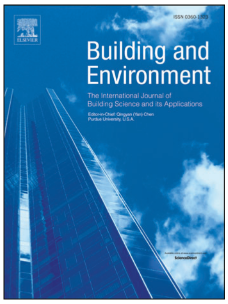

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Thermodynamic and exergoeconomic analysis of a non-domestic Passivhaus retrofit

Iván García Kerdan[a,d*], Rokia Raslan[b], Paul Ruyssevelt[a], Sandra Vaiciulyte[c], David Morillón Gálvez[d]

[a] Energy Institute, University College London, 14 Upper Woburn Pl, London, WC1H 0NN, U.K.
[b] Environmental Design and Engineering, University College London, 14 Upper Woburn Pl, London, WC1H 0NN, U.K.
[c] Faculty of Architecture, Computing and Humanities, Department of Mathematical Sciences, University of Greenwich, Old Royal Naval College, 30 Park Row, London SE10 9LS, U.K.
[d] Departamento de Mecánica y Energía, Instituto de Ingeniería, Universidad Nacional Autónoma de México, México, México

Abstract

This paper presents a thermodynamic and exergoeconomic analysis of a recently-retrofitted Passivhaus non-domestic building. The selected case study, a Community Centre located in London, underwent a deep-energy retrofit in 2011, becoming the first 'non-domestic Passivhaus' retrofit in the country. As the building was retrofitted per Passivhaus standards, which is based solely on First Law analysis, a thermodynamic investigation can provide a novel means by which to assess its exergy efficiency and cost-effectiveness. As such, the aim of this paper is to conduct a comprehensive exergy and exergoeconomic analysis, presenting novel performance indicators for the pre-retrofit and post-retrofit Passivhaus building. First law outputs show that the improvement presents high levels of energy savings (75.6%), reductions in carbon emissions (64.5%), and occupant thermal comfort improvement (28.8%). Second law outputs present a reduction in primary exergy input reduction of 56.4% and exergy destructions of 60.4%, leading to improve building exergy efficiency from 9.8% to 18.0%. Nevertheless, exergoeconomically the building did not perform as expected due to high capital cost and exergy destructions cost rates. These results give an insight into the thermodynamic impact of the Passivhaus approach, providing a critical assessment of the strengths and limitations of the standard under both thermodynamic laws.

Keywords:
energy; exergy; exergoeconomics; retrofits; building simulation; Passivhaus.

*Corresponding author at: Energy Institute, University College London, United Kingdom. Tel: +44 (0) 7867798730
E-mail address: i.kerdan.12@ucl.ac.uk (I. Garcia Kerdan)

1. Introduction

Exergy can be useful in explaining sustainability of different energy sources and technologies. Rosen and Dincer [1] considered exergy as the confluence of energy, environment and sustainable development, suggesting that exergy analysis provides an effective measurement for reducing environmental problems and achieving sustainable development. In sectors, such as the power generation or industrial processes, exergy methods have a certain degree of maturity that makes the analysis robust [2-9]; while in others such as the building sector, exergy analysis is still in its initial application stages and therefore more investigation is required. 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 quality demand of the building. Energy demand for heating, cooling, and DHW are low quality demands that are commonly satisfied by high quality sources. Gasparatos et al. [10] showed that the overall building sector exergy efficiency stands at roughly 12%, thus being the most thermodynamically inefficient economic sector in the UK. Unlike energy, exergy is not subject to a conservation law [11]. Exergy loss in a system/component can be associated with the transfer of thermal exergy from the system to the environment [12]. From a system consisting of *n* subcomponents, the total exergy destructions are equal to the sum of exergy destructions in all subcomponents [13].

The extent of research and application of exergy analysis in buildings has significantly increased in the last years, mainly supported by the creation of two IEA EBC Annexes [14, 15] and the 'LowEx - COSTeXergy' research group [16]. In 2012, Hepbasli [17] provided a comprehensive review of building exergy studies between 1994 and 2011. Table 1 shows an up to date list of the most important studies over the past four years (2012-2016).

Table 1 Exergy-based research applied to buildings and building systems (2012-2016)

Ref.	Author	Building/system type	Calculation and analysed end -uses	Location	Observations and main results
[18]	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 49% and exergy efficiency at 17%.
[19]	Caliskan et al. (2012)	Dwelling/Thermo-chemical and sensible energy thermal storage	Steady-state exergy analysis (heating)	Izmir, Turkey	Energy and exergy analyses of thermochemical TES systems at various reference temperatures (8°C, 9°C and 10°C) were performed. The exergy efficiencies of the charging and discharging process of thermochemical TES were found at 21.69% and 32.43, respectively. Maximum efficiencies were found at a reference temperature of 8 ºC.
[20]	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 10% and 16%, respectively. New configurations based on exergy theory reduced significantly primary energy input, lowering by almost 80%.
[21]	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.
[22]	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 19.35%, 37% and 31%, respectively, providing an overall system efficiency of 3.18%.
[23]	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, CO2 emissions, operation costs, and the nominal boiler power. Wall heating system also presented good results. The classical ceiling heating has the worst performance.
[24]	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.

[25]	Zhou and Gong (2013)	Residential building/Air Source heat pump	Dynamic exergy analysis (heating and cooling)	Ningbo, China	Dynamic exergy analysis of the whole building energy supply chain is analysed. 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 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 standard case was 5.12% and improved up to 7.93%
[26]	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 case, distribution systems have the biggest improvement potential, a subsystem often neglected in the analyses.
[27]	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
[28]	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 3.9%. The poorest performance was for the PV and solar thermal operated system with heat pump with an efficiency at 1.2%.
[29]	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 0.55%, and the useful exergetic efficiency is 0.0006%. This low value is due to the small increase in temperature with respect to the reference or dead state values.
[30]	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 2%, with a potential to be around 10-11%. Thermodynamic performance at a city level can improve when energy efficient design parameters are considered during planning and design steps in an urban area

Exergoeconomics considers not only the thermodynamic inefficiencies but also the costs associated with these inefficiencies, and the investment expenditure required to reduce them. Despite the amount of exergy research developed recently, the application of exergoeconomics in building energy design is scarce. Tozer and James [31], showed its practical application by comparing different absorption chillers, locating the best chiller for specific operating conditions. Ucar [32] applied exergoeconomics to determine optimal insulation thickness under different climatic conditions in Turkey. Campos-Celador et al. [33] evaluated the performance of a residential 5.5 kW micro-CHP obtaining exergetic costs of both mCHP products (heat and electricity). If considered together, CHP prices per kWh are much lower than traditional supply by 23.7 %. Baldvinsson and Nakata [34] applied exergoeconomics to compare a traditional boiler system to a DH network. The later, due to highest exergetic efficiency and lower exergy destructions, provided with a lower final fuel product price for both heating and DHW.

1.1 LowEx and Passivhaus buildings

Since the 'LowEx' approach, which aims to reduce the exergy destructions along building energy systems, was developed [14], researchers have been discussing its similarities and differences with the Passivhaus approach [17, 21]. 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 [35] 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 requirements in a cost-effective way. To achieve a Passivhaus/EnerPHit certification, the criteria indicated in Table must be met. As seen, the requirements for the EnerPHit standard are less strict than those for the new buildings.

Table 2 Passivhaus Standard/EnerPHit Standard Requirements [35].

	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] x 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 envelope insulation (U_{values} < 0.15 W/m²K), high performance glazing systems (U_{values} < 0.80 W/m²K), an airtight building fabric (<0.6 ach or <1.0 ach for retrofits), mechanical ventilation and heat recovery systems (η =75% or greater), and absence of thermal bridging.

Shukuya and Hammache [36] 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. [21] 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.

As demonstrated by the previous studies, 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. Hepbasli [17] emphasized that either 'LowEx' or 'Passivhaus' are not individual techniques but rather a group of technical methods. Table 3 shows an extensive but not exhaustive list of characteristics for each method, where similar techniques can be found in either approach.

