PV system)				
Available roof space	324 m^2			
PV array	N/A			
Type	N/A			

Table G - 2 Pre-retrofit Mayville: Occupancy profile (weekday) for each thermal zone

Hour	7	8	9	10	11	12	13	14	15	16	17	18
Basement	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0
Studio (Storage)	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0
Main Hall	0.1	0.1	0.2	0.5	0.5	0.9	0.5	0.5	0.5	0.5	0.3	0.1
Office GF and 1F	0.1	0.3	0.8	1.0	1.0	0.5	0.5	1.0	1.0	0.5	0.5	0.0
Reception	0.1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.1
Kitchen	0.0	0.0	0.0	0.3	0.3	1.0	1.0	0.8	0.3	0.0	0.0	0.0

Table G - 3 Pre-retrofit Mayville: Input assumptions for each thermal zone

Zone category	Lighting (W/m^2)	Equipment (W/m^2)	Ventilation (l/s/pers.)	Heating setpoint (°C)	Occupancy (m^2/person)	Activity level (W/person)
Office Basement	18.0	10.0	10	20	5.0	120
Studio (Storage)	12.0	4.0	5.5	18	2.0	113
Main Hall	18.0	2.0	12	20	6.0	140
Office GF and 1F	18.0	10.0	10	20	5.0	120
Reception	18.0	6.0	10	20	10.0	140
Kitchen	18.0	4.0	25	18	4.0	130

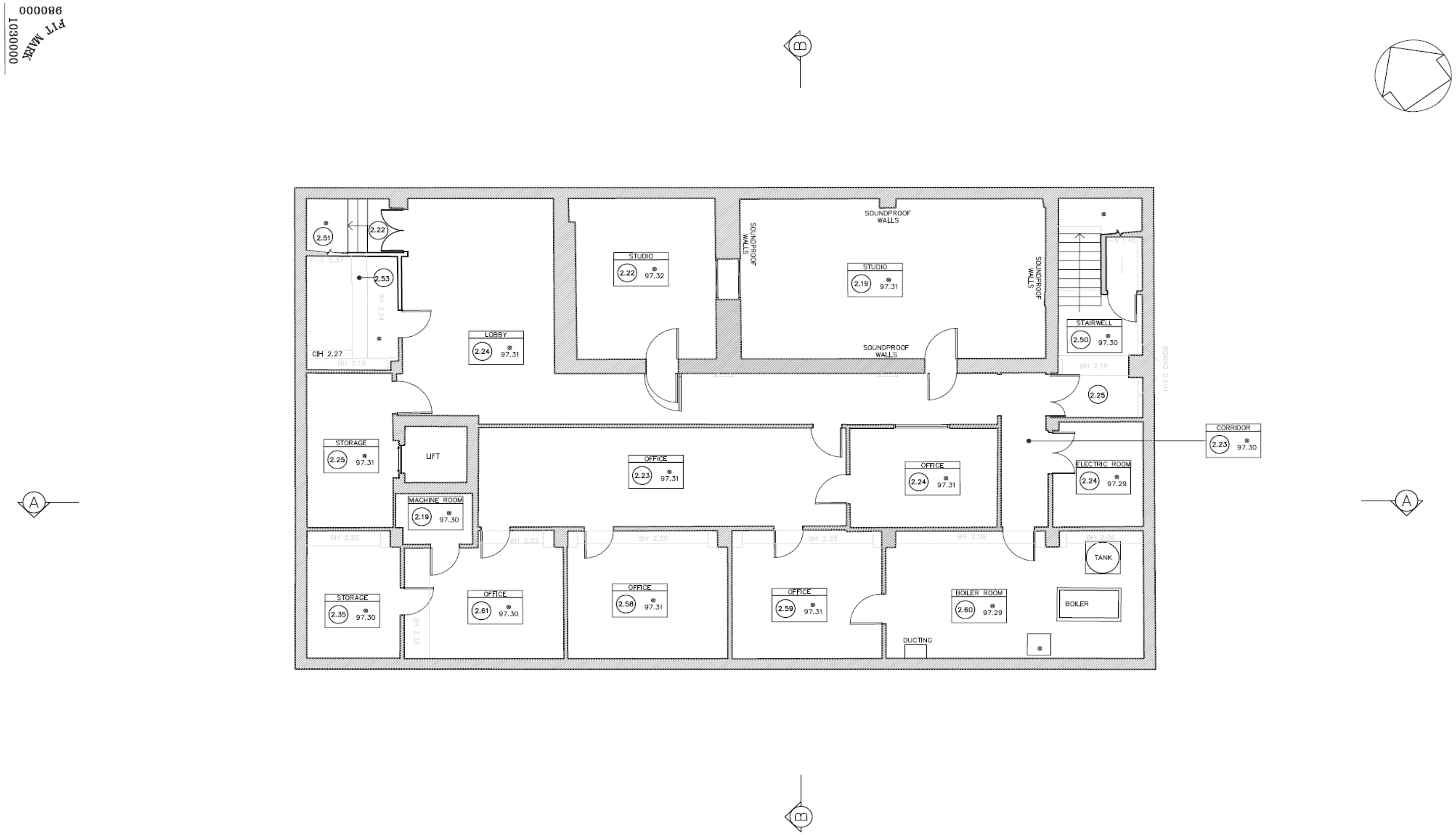


Figure G - 1 Architectural Plan Pre-retrofit Mayville Community Centre Basement

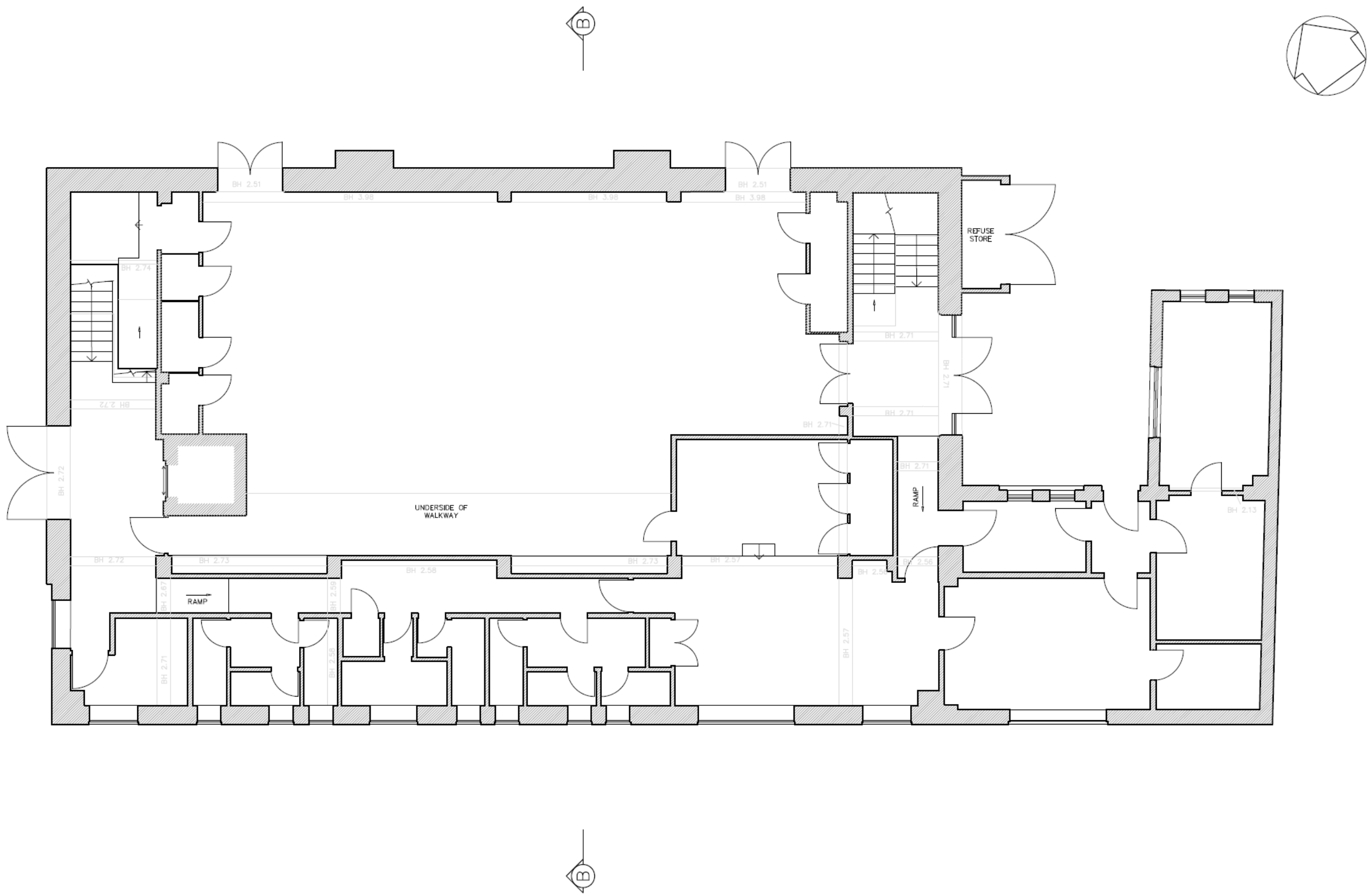


Figure G - 2 Architectural Plan Pre-retrofit Mayville Community Centre Ground Floor