Table 3 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
Energy quality match		x
Energy systems oriented		x
Envelope's thermal performance	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	x
Design adaptation to different climates		x
Performance gap reduction	x	
Esthetical	x	
Design flexibility		x
Heritage conservation		x
Use of renewable energy	x	x

In considering the importance and popularity of the Passivhaus approach among building practitioners, to the best of the authors' knowledge, no systematic exergy and exergoeconomic analysis has of yet been applied to a Passivhaus retrofitted building. Therefore, the actual thermodynamic performance of a building designed under Passivhaus standards remains unknown. The aim of this paper is therefore to investigate the thermodynamic and thermoeconomic performance of a recently-retrofitted Community Centre located in London, UK through the use of a novel exergoeconomic-based building simulation tool. The outputs from the exergy/exergoeconomics analysis will help provide crucial insights into the strengths and limitations of the Passivhaus standard.

2. Methods and materials

ExRET-Opt [37], a retrofit-oriented building simulation tool based on EnergyPlus capable of performing exergy and exergoeconomic balances has been used for the analysis. The modelling tool has embedded a comprehensive techno-economic retrofit database, which will be used to assess the economic characteristics of the Passivhaus design. Equations for dynamic exergy analysis and exergoeconomic analysis method have been outlined previously [38, 39]. Main equations used in this study can be found in Appendix A.

2.1 Exergy analysis

The exergy analysis framework within ExRET-Opt is implemented through a combination of different dynamic methods oriented to cover different energy streams (thermal end-use [15], electricity [40], renewables [41]). Thermodynamic assessments typically require an input-output abstraction of all the subsystems interacting in an energy system. To appropriately define exergy streams of buildings and their energy systems, a thermodynamic abstraction of the whole building system should be made [38]. Fig. 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 adapt the approach to any building.

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 (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 system level gives the advantage of providing individual component analysis capable of locating and improving single components.

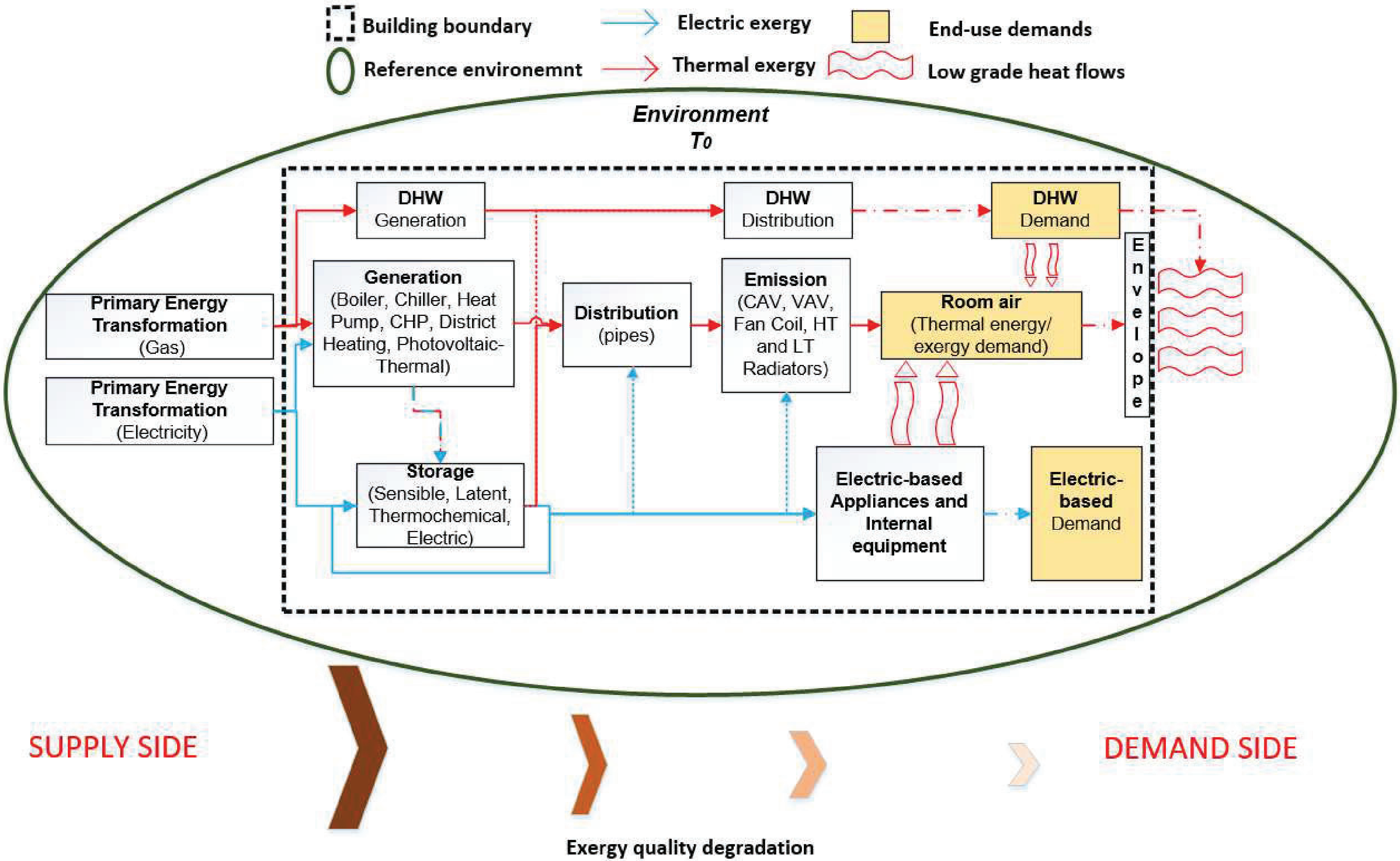


Fig. 1 Energy supply chain and subsystems for exergy calculations [38]

2.2 Thermoeconomics: SPECO and the exergoeconomic cost-benefit index

Economics are important in evaluating and comparing designs, and become essential in the assessment of retrofit projects. The selection of retrofit measures is a trade-off between the total capital investment and revenue due to energy savings. In retrofit 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. Additionally, to reduce uncertainties in the results, grant schemes, incentive programs, and subsidies should 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.

Contrary to exergy analysis integration in energy studies, the addition of exergoeconomics into a broader economic analysis applied to buildings is not as simple. Exergoeconomic methods consider cumulative exergy cost destruction through the energy supply chain; therefore, cost always increases in any real thermodynamic process. In ExRET-Opt, 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 with the SPECO method [42], delivering a novel return of investment indicator based on exergy, the *exergoeconomic cost-benefit index* ($Exec_{CB}$) [39]. This index is calculated as follows:

$$Exec_{CB} = \dot{C}_{D,sys} + \dot{Z}_{sys} - \dot{R} \quad (1)$$

where $\dot{C}_{D,sys}$ is the building's total exergy destruction cost, $\dot{Z}_{sys}$ is the levelised annual capital cost rate for the retrofit measure, and $\dot{R}$ is the levelised annual revenue rate generated by the retrofit project after implementation. For retrofit analysis, first, a benchmark value has to be calculated for the baseline building only composed by exergy destruction costs $\dot{C}_{D,sys,baseline}$. If the retrofitted building presents a $Exec_{CB,retrofit}$ significantly 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 → $Exec_{CB} > \dot{C}_{D,sys,baseline}$

ExRET-Opt, in addition to providing the user with exergy and exergoeconomic 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. This study focuses on analysing the pre-retrofit building as well as the post-retrofit building, aligned with Passivhaus requirements; thus, energy models with its techno-economic parameters have been developed for both cases.

3. Case Study

The case study building is located in Islington, London (UK). Built in 1890s, it was used as an electric generation power station for London's tram network. In 1973, the building was rescued from dereliction and turned into a community centre. Actual data for the pre-retrofit and post-retrofit building illustrated in the next sections was provided by the architecture firm through the 'Building Performance Evaluation' report [43].

3.1 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. Thus, 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 (Fig.) was created according to the technical drawings.

Fig. 2 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)

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 ventilated naturally during summer months. A schematic layout of the building system and subsystems is illustrated in Fig. 3.

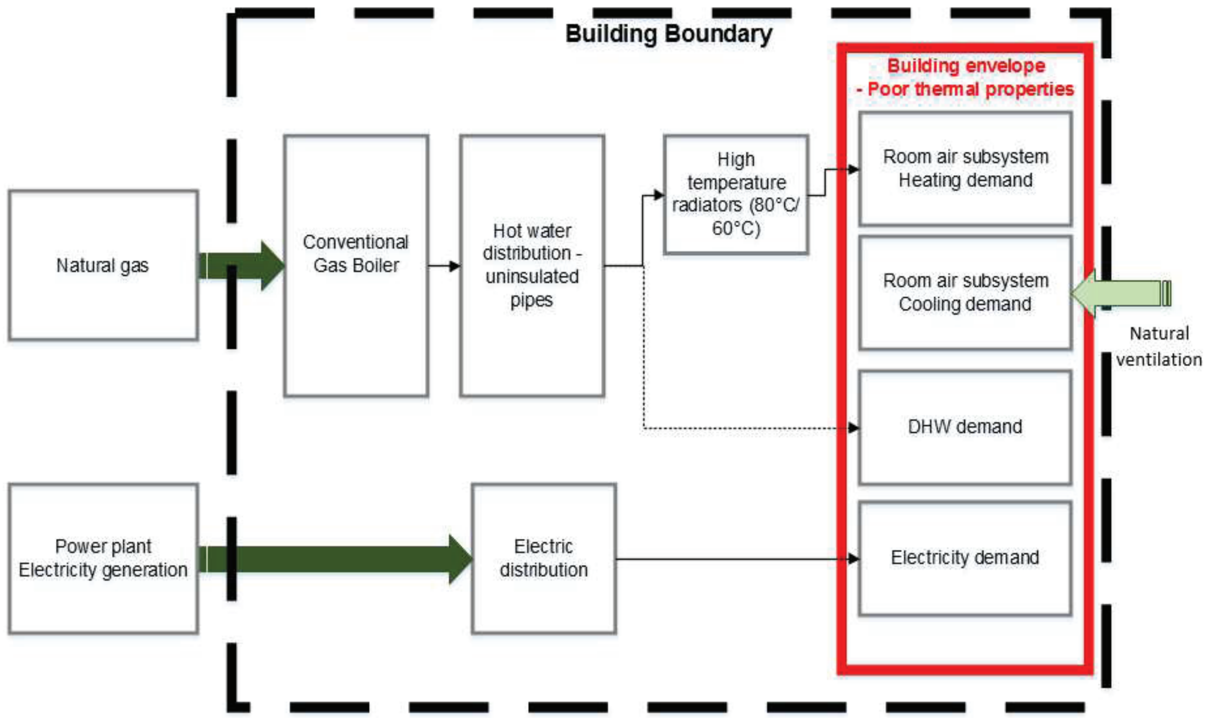


Fig. 3 Schematic layout of the energy system for the pre-retrofit Mayville Community Centre

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.

3.2 Post-retrofit building model description

In 2006, the architectural firm committed to retrofitting and extending 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 retrofit design resulted in the installation of high levels of insulation. The basement ground floor was insulated with 0.20m of XPS (U_{value} : 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}: 0.09 W/m^2-K), while the rest of the roof with 0.30m of glass fibre (U_{value}: 0.13 W/m^2-K).

With respect to the glazing system, triple-glazed air filled windows with wooden frames were installed. The carried-out airtightness test presented a value of 0.42 ach. Furthermore, an extra 35% of usable area was created (665 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 was also created according to the technical drawings and is illustrated in Fig. 4.

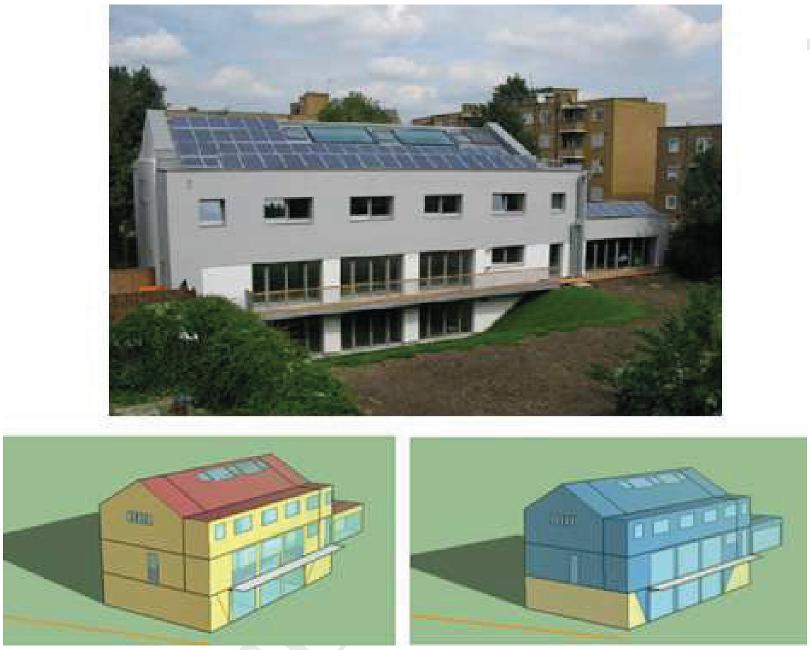


Fig. 4 Post-retrofit building model. Top: real building after retrofit, bottom left: south-west view, bottom right: south-west view (blue areas = above ground level, yellow areas = ground contact)

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 has been installed. The heat pump has been connected to medium temperature radiators with the capacity of using 45-50 °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) has been 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. 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 has been implemented along the building. To cover the demand of DHW, a 3 kW solar thermal system connected to a 300 litres water storage tank has been installed. The design also considered the installation of 116 m^2 of grid connected PV panels (18 kWp) to supply/export renewable electricity. Actual 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 Fig. 5.

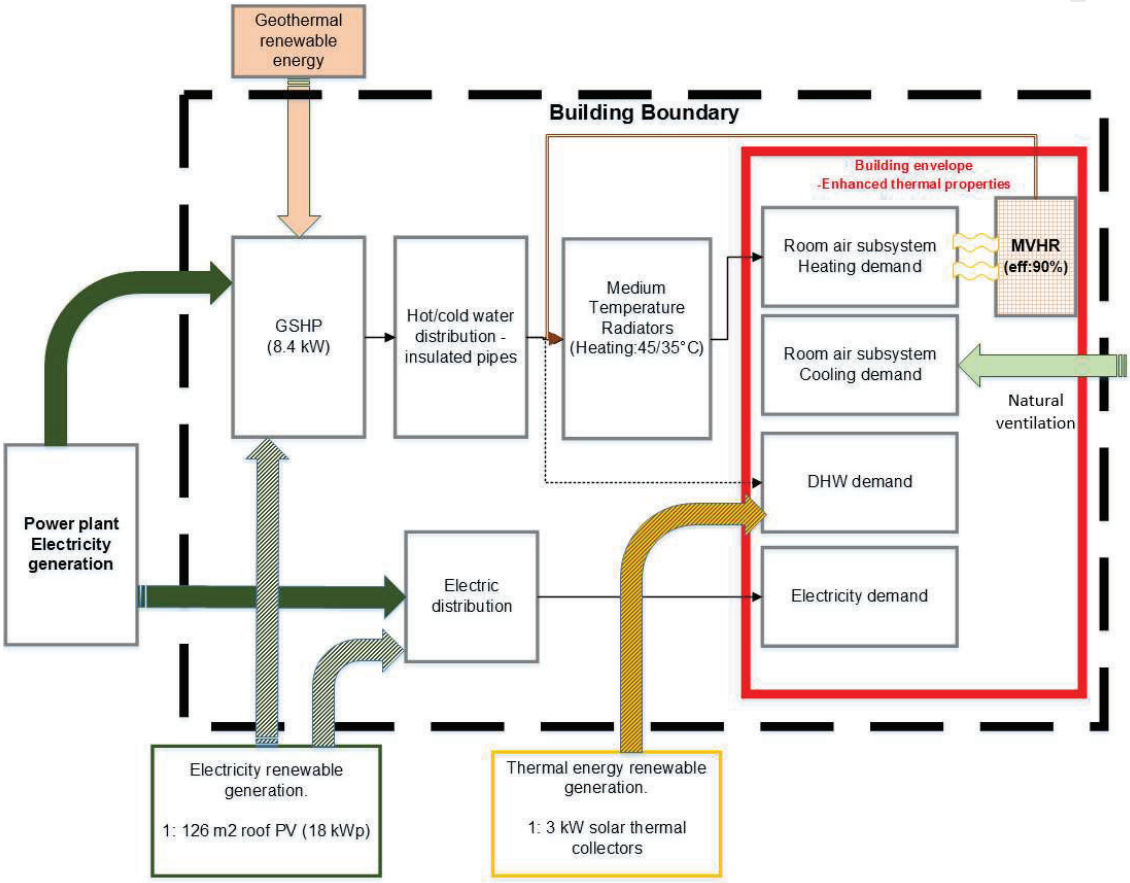


Fig. 5 Schematic layout of the energy system for the post-retrofit Community Centre

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 for the first year of operation, representing a net reduction of 54.3%.