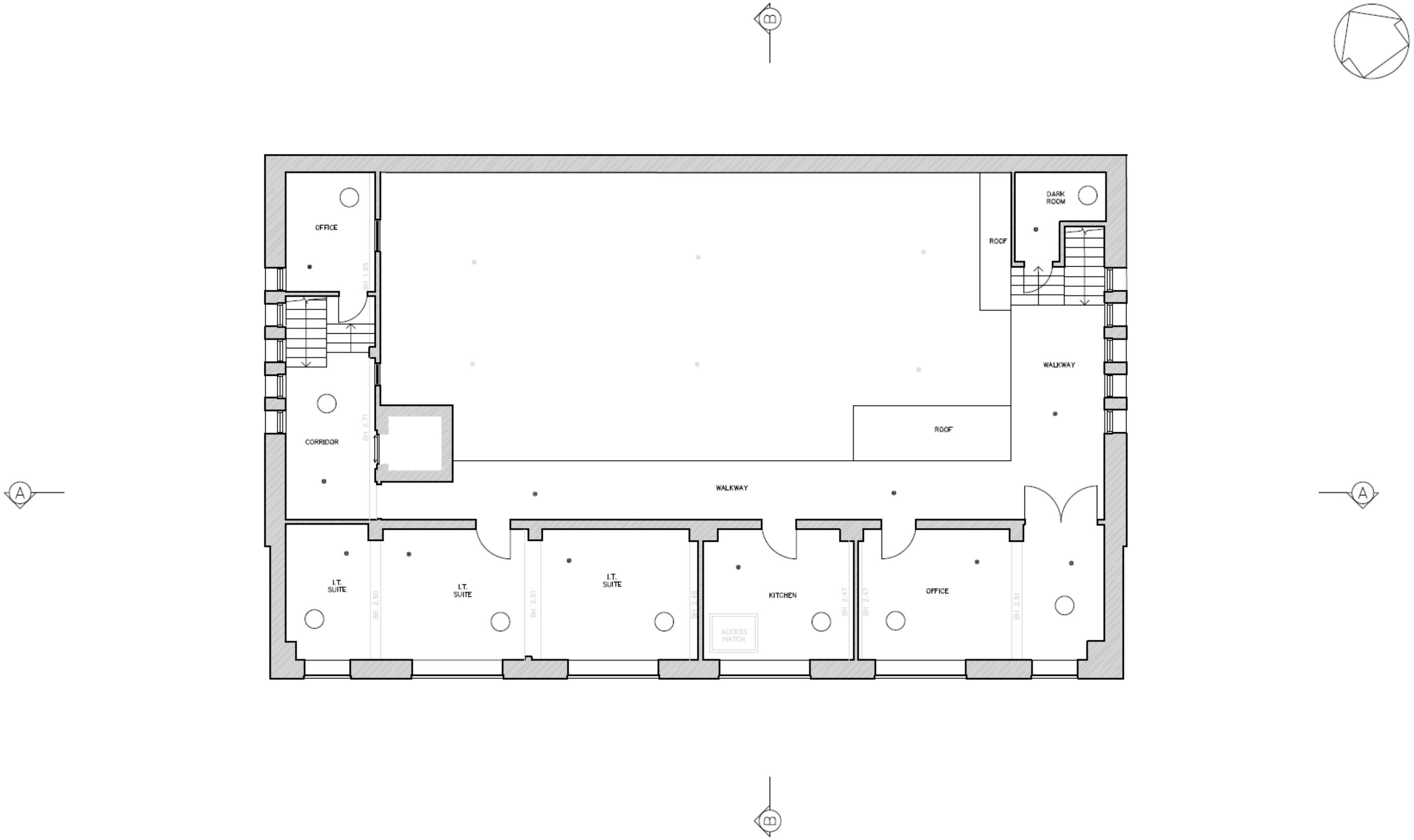


Figure G - 3 Architectural Plan Pre-retrofit Mayville Community Centre First Floor

Table G - 4 Pre-retrofit Mayville Community Centre: Comparison between Actual Building and Modelled building data using ASHRAE 14-2002 indices

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	TOTAL	
Electricity Use														
Actual Electricity kWh	2,806	2,806	2,806	2,161	2,161	2,161	2,225	2,225	2,225	2,468	2,468	2,468	**28,980**	
Modelled Electricity kWh	2,666	2,502	2,790	2,372	2,503	2,414	2,312	2,460	2,425	2,739	2,611	2,497	**30,292**	
M-S	140.3	303.6	15.9	-211.1	-341.8	-253.0	-87.1	-235.3	-199.9	-271.0	-143.1	-29.3	**140.3**	**MBE**
sqrt((M-S)^2/n)	1,639.6	7,678.6	21.0	3,714.3	9,735.6	5,332.0	632.6	4,614.6	3,330.7	6,120.1	1,705.3	71.4	**1,639.6**	**CVRMSE**
Gas Use														
Actual Gas kWh	35,289	23,696	21,114	15,818	15,097	7,170	5,883	9,177	7,502	13,336	12,881	22,204	**189,167**	
Modelled Gas kWh	33,340	24,527	22,266	16,540	13,167	6,789	4,329	5,406	7,203	14,017	12,758	21,653	**181,994**	
M-S	1,948.8	-830.6	-1,152.0	-722.2	1,930.3	380.8	1,554.4	3,771.3	299.3	-680.7	122.8	551.0	**1,948.8**	**MBE**
sqrt((M-S)^2/n)	316,475.4	57,487.2	110,595.8	43,463.2	310,517.7	12,085.3	201,354.4	1,185,225.3	7,465.0	38,612.7	1,257.1	25,297.3	**316,475.4**	**CVRMSE**

Next two figures show a monthly comparison between the real building and the modelled electricity and gas use respectively.

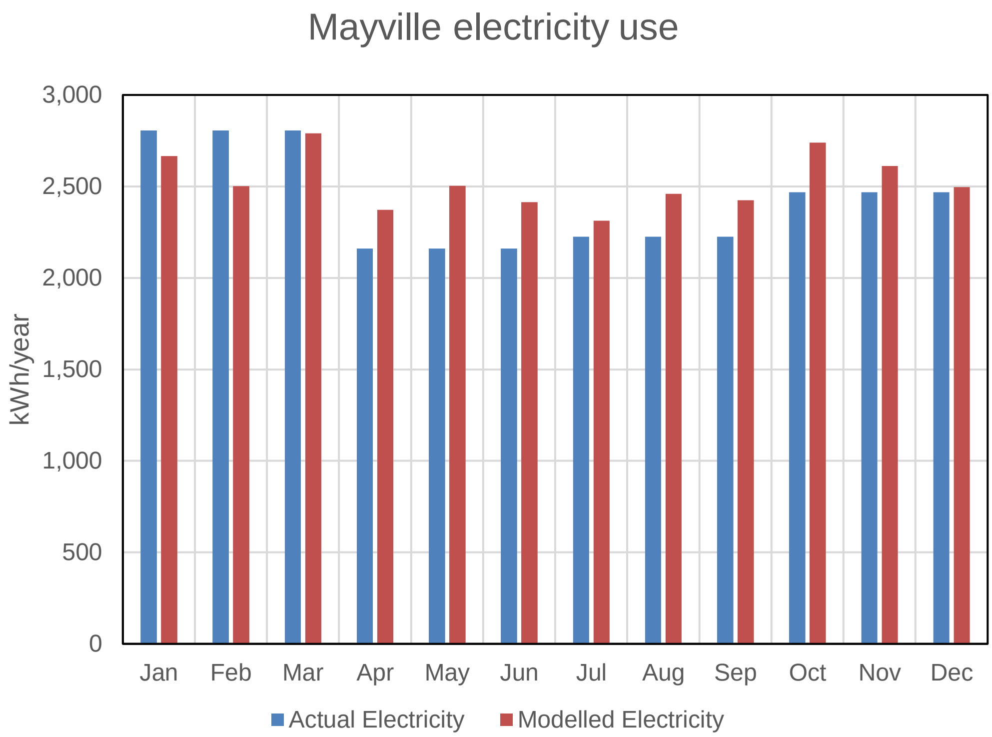


Figure G - 4 Pre-retrofit Mayville Community Centre: Monthly electricity use comparison between actual building and modelled building