3.3 Energy models calibration

With the support of ExRET-Opt [37], the application of the calibration module to minimise the performance gap between the measured and modelled data is required. The calibration modelling process consists of four main steps: 1. input probability distribution, 2. sample generation using Latin Hypercube Sampling (LHS) [44], 3. simulation runs and model output evaluation, and 4. model selection. LHS was selected to maintain simulations at an acceptable level (300 simulations). The tool, which has embedded SimLab, creates a spreadsheet with a predefined number of samples that is passed onto EnergyPlus for parametric simulation. As monthly data exist for the pre-retrofit and post-retrofit building, the model is 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) are used. The final model should have an MBE≤5% and a CV (RMSE)≤15% relative to monthly calibration data.

3.3.1 Pre-retrofit building calibration

The calibration analysis for the pre-retrofit building is focused on the total annual gas and electricity use. The predicted energy use is then compared to the actual monthly energy consumption data for 2010. Using ExRET-Opt calibration module the following coefficients for the selected model are obtained (Table 4):

Table 4 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%

3.3.2 Post-retrofit building calibration

As the post-retrofit building is fully electrically operated, the calibration analysis is based on the building's annual electricity use (49,120 kWh/year). However, for the post-retrofit building a more comprehensive calibration is performed, as sub-metered data by end-use was available. Fig. 6 gives a cumulative frequency distribution for all the simulated sample as well as the selected model.

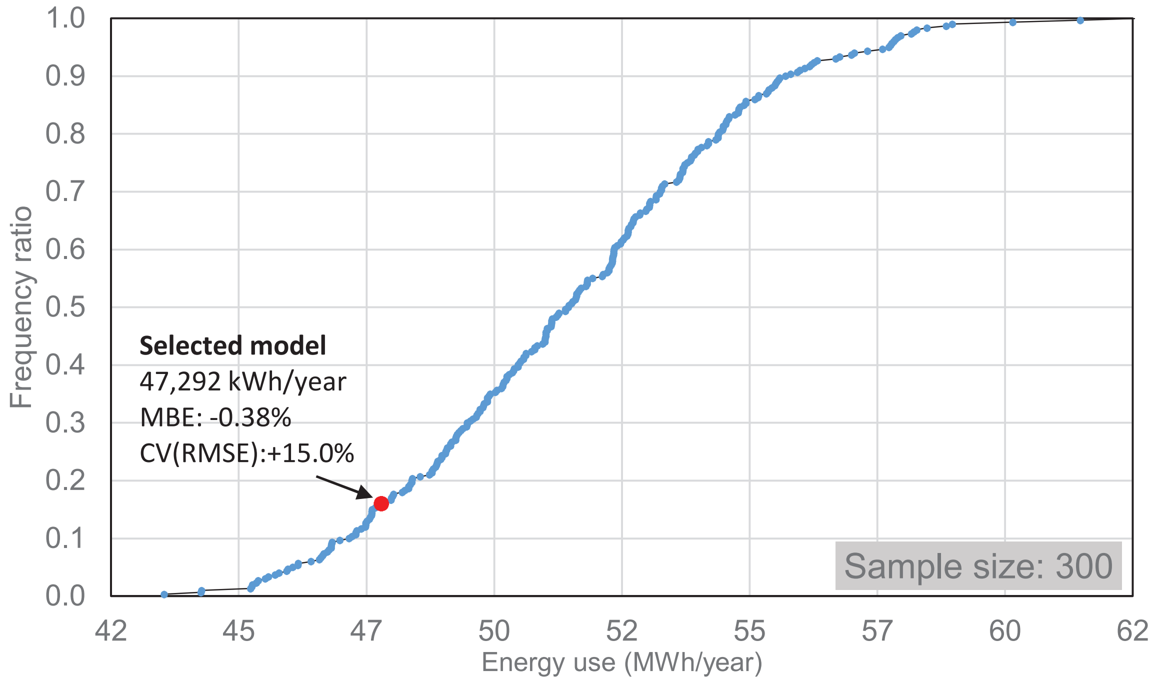


Fig. 6 Cumulative frequency distribution of the electrical end use for the simulated model using LHS

The red point, which represents the final model, presents the lowest MBE and CV(RMSE) between the actual and the simulated post retrofitted building (Table 5).

Table 5 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	--	--	--	--

As illustrated in Fig. 7, the total monthly electricity use between the real and modelled data are very similar; however, compared to the real data, the model presents the biggest differences 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.) and the difficulties to accurately model this behaviour.

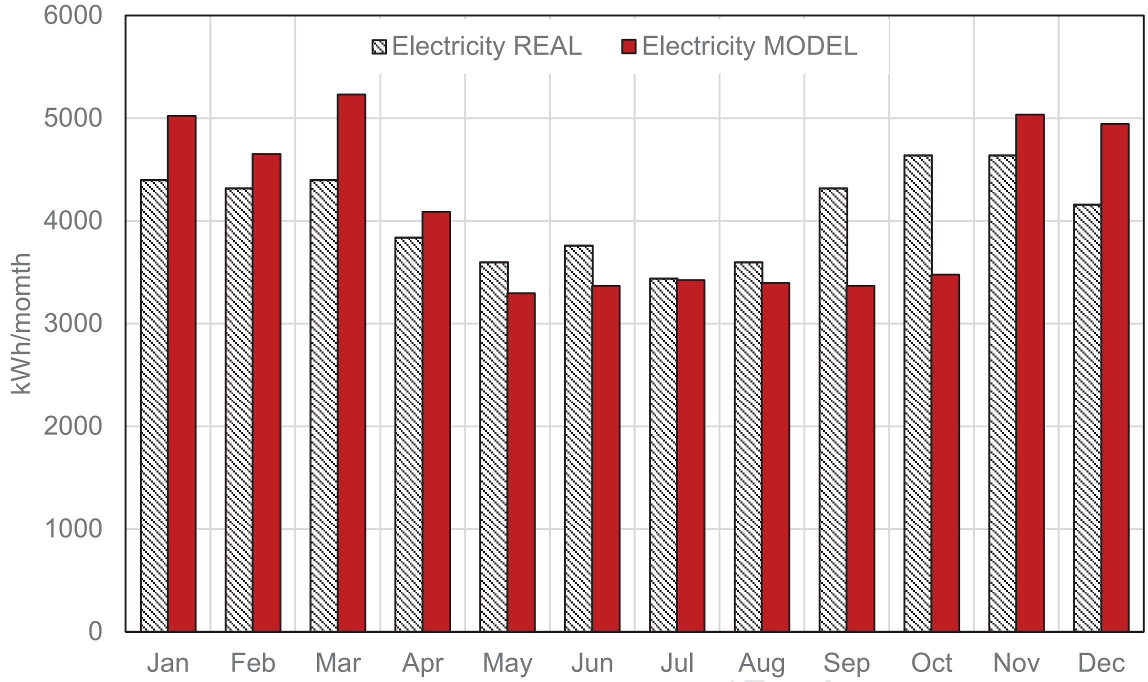
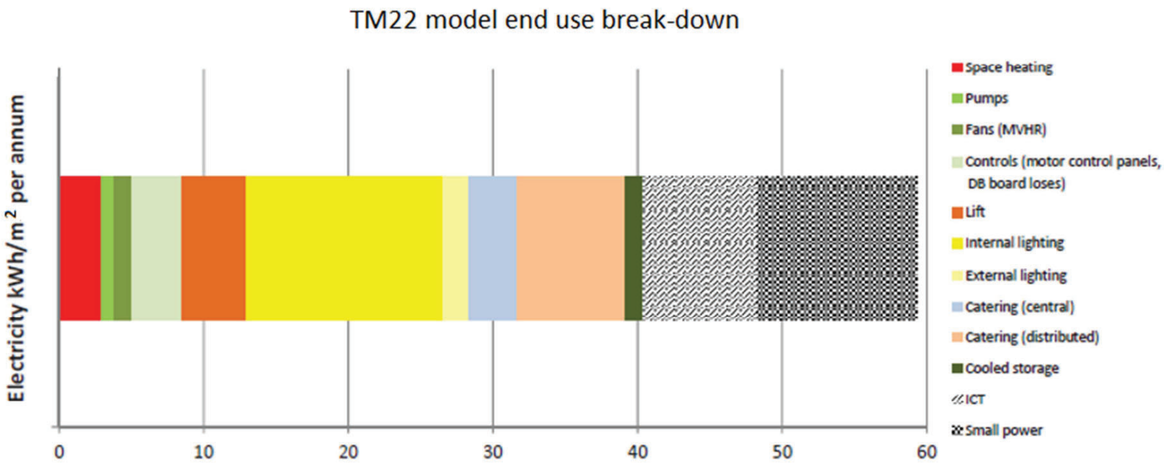


Fig. 7 Comparison of monthly measured and monthly modelled electricity

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%). Nevertheless, the model presents similar end-uses compared to the real building. To illustrate this, Fig 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. With the MBE and CV(RMSE) coefficients within acceptable range, it is concluded that the model is a good representation of the actual building.



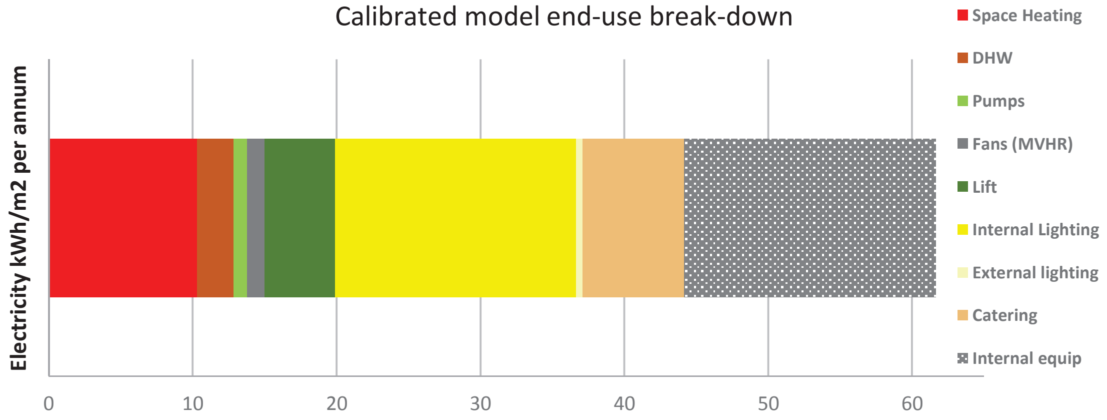


Fig. 8 Comparison of Measured end use break-down with the selected model

By analysing the PV electricity generation, the model gives a production of 14,709 kWh/year, only 3.9% more than the real production of 14,160 kWh/year. The model calculates an in-site utilisation of 13,527 kWh/year, a larger value than the measured of 10,846 kWh/year. Due to excess PV generation during low demand periods (e.g. weekends) and the lack of electric storage, the model calculates that 1,182 kWh/year are sent back to the grid, representing £57.3/year of extra income due to government incentives.

4. Results

4.1 Energy and economic analysis (First Law)

When comparing both cases, results show big differences in energy values. While the pre-retrofit building requires 30,292 kWh/year of electricity and 181,994 kWh/year of gas, the post-retrofit building, even though the usable floor area was expanded 35% by using the basement as new office space, is able to lower the total demand to just 47,293 kWh/year of electricity, representing a net reduction of 77.7%. Table 6 shows a comparison by end use for both cases.

Table 6 Annual energy demand by end-use for the pre-retrofit and post-retrofit models

End-use	Pre-retrofit Electricity (kWh)	Pre-retrofit Gas (kWh)	Pre-retrofit Total (kWh)	Post-retrofit Electricity (kWh)	Post-retrofit Gas (kWh)	Post-retrofit Total (kWh)
Heating	0	138,836		7,901	0	
Cooling	0	0		0	0	
Interior Lighting	16,553	0		12,835	0	
Exterior Lighting	374	0		359	0	
Interior Equipment	8,626	0		11,465	0	
Catering	0	18,452		5,433	0	
Lift	0	0		3,759	0	
Fans	0	0		515	0	
Pumps	4,739	0		721	0	
Heat Recovery	0	0		422	0	
Water Systems	0	24,707		1,954	0	
Inverter (PV)	0	0		1,930	0	
Total	**30,292**	**181,994**	**212,269**	**47,292**	**0**	**47,292**

A breakdown and a comparison of monthly energy use for both cases can be seen in Fig 9. It can be seen how during the winter period months the electricity use for the post-retrofit building 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.

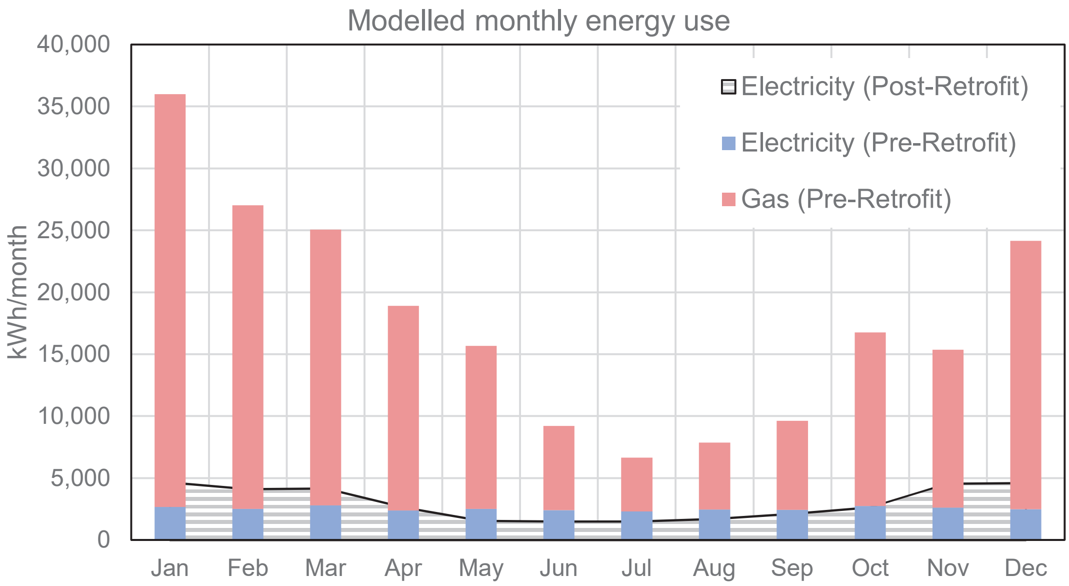


Fig. 9 Monthly energy use breakdown of modelled pre-retrofit and post-retrofit building

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 (gas ≈ 3.0 p/kWh, elec. ≈ 12.3 p/kWh). In this case, the model shows a reduction from £10,026/year (electricity: £3,656/year, gas: £6,370/year) to £4,379/year.

The model also calculates a potential annual income thanks to the RHI and FiT schemes (UK 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 £251.0/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% form the pre-retrofit energy bill). An energy bill breakdown comparison between cases for the base year is illustrated in Fig 10.