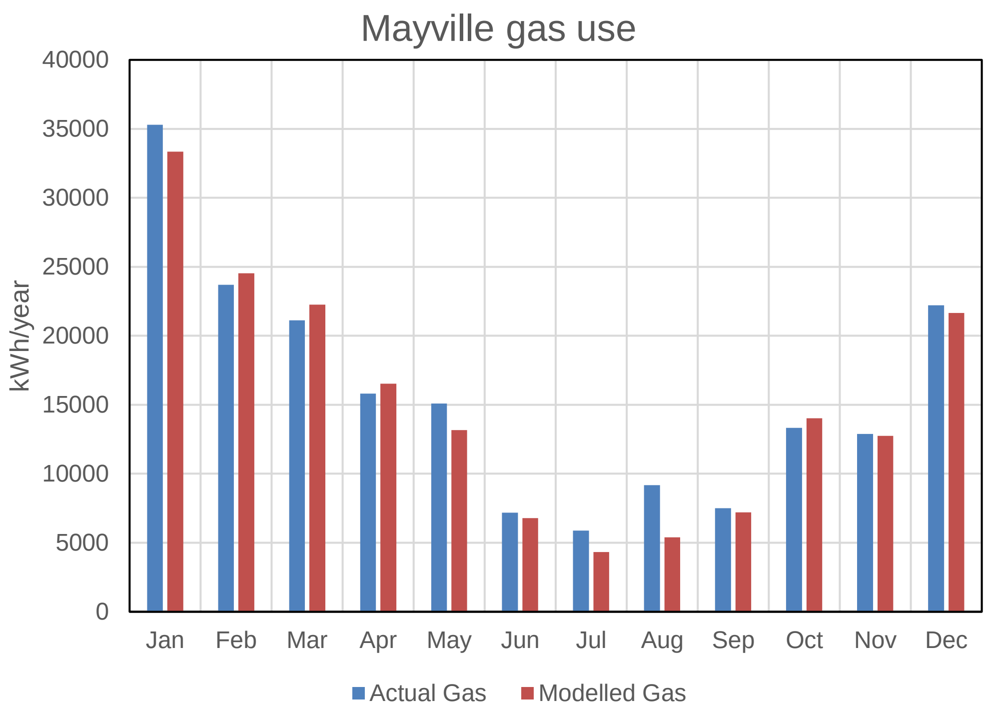


Figure G - 5 Pre-retrofit Mayville Community Centre: Monthly gas use comparison between actual building and modelled building

G.2 Post-retrofit Mayville Community Centre

Table G - 5 Post-retrofit Mayville Community Centre main characteristics

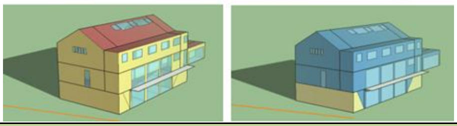
General Description	Three Storey Community Centre - Offices	 			
Building Type	Commercial				
Configuration	Low Rise-Shallow Plan				
Location	London				
Coordinates	51° 33' 03'' N, 0° 04′ 57'' W Decimal 51.550833^0, -0.082489^0				
Weather File	London Heathrow, UK				
Geometry					
Number of Floors	3	Total Floor Area	800m^2		
Opaque Materials	**Construction**			**U-Value Wm^2/K**	
External Walls (GF/1STF)	400mm Solid Wall – 300mm Extruded Polystyrene			0.109	
External Walls (Basement)	400mm Solid Wall – 200mm Expanded Polystyrene			0.160	
Basement Floor	300 mm Concrete Floor Slab – 80mm Phenolic Foam			0.173	
Ground Floor	300 mm Concrete Floor Slab – 300mm Cellular Glass			0.108	
Pitched Roof	Timber framed - 300mm Cellular Glass - Zinc finish			0.134	
Flat Roof	200 mm Concrete Slab – 300mm Cellular Glass			0.131	
Transparent Materials	**Property**	**U-Value W/m^{2}K**	**SHGC**	**VT**	
Glazing Material	6-13-6-13-6 Triple Glazed Air Filled-Low-e	1.598	0.613	0.696	
Glazing Area	23% of Total Wall Area				
Skylight Area	5% of Total Roof Area				
Shading	N/A				
Systems					
HVAC System Type	Mechanical Ventilation with Heat Recovery System				
Heating System	Heat Recovery System + 8.4kW Ground Source Heat Pump with radiators				
COP	4.5				
Fuel Type	Electricity				
Heating System Controls	Main System Thermostat – Thermostatic Valves on Radiators				
Cooling System	N/A (Natural Ventilation and Night Cooling)				
Ventilation	• Winter: Mechanical Ventilation Heat Recovery-Radius Heat Exchanger Eff= 0.75 • Summer: Mixed Mode Ventilation Heat Recovery-Radius Heat Exchanger Eff= 0.75 + Natural Ventilation				
Specific Fan Power	0.7 – 1.5 kPa				
DHW					
Generator Type	Single 3m^2 thermal vacuum tube panel + hot water tank GSHP for top-up				
Fuel Type	Solar energy - Electricity				
Lighting					
Type	T8 LFC				
Controls	manual-on-off				
Loads					
Occupancy	1 person/16m^2 - at average 140 watts= 8.75 W/m^2				
Equipment	73.4 W/m^2				
Lighting	10.6 W/m^2				
Rates					
Infiltration Rate	0.42 ach				
Renewables (PV system)					
Available roof space	398.6 m^2				
PV array	125m^2 of PV on pitched surface (inclination 30^o)				
Type	77 modules of 18kWp, c-Si-Monocrystalline				

Table G - 6 Occupancy profile (weekday) for each thermal zone. Post-retrofit Mayville

Hour	7	8	9	10	11	12	13	14	15	16	17	18
Office Basement	0.1	0.3	0.8	1.0	1.0	0.5	0.5	1.0	1.0	0.5	0.5	0.3
Studio	0.0	0.0	0.3	0.3	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.2
Main Hall	0.1	0.1	0.2	0.5	0.5	0.9	0.5	0.5	0.5	0.5	0.3	0.1
Office GF and 1F	0.1	0.3	0.8	1.0	1.0	0.5	0.5	1.0	1.0	0.5	0.5	0.3
Reception	0.1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.1
Kitchen	0.0	0.0	0.0	0.3	0.3	1.0	1.0	0.8	0.3	0.0	0.0	0.0

Table G - 7 Input assumptions for each thermal zone. Post-retrofit Mayville

Zone category	Lighting (W/m^2)	Equipment (W/m^2)	Ventilation (l/s/pers.)	Heating setpoint (°C)	Occupancy (m^2/person)	Activity level (W/person)
Office Basement	10.6	8.4	10	20	10.0	120
Studio	10.6	4.1	5.5	20	5.0	113
Main Hall	10.6	5.0	12	18	2.0	140
Office GF and 1F	10.6	8.4	10	18	10.0	140
Reception	10.6	4.1	10	20	20.0	140
Kitchen	10.6	10	25	18	4.0	130