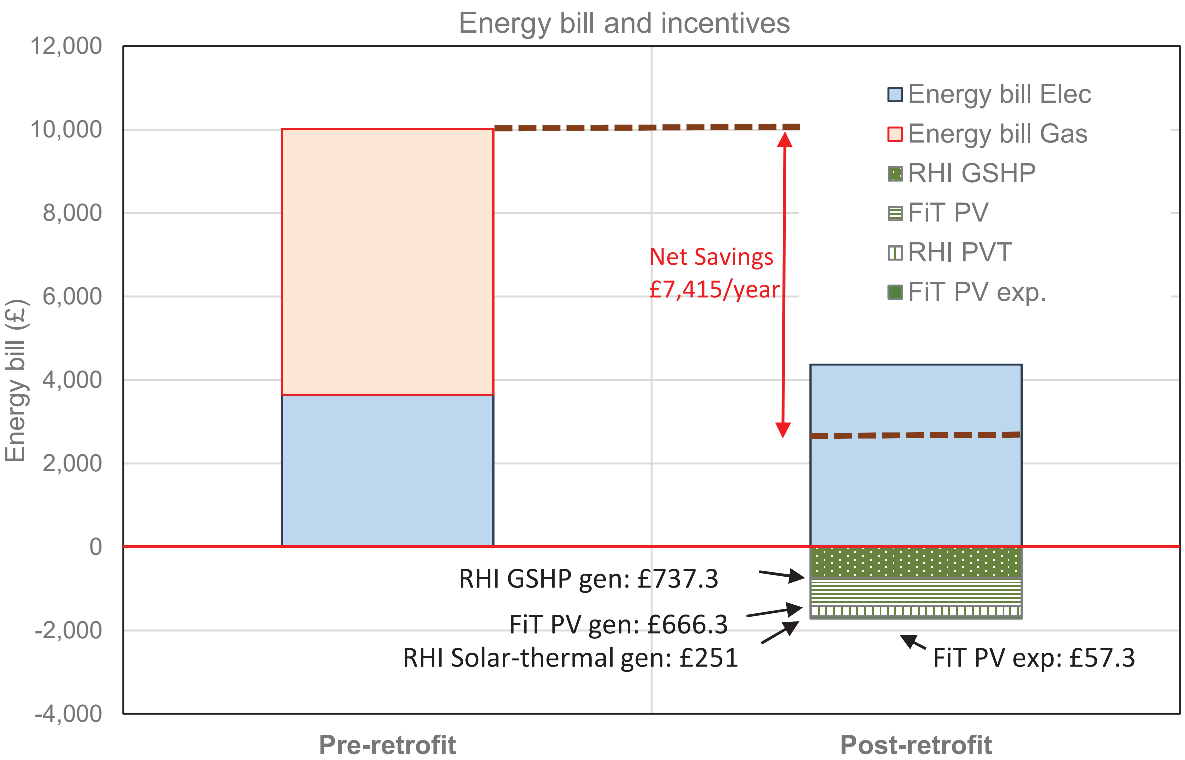


Fig. 10 Annual energy bill comparison between pre-retrofit and post-retrofit building

The architectural firm/design team has reported a project total investment of about £1.6 million; however, the report does not provide detailed capital investment data for energy oriented measures, thus it was difficult to account the investment exclusively used for this type of equipment. The capabilities of ExRET-Opt have allowed the estimation of the total capital investment for the retrofit 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. 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). This figure is interesting, since most of the investment for a Passivhaus project was dedicated to active systems. As a single measure, PV/T panels represents almost 37% of the total investment, followed by glazing (17.5%) and roof insulation (10.4%). The technoeconomic values should be carefully considered as significant uncertainties may exist in regards to the difference between real and modelled prices. Fig 11 illustrates the capital investment for each measure type for the Passivhaus design.

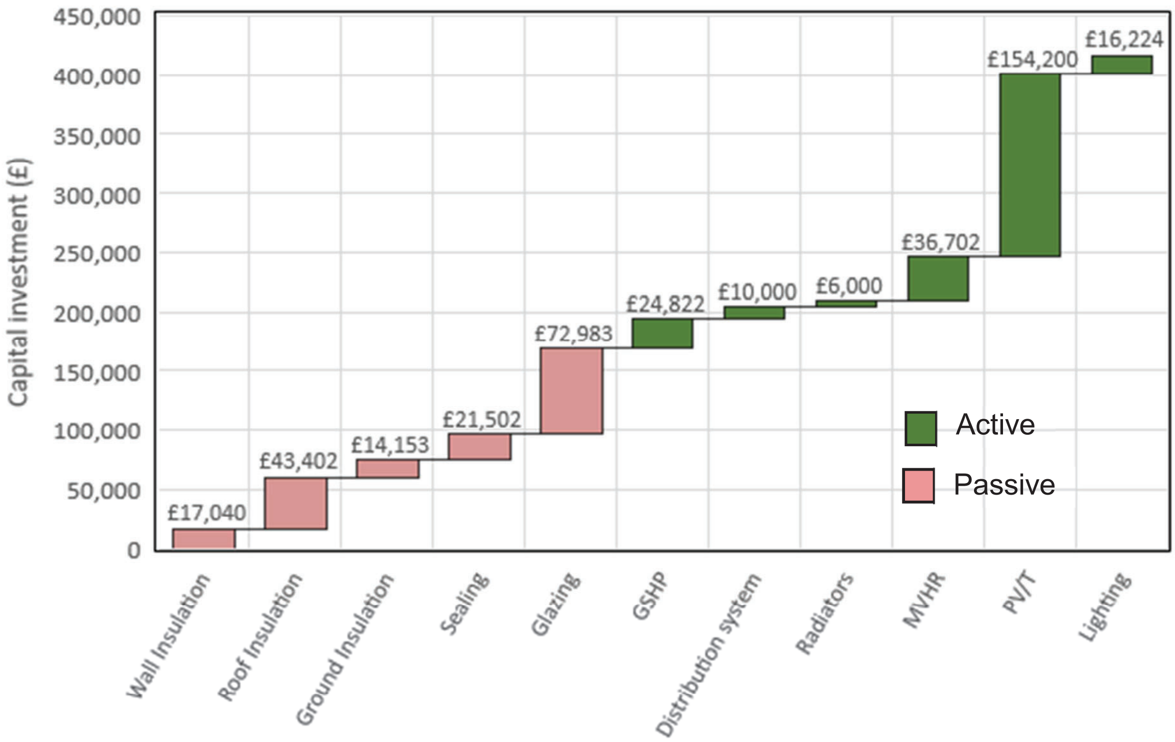


Fig. 11 Retrofit design capital investment per technology calculated by ExRET-Opt

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. 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 annual revenues of this Passivhaus project are not sufficient to deliver a cost-effective retrofit design.

4.1.1 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 should be taken with care because of ExRET-Opt inability to model in detail occupants' behaviour.

To calculate carbon emissions, a disaggregation by fuel type should be considered as each energy source has embedded different emission factors. For the UK, the model considers the values provided by Pout [45] (Table 7).

Table 7 Emission factors for different energy sources [45]

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

Therefore, the total emissions in the pre-retrofit building represents 108.8 tCO_2/year, while for the post-retrofit building this was reduced to 38.6 tCO_2/year, a decrease by 64.5%.

4.2 Exergy and exergoeconomic analysis (First and Second Law)

4.2.1 Primary exergy indicators

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 293,505 kWh/year. By product type, heating requires the largest share (48.9%), followed by electric equipment (42.3%) and DHW (8.7%). For the post-retrofit building the primary exergy input is found at 127,929 kWh/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 Fig 12.

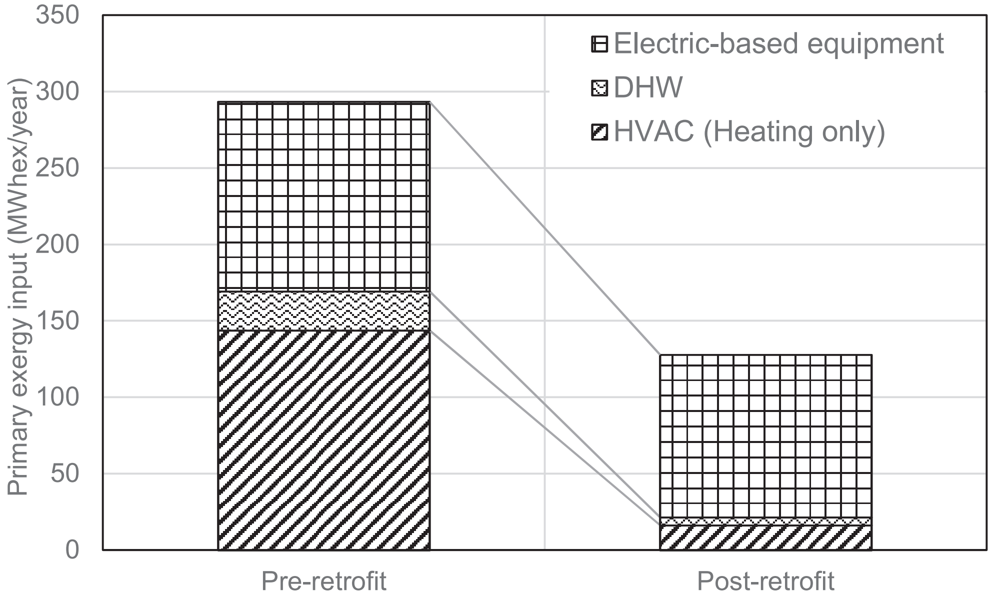


Fig. 12 A comparison of primary exergy input by end-use for the pre and post-retrofit building

Fig 13 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 143,707 kWh/year, the GSHP, combined with the MVHR system, requires just 16,385 kWh/year. As seen at the last part of the supply chain, the thermal exergy demand was also reduced, from a pre-retrofit value of 5,282 kWh/year to 1,698 kWh/year, demonstrating the impact of the Passivhaus envelope's thermal characteristics.