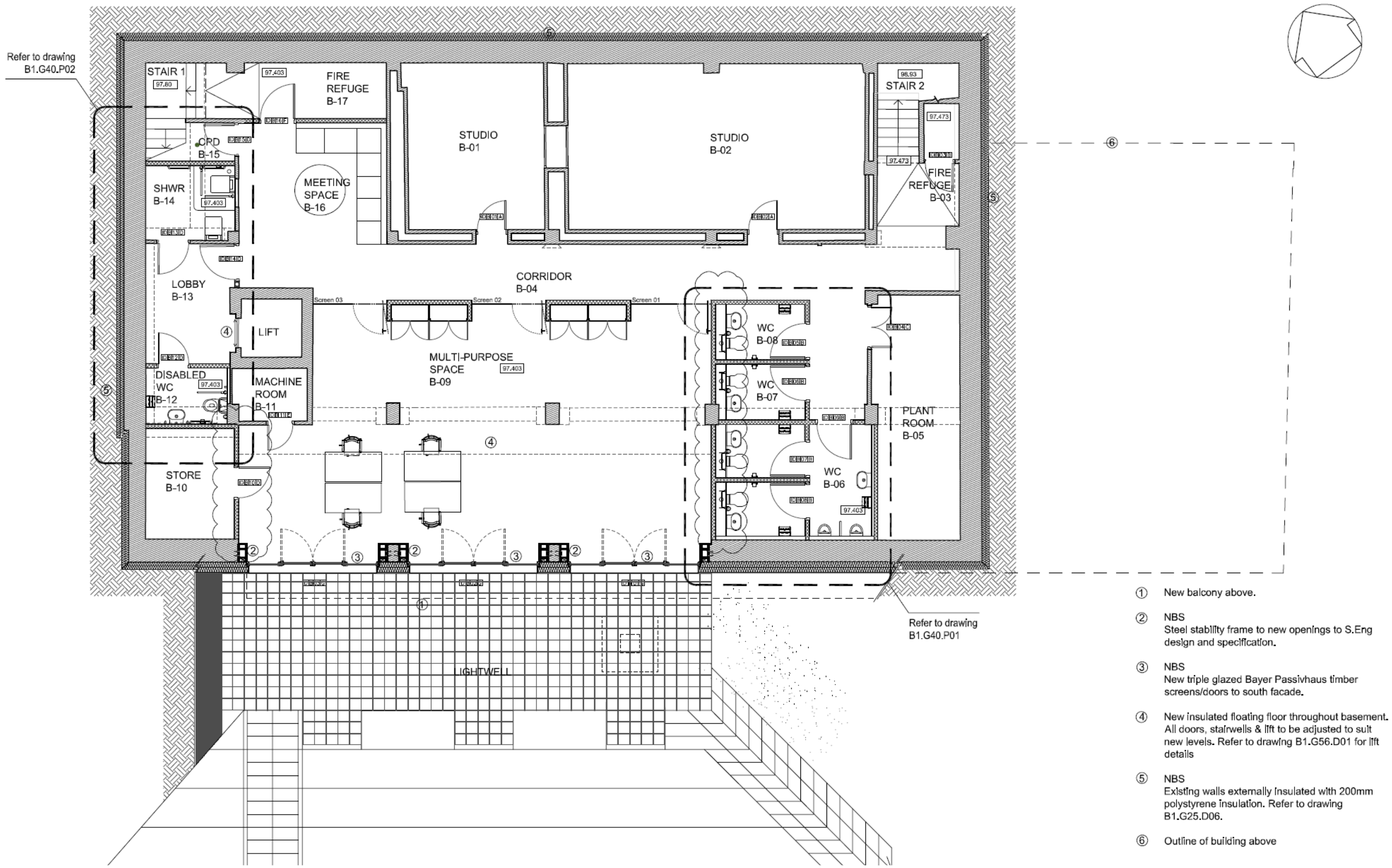


Figure G - 6 Architectural Plan Post-retrofit Mayville Community Centre Basement

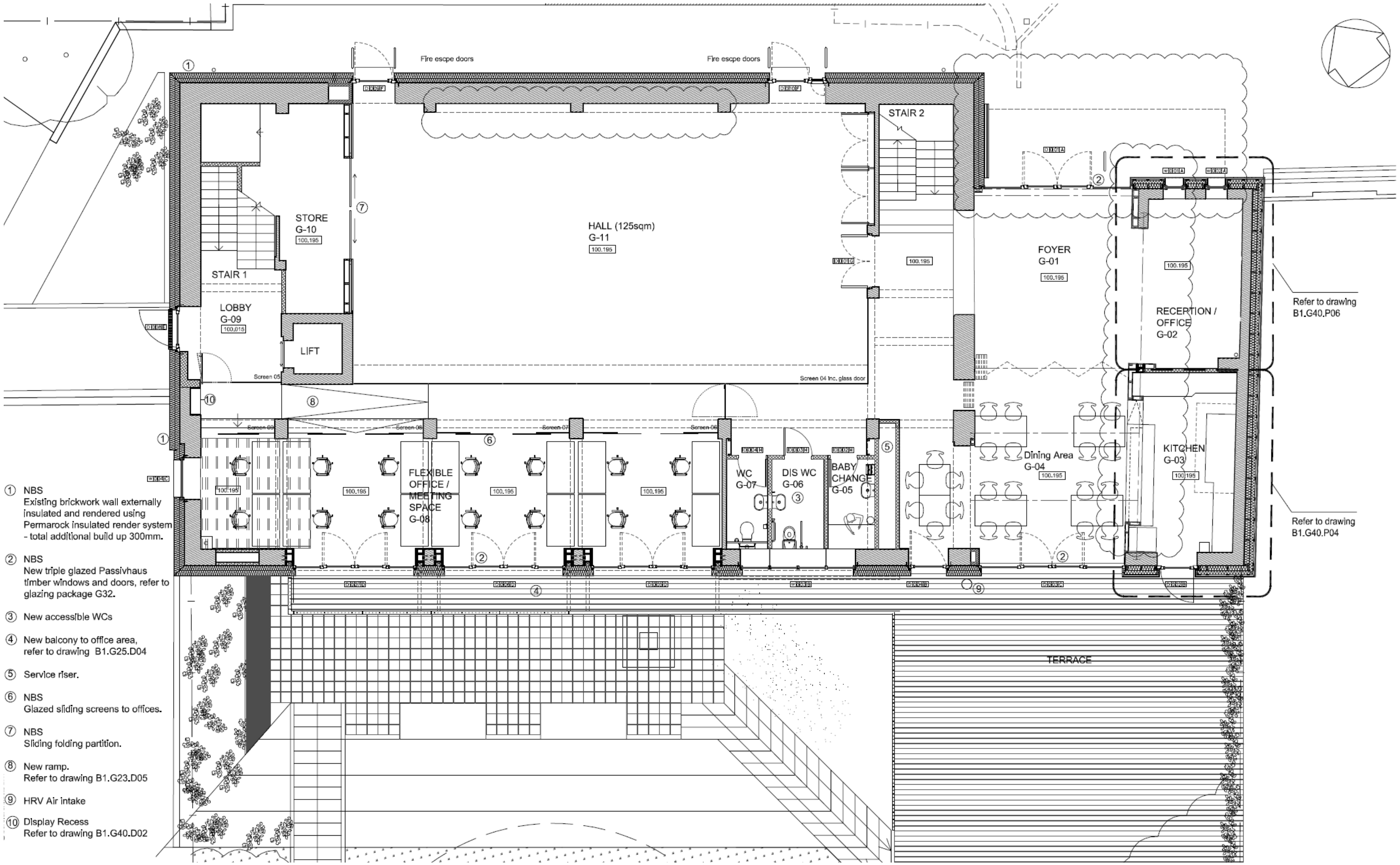
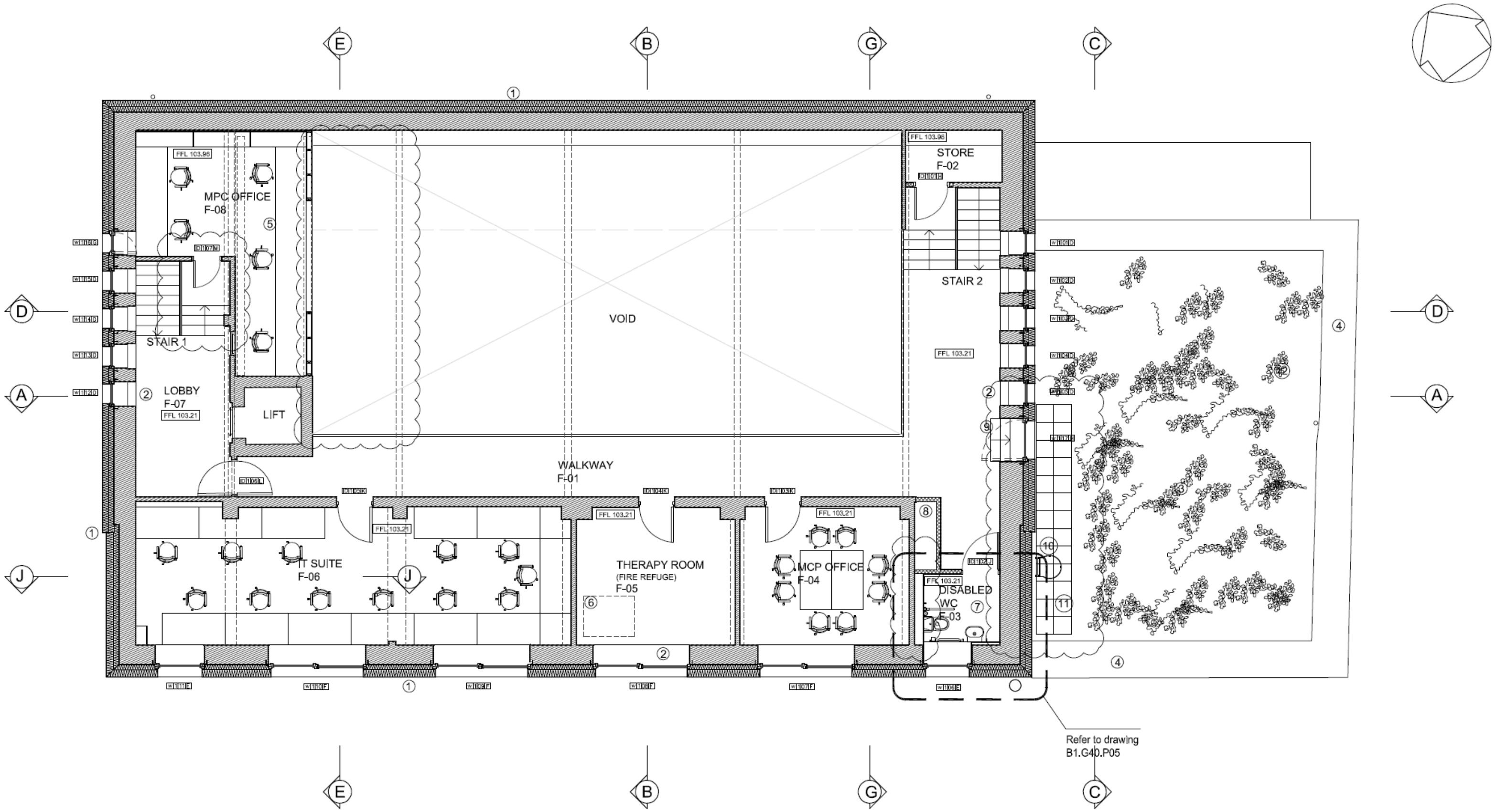


Figure G - 7 Architectural Plan Post-retrofit Mayville Community Centre Ground Floor



① NBS
Existing brickwork wall externally insulated and rendered using Permarock insulated render system - total additional build up 300mm.

NOTE - Increase in thickness of Permarock EPS insulation to upper level of south elevation and rear portion of east and west elevations with total build-up 330mm.

② NBS
New triple glazed Bayer Passivhaus timber windows, refer to glazing package G32.

③ Ecological roof garden.

④ NBS
Zinc copings to parapets.

⑤ New office space over stores below.

⑥ Existing roof hatch to be infilled. Refer to drawing B1.G35.P01

⑦ New accessible WC.

⑧ Service riser.

⑨ New opening with triple glazed Bayer Passivhaus timber door, refer to drawing B1.G32.D02.

⑩ NBS
Secure access ladder to top roof installed in conjunction with mansafe system for roof maintenance.

⑪ NBS
New paving on adjustable pedestals.
Refer to drawing B1.G24.D12

Figure G - 8 Architectural Plan Post-retrofit Mayville Community Centre First Floor

Table G - 8 Post-retrofit Mayville Community Centre : Comparison between Actual Building and Modelled building data using ASHRAE 14-2002 indices

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	TOTAL	
Electricity Use														
Actual Electricity kWh	4,400	4,320	4,400	3,840	3,600	3,760	3,440	3,600	4,320	4,640	4,640	4,160	**49,120**	
Modelled Electricity kWh	5,022	4,653	5,232	4,088	3,297	3,369	3,423	3,397	3,368	3,478	5,036	4,946	**49,309**	
M-S	-621.9	-332.6	-832.5	-248.3	303.2	391.2	17.3	203.2	951.9	1,161.6	-396.2	-785.9	**-0.38%**	**MBE**
sqrt((M-S)^2/n)	32,228.8	9,219.7	57,753.3	5,136.9	7,658.3	12,751.2	25.0	3,441.5	75,506.3	112,450.6	13,081.0	51,469.9	**15.00%**	**CVRMSE**
Gas Use														
Actual Gas kWh	---	---	---	---	---	---	---	---	---	---	---	---	---	
Modelled Gas kWh	---	---	---	---	---	---	---	---	---	---	---	---	---	
M-S	---	---	---	---	---	---	---	---	---	---	---	---	---	**MBE**
sqrt((M-S)^2/n)	---	---	---	---	---	---	---	---	---	---	---	---	---	**CVRMSE**

G.3 Interview with Justin Bere (Mayville Passivhaus project architect)

The transcript has been taken from the Architects' Journal webpage. The interview was conducted on the 23 February, 2012 and can be found in the following link: https://www.architectsjournal.co.uk/home/passivhaus-community-centre-mayville-by-bere-architects/8626797.article

Why did you decide to go for Passivhaus?

Initially I was asked to look at the building to advise on putting in a biomass plant, but we started instead by looking at how to save energy. The basement was dark and unused, so we suggested excavating and adding south-facing windows, which would bring light in and generate heat for the building. There was no budget so it wasn't a matter of 'we can't afford that'. There was no money, full stop.

Did Passivhaus restrict your design options?

No. It shows you that if you waste energy in one place, you need to compensate for it somewhere else. You could put big windows on the north side but then you would have to add more insulation to the envelope.

I don't think we would have received permission from Homes for Islington to excavate and add all the windows overlooking the south garden if we hadn't been able to use Passive House Planning Package to demonstrate the long-term energy and comfort benefits.

This is London's first non-domestic Passivhaus, and all the funders liked that. We received about £260,000 from the council for renewables and the 90 per cent heat-recovery ventilation. The Carbon Trust, the Big Lottery Fund and the Community Builders Fund were also among those that helped fund the project.

Is the building more complicated to use and look after?

It's much simpler than a normal building. Typically a building this size would have a building management system, but we decided to keep controls really simple. Our controls are no more complicated than a domestic thermostat. A ground-source heat pump supplies any heat needed to the radiators, which have simple thermostatic valves.

All lights are manually switched on and off. Presence detectors are used to switch lights off if they are forgotten. External retractable blinds (and insulation) help keep the building cool in the summer, and are adjustable so we get the light in but not the heat. These are very easy to operate.

What were the biggest successes of the project?

The redeveloped centre has helped lift the surrounding area; its white and grey render transforms the estate; its gardens are now actively used by the community. Users of all ages are excited by how their building is heated mostly by the sun.

The airtightness at 0.43ach-1 at 50Pa was a triumph on any project - especially a retrofit - and provides QA on the fabric, allowing the services to be sized and operated in accordance with the design model. This is an all-electric building and by fabric-first measures and sensible controls, I think we will keep electrical and primary energy consumption so low that the PV will provide about half the energy requirements of the building.

Running costs will be about £800 a year compared to £10,000 before (with no feed-in tariff). The building uses 90 per cent less energy than it did before, with less than 10 per cent of the running costs, and it’s really warm in winter and cool in summer.

Appendix H: Mayville Community Centre optimisation outputs

This appendix presents the database for all Pareto solutions obtained from the MOO study presented in Chapter 8 as well as the MCDM solution tables.

Note: The tables show its corresponding design variables in a coded format which can be reviewed checking the retrofit database presented in Appendix B.5. For example, a value of 3.08 in the wall insulation column corresponds to insulation I3: Expanded polystyrene (EPS) and the .08 corresponds to the thickness (.08m.

H.1 Pareto solutions from the energy/economic based approach

Table H - 1 Pareto optimal solutions with design variables and objectives outputs from the energy/economic MOO study. Mayville Community Centre case study

Solution	X^{HVAC}	X^{wall} Wall Insulation (m)	X^{roof} Roof Insulation (m)	X^{ground} Ground Insulation (m)	$X^{\mathrm{wall\_BS}}$ Basement Wall Insulation (m)	$X^{\mathrm{roof\_Pi}}$ Pitched Roof Insulation (m)	$X^{\mathrm{ground\_BS}}$ Basement Ground Insulation (m)	X^{seal} (ach)	X^{glaz}	X^{light} Light techn.	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)	EUI (kWh/m²-year)	**Dis-comfort** (hours)	$NPV_{50years}$ (£)
1	31	5.15	2.08	6.14	2.04	2.03	7.04	0.8	2	2	10	20	21	272.4	853	148667
2	31	6.03	4.13	3.14	4.06	4.06	5.085	0.7	3	1	10	20	22	279.7	720	137624
3	21	7.03	7.15	1.12	8.01	2.15	7.04	0.8	0	2	10	20	21	64.7	703	113534
4	21	5.15	2.2	1.12	8.01	1.05	7.04	0.8	0	2	10	20	21	64.2	703	112271
5	21	6.06	3.05	3.08	6.16	2.11	6.05	0.9	0	2	10	20	18	67.8	669	105952
6	21	5.15	7.1	7.1	1.06	4.09	3.3	0.9	0	1	20	20	20	66.0	664	98426
7	21	2.15	1.03	3.3	4.15	3.15	3.2	1	0	2	20	20	20	66.5	646	97622
8	21	3.14	5.1	4.12	2.25	3.12	1.1	1	1	2	10	20	21	65.9	640	79773
9	28	2.01	2.13	4.04	9.01	8.04	6.02	1	5	1	10	20	18	340.8	550	71297

H.2 Pareto solutions from the exergy/exergoeconomic based approach

Table H - 2 Pareto optimal solutions with design variables and objectives outputs from the exergy/exergoeconomic MOO study. Mayville Community Centre case study

Solution	X^{HVAC}	X^{wall} Wall Insulation (m)	X^{roof} Roof Insulation (m)	X^{ground} Ground Insulation (m)	$X^{\mathrm{wall\_BS}}$ Basement Wall Insulation (m)	$X^{\mathrm{roof\_Pi}}$ Pitched Roof Insulation (m)	$X^{\mathrm{ground\_BS}}$ Basement Ground Insulation (m)	X^{seal} (ach)	X^{glaz}	X^{light} Light techn.	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)	$Ex_{destbui}$ (kWh/m^2-year)	Dis-comfort (hours)	$Exec_{CB}$ (£/h)
1	29	1.3	2.07	1.13	1.3	2.06	2.2	0.9	7	2	10	20	19	111.2	659	0.20
2	28	6.2	6.12	2.14	9.01	6.06	1.12	0.9	2	2	20	0	19	238.8	584	0.90
3	26	5.075	4.11	1.2	6.18	4.18	6.12	1	6	2	10	20	21	114.2	641	0.27
4	26	3.13	6.02	0	5.2	1.25	7.05	0.9	2	1	30	20	21	108.8	657	0.23
5	29	5.3	2.08	8.01	3.25	1.11	1.12	0.9	2	2	20	20	19	111.4	659	0.02
6	29	3.25	3.04	6.14	3.07	2.06	4.13	1	3	2	30	0	20	117.8	625	0.28
7	29	1.02	4.09	4.12	2.14	6.05	4.11	1	0	3	0	0	20	123.3	647	0.10
8	29	6.1	4.07	4.04	3.14	3.06	3.15	1	6	2	30	0	20	118.5	630	0.28
9	29	6.1	4.07	4.04	3.14	3.06	3.15	1	6	2	30	0	21	118.3	631	0.26
10	26	3.13	4.08	8.03	4.3	4.15	3.15	1	0	1	0	20	19	115.4	644	0.13
11	29	2.09	4.3	7.08	2.25	5.3	3.03	0.9	6	2	30	20	18	111.4	653	0.24
12	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19	109.3	666	-0.11
13	15	1.03	3.09	1.06	5.2	7.05	8.025	0.8	0	3	0	20	20	102.9	791	0.23
14	29	6.08	7.08	2.06	7.3	3.04	2.2	0.9	0	1	20	20	20	127.8	664	-0.01