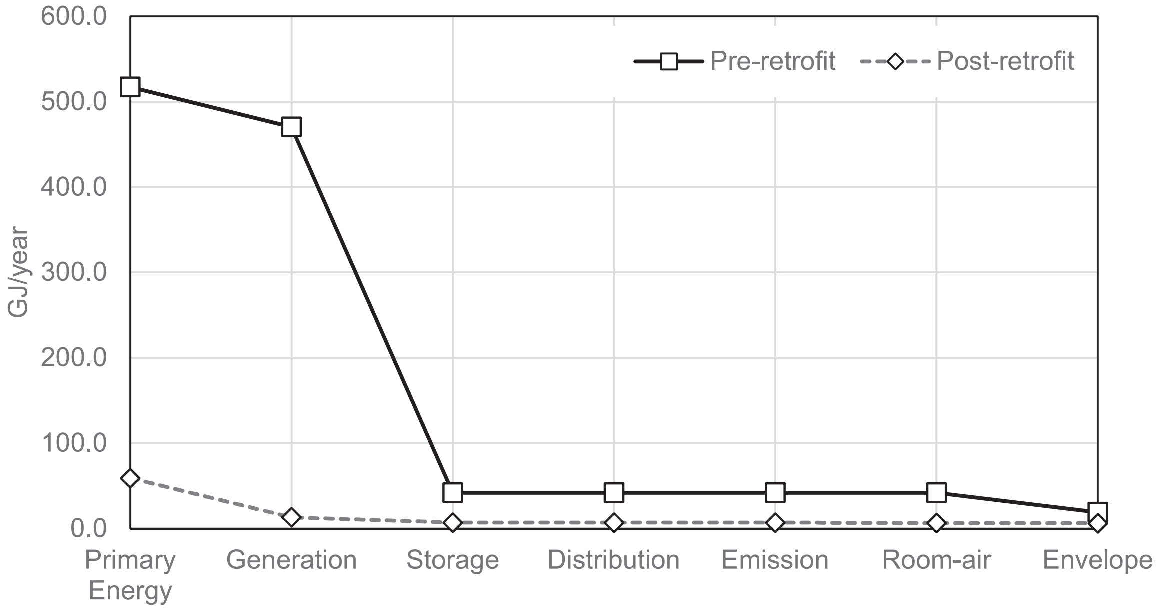


Fig. 13 Exergy use comparison for heating demand throughout the building energy supply chain

4.2.2 Exergy efficiency and exergy destructions breakdown by sub-systems

By analysing the whole building energy system, a comparison of exergy destructions among subsystems can be considered. These results would help determine end-use thermodynamic efficiencies as well as the overall building exergy efficiency. Table 8 provides a comparison of exergy input, output, exergy destructions and efficiency for the various components for the pre-retrofit and post retrofit building.

Table 8 Exergy input, destructions and efficiencies by building subsystems

	Pre-retrofit			Post -retrofit		
Building subsystems	**Exergy Input (kWh/year)**	**Exergy destructions (kWh/year)**	**Subsystem efficiency (%)**	**Exergy Input (kWh/year)**	**Exergy destructions (kWh/year)**	**Subsystem efficiency (%)**
HVAC system						
Primary Energy	143,707	13,051	90.9%	16,385	12,768	22.1%
Generation	130,656	118,982	8.9%	3,617	1,695	53.1%
Storage	11,674	--	--	1,922	--	--
Distribution	11,674	740	93.7%	1,922	30	98.4%
Emission	10,934	320	97.1%	1,892	105	94.5%
Room	10,614	5,332	49.8%	1,787	89	95.0%
Envelope (Demand)	5,282	---	---	1,698	---	---
DHW system						
Primary Energy	25,547	1,533	94.0%	5,194	312	94.0%
Generation	24,014	21,499	10.5%	4,882	4,676	4.2%
Distribution	2,515	943	62.5%	206	77	62.5%

Demand	1,572	---	---	129	---	---
Electric equipment						
Primary Energy	124,252	75,526	39.2%	106,350	64,644	39.2%
Storage	48,726	--	--	41,706	--	--
Distribution	48,726	26,769	45.1%	41,706	20,522	50.8%
Demand	21,957	---	---	21,184	---	---

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 and the MVHR, switch the largest share of irreversibilities to the primary energy generation subsystem, as electricity is required for electric-based appliances in the buildings. 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 recovered by the system. The second largest destructions are found at the appliances itself, as it mainly depends on the equipment's energy efficiency. In a detailed analysis, irreversibilities are found in different ratios for both cases. Fig 14 illustrates the differences between the building types, showing the share of destructions per component.

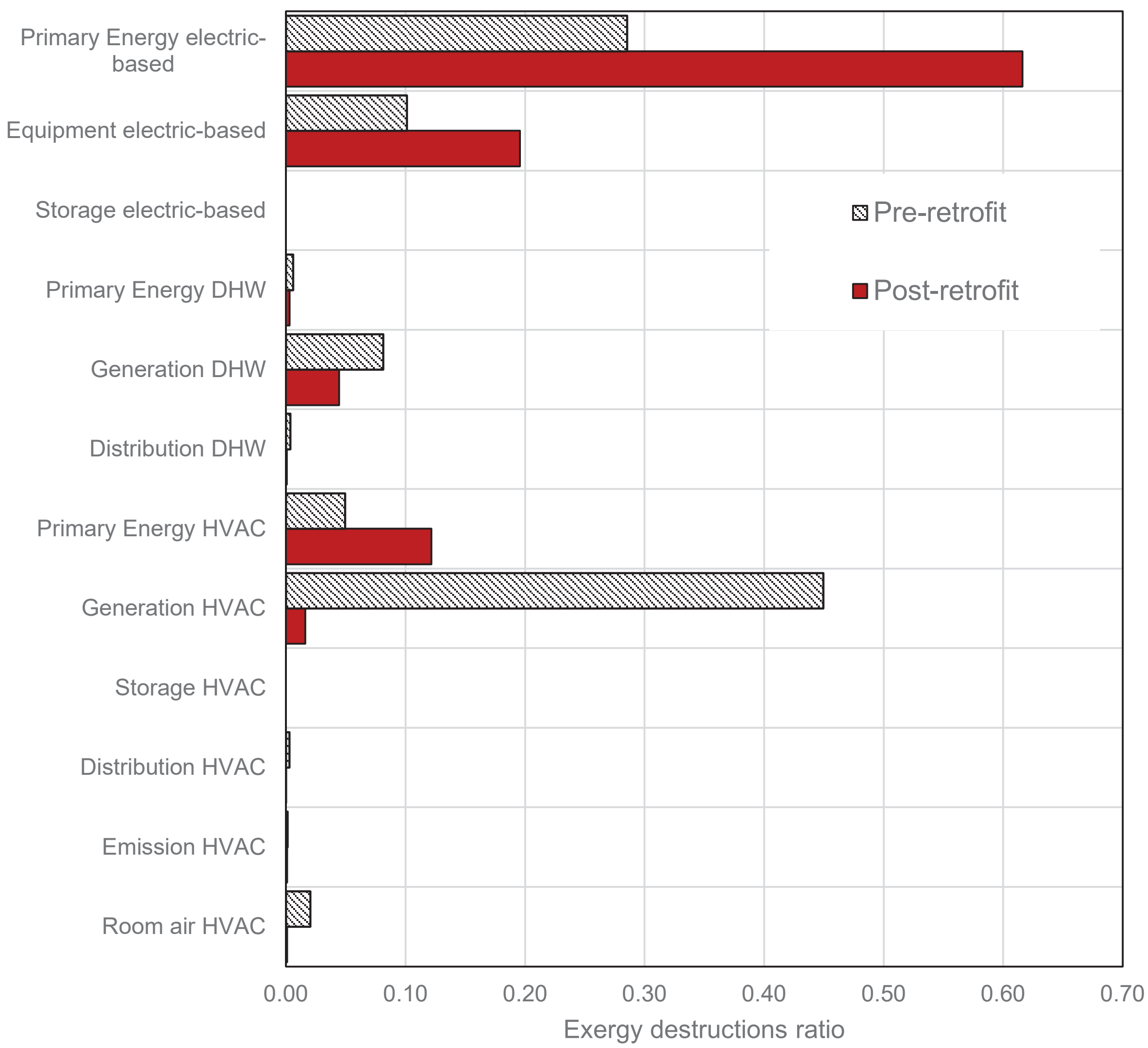


Fig. 14 Exergy destruction ratio of all energy subsystems for pre and post retrofit building