H.3 MCDM – Compromise programming outputs for the energy/economic-based approach

Table H - 3 Sample of 'optimal solutions' obtained from the energy/economic-based Pareto front using Compromise Programming

p_{eui}	p_{com}	p_{NPV}	[min] α_{cheb}	EUI (kWh/m^2-year)	*Dis-comfort* (hours)	NPV_{50y} (£)	X^{HVAC} (Type)	X^{wall} (m)	X^{roof} (m)	X^{ground} (m)	$X^{\text{wall\_BS}}$ (m)	$X^{\text{roof\_Pi}}$ (m)	$X^{\text{ground\_BS}}$ (m)	X^{seal} (ach)	X^{glaz} type	X^{light} Light techn	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)
1	0	0	1.12	64.2	703	112271	21	5.15	2.2	1.12	8.01	1.05	7.04	0.8	0	2	10	20	21
0.9	0.1	0	0.04	65.9	640	79773	21	3.14	5.1	4.12	2.25	3.12	1.1	1	1	2	10	20	21
0.9	0	0.1	0.05	64.2	703	112271	21	5.15	2.2	1.12	8.01	1.05	7.04	0.8	0	2	10	20	21
0.8	0.2	0	0.06	65.9	640	79773	21	3.14	5.1	4.12	2.25	3.12	1.1	1	1	2	10	20	21
0.8	0.1	0.1	0.10	64.7	703	113534	21	7.03	7.15	1.12	8.01	2.15	7.04	0.8	0	2	10	20	21
0.8	0	0.2	0.09	64.7	703	113534	21	7.03	7.15	1.12	8.01	2.15	7.04	0.8	0	2	10	20	21
0.7	0.3	0	0.09	65.9	640	79773	21	3.14	5.1	4.12	2.25	3.12	1.1	1	1	2	10	20	21
0.7	0.2	0.1	0.14	66.5	646	97622	21	2.15	1.03	3.3	4.15	3.15	3.2	1	0	2	20	20	20
0.7	0.1	0.2	0.14	64.7	703	113534	21	7.03	7.15	1.12	8.01	2.15	7.04	0.8	0	2	10	20	21
0.7	0	0.3	0.14	64.7	703	113534	21	7.03	7.15	1.12	8.01	2.15	7.04	0.8	0	2	10	20	21
0.6	0.4	0	0.12	65.9	640	79773	21	3.14	5.1	4.12	2.25	3.12	1.1	1	1	2	10	20	21
0.6	0.3	0.1	0.17	66.5	646	97622	21	2.15	1.03	3.3	4.15	3.15	3.2	1	0	2	20	20	20
0.6	0.2	0.2	0.19	64.7	703	113534	21	7.03	7.15	1.12	8.01	2.15	7.04	0.8	0	2	10	20	21
0.6	0.1	0.3	0.19	64.7	703	113534	21	7.03	7.15	1.12	8.01	2.15	7.04	0.8	0	2	10	20	21
0.6	0	0.4	0.18	64.7	703	113534	21	7.03	7.15	1.12	8.01	2.15	7.04	0.8	0	2	10	20	21
0.5	0.5	0	0.15	65.9	640	79773	21	3.14	5.1	4.12	2.25	3.12	1.1	1	1	2	10	20	21
0.5	0.4	0.1	0.20	66.5	646	97622	21	2.15	1.03	3.3	4.15	3.15	3.2	1	0	2	20	20	20
0.5	0.3	0.2	0.23	66.5	646	97622	21	2.15	1.03	3.3	4.15	3.15	3.2	1	0	2	20	20	20
0.5	0.2	0.3	0.24	64.7	703	113534	21	7.03	7.15	1.12	8.01	2.15	7.04	0.8	0	2	10	20	21
0.5	0.1	0.4	0.23	64.7	703	113534	21	7.03	7.15	1.12	8.01	2.15	7.04	0.8	0	2	10	20	21
0.5	0	0.5	0.23	64.7	703	113534	21	7.03	7.15	1.12	8.01	2.15	7.04	0.8	0	2	10	20	21

Table H - 3 cont. Sample of 'optimal solutions' obtained from the energy/economic-based Pareto front using Compromise Programming

p_{eui}	p_{com}	p_{NPV}	[min] α_{cheb}	EUI (kWh/m^2-year)	*Dis-comfort* (hours)	NPV_{50y} (£)	X^{HVAC} (Type)	X^{wall} (m)	X^{roof} (m)	X^{ground} (m)	X^{wall_BS} (m)	X^{roof_Pi} (m)	X^{ground_BS} (m)	X^{seal} (ach)	X^{glaz} type	X^{light} Light techn	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)
0.4	0.6	0	0.18	65.9	640	79773	21	3.14	5.1	4.12	2.25	3.12	1.1	1	1	2	10	20	21
0.4	0.5	0.1	0.23	66.5	646	97622	21	2.15	1.03	3.3	4.15	3.15	3.2	1	0	2	20	20	20
0.4	0.4	0.2	0.26	66.5	646	97622	21	2.15	1.03	3.3	4.15	3.15	3.2	1	0	2	20	20	20
0.4	0.3	0.3	0.29	64.7	703	113534	21	7.03	7.15	1.12	8.01	2.15	7.04	0.8	0	2	10	20	21
0.4	0.2	0.4	0.28	64.7	703	113534	21	7.03	7.15	1.12	8.01	2.15	7.04	0.8	0	2	10	20	21
0.4	0.1	0.5	0.28	64.7	703	113534	21	7.03	7.15	1.12	8.01	2.15	7.04	0.8	0	2	10	20	21
0.4	0	0.6	0.27	64.7	703	113534	21	7.03	7.15	1.12	8.01	2.15	7.04	0.8	0	2	10	20	21
0.3	0.7	0	0.21	65.9	640	79773	21	3.14	5.1	4.12	2.25	3.12	1.1	1	1	2	10	20	21
0.3	0.6	0.1	0.26	66.5	646	97622	21	2.15	1.03	3.3	4.15	3.15	3.2	1	0	2	20	20	20
0.3	0.5	0.2	0.29	66.5	646	97622	21	2.15	1.03	3.3	4.15	3.15	3.2	1	0	2	20	20	20
0.3	0.4	0.3	0.33	66.5	646	97622	21	2.15	1.03	3.3	4.15	3.15	3.2	1	0	2	20	20	20
0.3	0.3	0.4	0.33	64.7	703	113534	21	7.03	7.15	1.12	8.01	2.15	7.04	0.8	0	2	10	20	21
0.3	0.2	0.5	0.33	64.7	703	113534	21	7.03	7.15	1.12	8.01	2.15	7.04	0.8	0	2	10	20	21
0.3	0.1	0.6	0.32	64.7	703	113534	21	7.03	7.15	1.12	8.01	2.15	7.04	0.8	0	2	10	20	21
0.3	0	0.7	0.23	272.4	853	148667	31	5.15	2.08	6.14	2.04	2.03	7.04	0.8	2	2	10	20	21
0.2	0.8	0	0.20	340.8	550	71297	28	2.01	2.13	4.04	9.01	8.04	6.02	1	5	1	10	20	18
0.2	0.7	0.1	0.29	66.5	646	97622	21	2.15	1.03	3.3	4.15	3.15	3.2	1	0	2	20	20	20
0.2	0.6	0.2	0.32	66.5	646	97622	21	2.15	1.03	3.3	4.15	3.15	3.2	1	0	2	20	20	20
0.2	0.5	0.3	0.36	66.5	646	97622	21	2.15	1.03	3.3	4.15	3.15	3.2	1	0	2	20	20	20
0.2	0.4	0.4	0.38	67.8	669	105952	21	6.06	3.05	3.08	6.16	2.11	6.05	0.9	0	2	10	20	18
0.2	0.3	0.5	0.38	64.7	703	113534	21	7.03	7.15	1.12	8.01	2.15	7.04	0.8	0	2	10	20	21
0.2	0.2	0.6	0.35	272.4	853	148667	31	5.15	2.08	6.14	2.04	2.03	7.04	0.8	2	2	10	20	21

Table H - 3 cont. Sample of 'optimal solutions' obtained from the energy/economic-based Pareto front using Compromise Programming

p_{eui}	p_{com}	p_{NPV}	[min] α_{cheb}	EUI (kWh/ m^2-year)	*Dis-comfort* (hours)	NPV_{50y} (£)	X^{HVAC} (Type)	X^{wall} (m)	X^{roof} (m)	X^{ground} (m)	X^{wall_BS} (m)	X^{roof_Pi} (m)	X^{ground_BS} (m)	X^{seal} (ach)	X^{glaz} type	X^{light} Light techn	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)
0.2	0.1	0.7	0.25	272.4	853	148667	31	5.15	2.08	6.14	2.04	2.03	7.04	0.8	2	2	10	20	21
0.2	0	0.8	0.15	272.4	853	148667	31	5.15	2.08	6.14	2.04	2.03	7.04	0.8	2	2	10	20	21
0.1	0.9	0	0.10	340.8	550	71297	28	2.01	2.13	4.04	9.01	8.04	6.02	1	5	1	10	20	18
0.1	0.8	0.1	0.20	340.8	550	71297	28	2.01	2.13	4.04	9.01	8.04	6.02	1	5	1	10	20	18
0.1	0.7	0.2	0.30	340.8	550	71297	28	2.01	2.13	4.04	9.01	8.04	6.02	1	5	1	10	20	18
0.1	0.6	0.3	0.39	66.5	646	97622	21	2.15	1.03	3.3	4.15	3.15	3.2	1	0	2	20	20	20
0.1	0.5	0.4	0.42	279.7	720	137624	31	6.03	4.13	3.14	4.06	4.06	5.085	0.7	3	1	10	20	22
0.1	0.4	0.5	0.37	279.7	720	137624	31	6.03	4.13	3.14	4.06	4.06	5.085	0.7	3	1	10	20	22
0.1	0.3	0.6	0.33	279.7	720	137624	31	6.03	4.13	3.14	4.06	4.06	5.085	0.7	3	1	10	20	22
0.1	0.2	0.7	0.28	272.4	853	148667	31	5.15	2.08	6.14	2.04	2.03	7.04	0.8	2	2	10	20	21
0.1	0.1	0.8	0.18	272.4	853	148667	31	5.15	2.08	6.14	2.04	2.03	7.04	0.8	2	2	10	20	21
0.1	0	0.9	0.08	272.4	853	148667	31	5.15	2.08	6.14	2.04	2.03	7.04	0.8	2	2	10	20	21
0	1	0	0.00	340.8	550	71297	28	2.01	2.13	4.04	9.01	8.04	6.02	1	5	1	10	20	18
0	0.9	0.1	0.10	340.8	550	71297	28	2.01	2.13	4.04	9.01	8.04	6.02	1	5	1	10	20	18
0	0.8	0.2	0.20	340.8	550	71297	28	2.01	2.13	4.04	9.01	8.04	6.02	1	5	1	10	20	18
0	0.7	0.3	0.30	340.8	550	71297	28	2.01	2.13	4.04	9.01	8.04	6.02	1	5	1	10	20	18
0	0.6	0.4	0.39	279.7	720	137624	31	6.03	4.13	3.14	4.06	4.06	5.085	0.7	3	1	10	20	22
0	0.5	0.5	0.35	279.7	720	137624	31	6.03	4.13	3.14	4.06	4.06	5.085	0.7	3	1	10	20	22
0	0.4	0.6	0.31	279.7	720	137624	31	6.03	4.13	3.14	4.06	4.06	5.085	0.7	3	1	10	20	22
0	0.3	0.7	0.27	279.7	720	137624	31	6.03	4.13	3.14	4.06	4.06	5.085	0.7	3	1	10	20	22
0	0.2	0.8	0.20	272.4	853	148667	31	5.15	2.08	6.14	2.04	2.03	7.04	0.8	2	2	10	20	21
0	0.1	0.9	0.10	272.4	853	148667	31	5.15	2.08	6.14	2.04	2.03	7.04	0.8	2	2	10	20	21
0	0	1	0.00	272.4	853	148667	31	5.15	2.08	6.14	2.04	2.03	7.04	0.8	2	2	10	20	21

H.4 MCDM – Compromise programming outputs for the exergy/exergoeconomic-based approach

Table H - 4 Sample of 'optimal solutions' obtained from the exergy/exergoeconomic-based Pareto front using Compromise Programming

p_{eui}	p_{com}	p_{NPV}	[min] α_{cheb}	Ex_{destbu} (kWh/m[2]-year)	*Dis-comfort* (hours)	$Exec_{CB}$ (£/h)	X^{HVAC} (Type)	X^{wall} (m)	X^{roof} (m)	X^{ground} (m)	$X^{\text{wall\_BS}}$ (m)	$X^{\text{roof\_Pi}}$ (m)	$X^{\text{ground\_BS}}$ (m)	X^{seal} (ach)	X^{glaz} type	X^{light} Light techn	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)
1	0	0	0.00	102.9	791	0.23	15	1.03	3.09	1.06	5.2	7.05	8.025	0.8	0	3	0	20	20
0.9	0.1	0	0.07	108.8	657	0.23	26	3.13	6.02	0	5.2	1.25	7.05	0.9	2	1	30	20	21
0.9	0	0.1	0.03	102.9	791	0.23	15	1.03	3.09	1.06	5.2	7.05	8.025	0.8	0	3	0	20	20
0.8	0.2	0	0.10	108.8	657	0.23	26	3.13	6.02	0	5.2	1.25	7.05	0.9	2	1	30	20	21
0.8	0.1	0.1	0.08	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0.8	0	0.2	0.04	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0.7	0.3	0	0.14	108.8	657	0.23	26	3.13	6.02	0	5.2	1.25	7.05	0.9	2	1	30	20	21
0.7	0.2	0.1	0.11	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0.7	0.1	0.2	0.07	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0.7	0	0.3	0.03	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0.6	0.4	0	0.14	117.8	625	0.28	29	3.25	3.04	6.14	3.07	2.06	4.13	1	3	2	30	0	20
0.6	0.3	0.1	0.15	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0.6	0.2	0.2	0.11	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0.6	0.1	0.3	0.07	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0.6	0	0.4	0.03	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0.5	0.5	0	0.15	117.8	625	0.28	29	3.25	3.04	6.14	3.07	2.06	4.13	1	3	2	30	0	20
0.5	0.4	0.1	0.17	117.8	625	0.28	29	3.25	3.04	6.14	3.07	2.06	4.13	1	3	2	30	0	20
0.5	0.3	0.2	0.14	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0.5	0.2	0.3	0.10	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0.5	0.1	0.4	0.06	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0.5	0	0.5	0.02	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0.4	0.6	0	0.16	117.8	625	0.28	29	3.25	3.04	6.14	3.07	2.06	4.13	1	3	2	30	0	20

Table H - 4 cont. Sample of 'optimal solutions' obtained from the exergy/exergoeconomic-based Pareto front using Compromise Programming

p_{eui}	p_{com}	p_{NPV}	[min] α_{cheb}	Ex_{destbu} (kWh/m^2-year)	Dis-comfort (hours)	$Exec_{CB}$ (£/h)	X^{HVAC} (Type)	X^{wall} (m)	X^{roof} (m)	X^{ground} (m)	X^{wall_BS} (m)	X^{roof_Pi} (m)	X^{ground_BS} (m)	X^{seal} (ach)	X^{glaz} type	X^{light} Light techn	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)
0.4	0.5	0.1	0.18	117.8	625	0.28	29	3.25	3.04	6.14	3.07	2.06	4.13	1	3	2	30	0	20
0.4	0.4	0.2	0.18	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0.4	0.3	0.3	0.14	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0.4	0.2	0.4	0.10	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0.4	0.1	0.5	0.06	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0.4	0	0.6	0.02	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0.3	0.7	0	0.17	117.8	625	0.28	29	3.25	3.04	6.14	3.07	2.06	4.13	1	3	2	30	0	20
0.3	0.6	0.1	0.19	117.8	625	0.28	29	3.25	3.04	6.14	3.07	2.06	4.13	1	3	2	30	0	20
0.3	0.5	0.2	0.21	117.8	625	0.28	29	3.25	3.04	6.14	3.07	2.06	4.13	1	3	2	30	0	20
0.3	0.4	0.3	0.17	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0.3	0.3	0.4	0.13	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0.3	0.2	0.5	0.09	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0.3	0.1	0.6	0.05	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0.3	0	0.7	0.01	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0.2	0.8	0	0.18	117.8	625	0.28	29	3.25	3.04	6.14	3.07	2.06	4.13	1	3	2	30	0	20
0.2	0.7	0.1	0.20	117.8	625	0.28	29	3.25	3.04	6.14	3.07	2.06	4.13	1	3	2	30	0	20
0.2	0.6	0.2	0.22	117.8	625	0.28	29	3.25	3.04	6.14	3.07	2.06	4.13	1	3	2	30	0	20
0.2	0.5	0.3	0.21	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0.2	0.4	0.4	0.17	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0.2	0.3	0.5	0.13	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0.2	0.2	0.6	0.09	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0.2	0.1	0.7	0.05	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0.2	0	0.8	0.01	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19

Table H - 4 cont. Sample of 'optimal solutions' obtained from the exergy/exergoeconomic-based Pareto front using Compromise Programming

p_{eui}	p_{com}	p_{NPV}	[min] α_{cheb}	Ex_{destbu} (kWh/ m^2-year)	*Dis-comfort* (hours)	$Exec_{CB}$ (£/h)	X^{HVAC} (Type)	X^{wall} (m)	X^{roof} (m)	X^{ground} (m)	$X^{\text{wall\_BS}}$ (m)	$X^{\text{roof\_Pi}}$ (m)	$X^{\text{ground\_BS}}$ (m)	X^{seal} (ach)	X^{glaz} type	X^{light} Light techn	X^{PV} % roof panels	X^{wind} (kW)	X^{heat} (°C)
0.1	0.9	0	0.10	238.8	584	0.90	28	6.2	6.12	2.14	9.01	6.06	1.12	0.9	2	2	20	0	19
0.1	0.8	0.1	0.20	238.8	584	0.90	28	6.2	6.12	2.14	9.01	6.06	1.12	0.9	2	2	20	0	19
0.1	0.7	0.2	0.23	117.8	625	0.28	29	3.25	3.04	6.14	3.07	2.06	4.13	1	3	2	30	0	20
0.1	0.6	0.3	0.24	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0.1	0.5	0.4	0.20	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0.1	0.4	0.5	0.16	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0.1	0.3	0.6	0.12	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0.1	0.2	0.7	0.08	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0.1	0.1	0.8	0.04	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0.1	0	0.9	0.00	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0	1	0	0.00	238.8	584	0.90	28	6.2	6.12	2.14	9.01	6.06	1.12	0.9	2	2	20	0	19
0	0.9	0.1	0.10	238.8	584	0.90	28	6.2	6.12	2.14	9.01	6.06	1.12	0.9	2	2	20	0	19
0	0.8	0.2	0.20	238.8	584	0.90	28	6.2	6.12	2.14	9.01	6.06	1.12	0.9	2	2	20	0	19
0	0.7	0.3	0.25	117.8	625	0.28	29	3.25	3.04	6.14	3.07	2.06	4.13	1	3	2	30	0	20
0	0.6	0.4	0.24	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0	0.5	0.5	0.20	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0	0.4	0.6	0.16	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0	0.3	0.7	0.12	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0	0.2	0.8	0.08	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0	0.1	0.9	0.04	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19
0	0	1	0.00	109.3	666	-0.11	29	5.065	1.04	7.03	2.03	1.12	1.07	0.9	0	2	20	0	19

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36	figure	Figure 2-4 Types of existing retrofit tool kits separated by simulation engine. Source: Lee et al. (2015)	Lee S. H. Hong T. Piette M. A. & Taylor-Lange S. C. 2015. Energy retrofit analysis toolkits for commercial buildings: A review. Energy 89 1087-1100.	© 2015 Elsevier https://s100.copyright.com/AppDispatchServlet	23.03.17	yes	4074920362874
41	figure	Figure 2-7 Typical objective in building optimisation research. Source: Evins, 2013.	Evins R. 2013. A review of computational optimisation methods applied to sustainable building design. Renewable and Sustainable Energy Reviews 22 230-245.	© 2013 Elsevier https://s100.copyright.com/AppDispatchServlet	23.03.17	yes	4074910659932
43	figure	Figure 2-8 Graphical representation of a Pareto front. Source: Nguyen et al., 2014.	Nguyen A.-T. Reiter S. & Rigo P. 2014. A review on simulation-based optimization methods applied to building performance analysis. Applied Energy 113 1043-1058.	© 2014 Elsevier https://s100.copyright.com/AppDispatchServlet	23.03.17	yes	4074910842261
45	figure	Figure 2-10 Studies frequency of combination between building energy simulation tools and optimisation tools. Source: Attia et al. (2013).	Attia S. Hamdy M. O'Brien W. & Carlucci S. 2013. Assessing gaps and needs for integrating building performance optimization tools in net zero energy buildings design. Energy and Buildings 60 110-124.	© 2013 Elsevier https://s100.copyright.com/AppDispatchServlet	23.03.17	yes	4074910980268
56	figure	Figure 3-3 Interdisciplinary triangle covered by the field of exergy analysis. Taken from Rosen and Dincer (2001).	Rosen M. A. & Dincer I. 2001. Exergy as the confluence of energy environment and sustainable development. Exergy An International Journal 1 3-13.	© 2001 Elsevier https://s100.copyright.com/AppDispatchServlet	23.03.17	yes	4074911134258
57	figure	Figure 3-4 Relation between exergy efficiency, environmental impact and exergy-based sustainability. Source: Rosen et.al (2008).	Rosen M. A. Dincer I. & Kanoglu M. 2008. Role of exergy in increasing efficiency and sustainability and reducing environmental impact. Energy Policy 36 128-137.	© 2008 Elsevier https://s100.copyright.com/AppDispatchServlet	23.03.17	yes	4074911279187

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63	figure	Figure 3-7 General scheme of a typical energy supply chain. Source: Nieuwlaar and Dijk, 1993	Nieuwlaar E. & Dijk D. 1993. Exergy evaluation of space-heating options. Energy 18 779-790.	© 1993 Elsevier https://s100.copyright.com/AppDispatchServlet	23.03.17	yes	4074911409097
65	figure	Figure 3-8 Heating chain and subsystems for exergy calculations. Source: Schlueter and Thesseling (2009) via Schmidt, 2004	Schlueter A. & Thesseling F. 2009. Building information model based energy/exergy performance assessment in early design stages. Automation in Construction 18 153-163.	© 2009 Elsevier https://s100.copyright.com/AppDispatchServlet	23.03.17	yes	4074920362874
65	figure	Figure 3-9 Building energy system decomposition by Favrat et.al. 2008.	Favrat D. Marechal F. & Epelly O. 2008. The challenge of introducing an exergy indicator in a local law on energy. Energy 33 130-136.	© 2008 Elsevier https://s100.copyright.com/AppDispatchServlet	23.03.17	yes	4074920156724
78	figure	Figure 3-13 Exergy-based tool: Design Performance Viewer implementation framework. Source: Schlueter and Thesseling 2009.	Schlueter A. & Thesseling F. 2009. Building information model based energy/exergy performance assessment in early design stages. Automation in Construction 18 153-163.	© 2009 Elsevier https://s100.copyright.com/AppDispatchServlet	23.03.17	yes	4074920362874
84	figure	Figure 3-16 SPECO framework. Source: Lazzaretto and Tsatsaronis, 2006.	Lazzaretto A. & Tsatsaronis G. 2006. SPECO: A systematic and general methodology for calculating efficiencies and costs in thermal systems. Energy 31 1257-1289.	© 2006 Elsevier	23.03.17	yes	4074920914644
84	figure	Figure 3-17 Optimisation of product cost as a function of exergy efficiency. Source: Tsatsaronis, 1993	Tsatsaronis G. 1993. Thermoeconomic analysis and optimization of energy systems. Progress in Energy and Combustion Science 19 227-257.	© 1993 Elsevier https://s100.copyright.com/AppDispatchServlet	23.03.17	yes	4074920988224
n/a	Published own work	Modelling the energy and exergy utilisation of the Mexican non-domestic sector: A study by climatic regions	Garcia Kerdan, I., Morillón Gálvez, D., Raslan, R., Ruyssevelt, P. 2015. Modelling the energy and exergy utilisation of the Mexican non-domestic sector: A study by climatic regions, Energy Policy, 77, 191-206.	© 2015 Elsevier https://s100.copyright.com/AppDispatchServlet	23.03.17	yes	4074930060644

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n/a	Published own work	An exergy-based multi-objective optimisation model for energy retrofit strategies in non-domestic buildings	Garcia Kerdan, I., Raslan, R., Ruyssevelt, P. 2016. An exergy-based multi-objective optimisation model for energy retrofit strategies in non-domestic buildings, Energy. 117(2):506–522.	© 2016 Elsevier https://s100.copyright.com/AppDispatchServlet	23.03.17	yes	4074921421816
n/a	Published own work	An exergoeconomic-based parametric study to examine the effects of active and passive energy retrofit strategies for buildings	Garcia Kerdan, I., Raslan, R., Ruyssevelt, P., Morillón Gálvez, D. 2016. An exergoeconomic-based parametric study to examine the effects of active and passive energy retrofit strategies for buildings, Energy and Buildings, 133, 155-171	© 2016 Elsevier https://s100.copyright.com/AppDispatchServlet	23.03.17	yes	4074921497086
n/a	Published own work	ExRET-Opt: An automated exergy/exergoeconomic simulation framework for building energy retrofit analysis and design optimisation	Garcia Kerdan, I., Raslan, R., Ruyssevelt, P., Morillón Gálvez, D. 2017. ExRET-Opt: An automated exergy/exergoeconomic simulation framework for building energy retrofit analysis and design optimisation, Applied Energy, 192, 33-58	© 2017 Elsevier https://s100.copyright.com/AppDispatchServlet	23.03.17	yes	501250440
n/a	Published own work	The role of an exergy-based building stock model for exploration of future decarbonisation scenarios and policy making	Garcia Kerdan, I., Raslan, R., Ruyssevelt, P., Morillón Gálvez, D. 2017. The role of an exergy-based building stock model for exploration of future decarbonisation scenarios and policy making, Energy Policy, 105, 467-483.	© 2017 Elsevier https://s100.copyright.com/AppDispatchServlet	24.03.17	yes	4075430186711
n/a	Published own work	Thermodynamic and exergoeconomic analysis of a non-domestic Passivhaus retrofit	Garcia Kerdan, I., Raslan, R., Ruyssevelt, P., Vaiciulyte, S., Morillón Gálvez, D. 2017. Thermodynamic and exergoeconomic analysis of a non-domestic Passivhaus retrofit, Building and Environment, 117, 100-117.	© 2017 Elsevier https://s100.copyright.com/AppDispatchServlet	23.03.17	yes	4074921122082