By analysing the true thermodynamic efficiencies (Ψ) by end-use, it is found that for the pre-retrofit building, the HVAC system has an efficiency of 3.7%, the DHW of 6.2%, and electric-based appliances of 17.7%. The post retrofit building improved efficiencies at the HVAC system (Ψ =10.4%) and electric appliances (Ψ =19.9%), but with a decrease in DHW efficiency (Ψ =2.5%). The total exergy demand considering HVAC, DHW, and electric-based equipment for the pre-retrofit building is found at 28,810 kWh/year with global annual exergy destructions of 264,695 kWh/year, resulting in a total building exergy efficiency (ψ_{bui}) of 9.8%. On the other hand, the post-retrofit building has a total exergy demand of 23,011 kWh/year and exergy destructions of 104,918 kWh/year, resulting in an exergy efficiency of 18.0%. This design, at least from an exergy perspective, can also be considered as a 'Low-Exergy" design, however exergoeconomic indicators remain to be seen.

4.2.3 Exergoeconomic indicators

Fig 15 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.

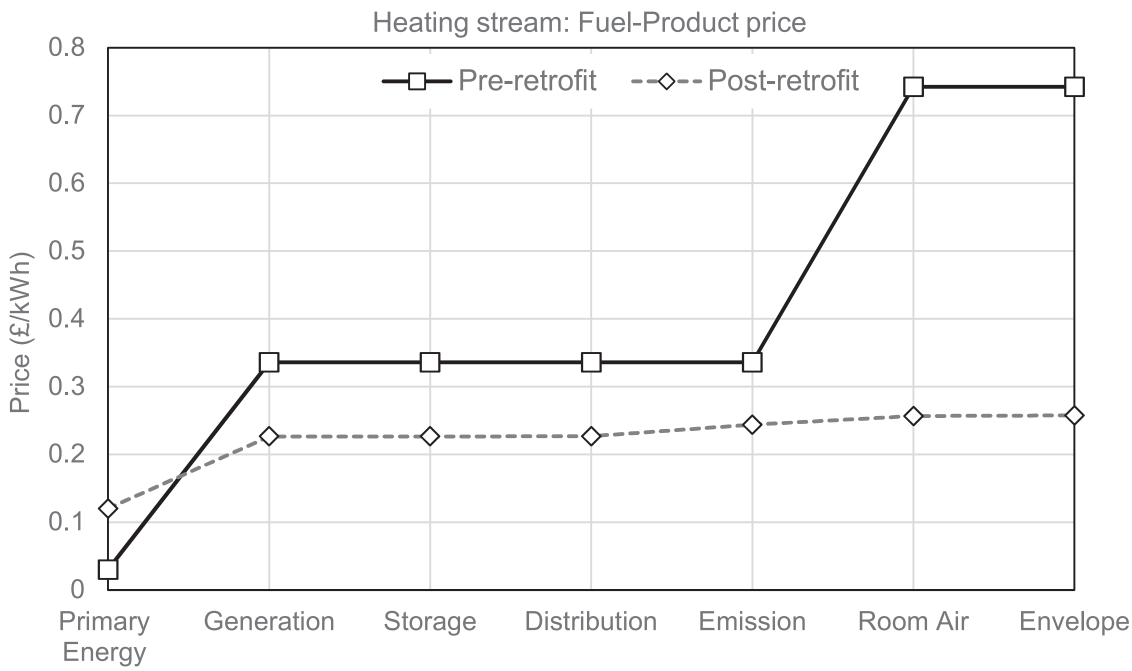


Fig. 15 Heating stream product cost formation for the pre-retrofit and post-retrofit

Table 9 provides exergoeconomic outputs by subsystems for both cases, presenting exergy streams price formation, annual exergy destruction cost, as well as exergoeconomic factors and relative cost differences along the whole building energy supply chain. The calculation framework for these indicators is presented in Appendix A.

Table 9 Exergoeconomic indicators by building subsystems

	Pre-retrofit					Post-retrofit				
Building subsystems	**Exergy price Fuel (£/kWh)**	**Exergy price Product (£/kWh)**	**Exergy destructions cost (£/year)**	**Exergoeconomic factor f_k (-)**	**Relative cost difference r_k**	**Exergy price Fuel (£/kWh)**	**Exergy price Product (£/kWh)**	**Exergy destructions cost (£/year)**	**Exergoeconomic factor f_k (-)**	**Relative cost difference r_k**
HVAC system										
Primary Energy	---	0.03	---	---	---	---	0.12	---	---	---
Generation	0.03	0.34	3,569	0.00	10.19	0.12	0.23	203	0.01	0.89
Storage	0.34	0.34	0	0.00	0.00	0.23	0.23	0	0.00	0.00
Distribution	0.34	0.34	248	0.00	0.00	0.23	0.24	7	1.00	0.08
Emission	0.34	0.35	107	0.00	0.04	0.24	0.26	26	0.00	0.05
Room	0.35	0.74	1,866	0.00	1.12	0.26	0.26	23	0.00	0.00
Envelope (Demand)	0.74	---	---	---	---	0.26	---	---	---	---
DHW system										
Primary Energy	---	0.03	---	---	---	---	0.12	---	---	---
Generation	0.03	0.37	645	0.00	11.33	0.12	1.70	561	0.44	13.20
Distribution	0.37	0.44	349	0.00	0.20	1.70	1.90	132	1.00	0.11
Demand	0.44	---	---	---	---	1.90	---	---	---	---
Electric equipment										
Primary Energy	---	0.12	---	---	---	---	0.12	---	---	---
Storage	0.12	0.12	0.00	0.00	0.00	0.12	0.12	0	0.00	0.00
Distribution	0.12	0.27	3,212	0.00	1.22	0.12	0.24	2,463	6.31E-05	0.97
Demand	0.27	---	---	---	---	0.24	---	---	---	---

Apart from improving the building's thermal properties and HVAC system, which reduced exergy destruction cost of the generation subsystem by 94.3% (from £3,569 to £203); exergoeconomic results also suggest that exist a high potential for achieving a better post-retrofit design by 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. 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), or ideally, by maximising the use of daylighting; this becomes more difficult when dealing with existing buildings. Daylight, in terms of exergy, represents the highest thermodynamic efficiency, and thus should be highly promoted. The problem with the rest of the electrical appliances (computers, printers, microwaves, electric ovens, etc.), should also be regarded as a major issue with the only solution being the installation of higher electric-efficient equipment.

Table 10 presents whole-building system exergy and exergoeconomic indices obtained for both cases. As showed, the total exergy destruction cost rate ($\dot{\boldsymbol{C}}_{\boldsymbol{D,sys}}$) 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 ($\dot{\boldsymbol{Z}}_{\boldsymbol{sys}}$) 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 not only economically but also exergoeconomically. In addition, if government incentives are not considered, the post-retrofit $Exec_{CB}$ increases to £1.52/h, almost the same value as the pre-retrofit building.

Table 10 Comparison of pre-retrofit and post-retrofit building exergoeconomic values

Baseline characteristics	Pre-retrofit	Post-retrofit
Exergy input (fuel) (GJ)	1,056.6	460.5
Exergy demand (product) (GJ)	103.7	82.8
Exergy destructions (GJ)	952.9	377.7
Exergy efficiency HVAC	3.7%	10.4%
Exergy efficiency DHW	6.2%	2.5%
Exergy efficiency Electric equip.	17.7%	19.9%
Exergy efficiency Building	9.8%	18.0%
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	1.54	0.38
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 Fig 16. 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.

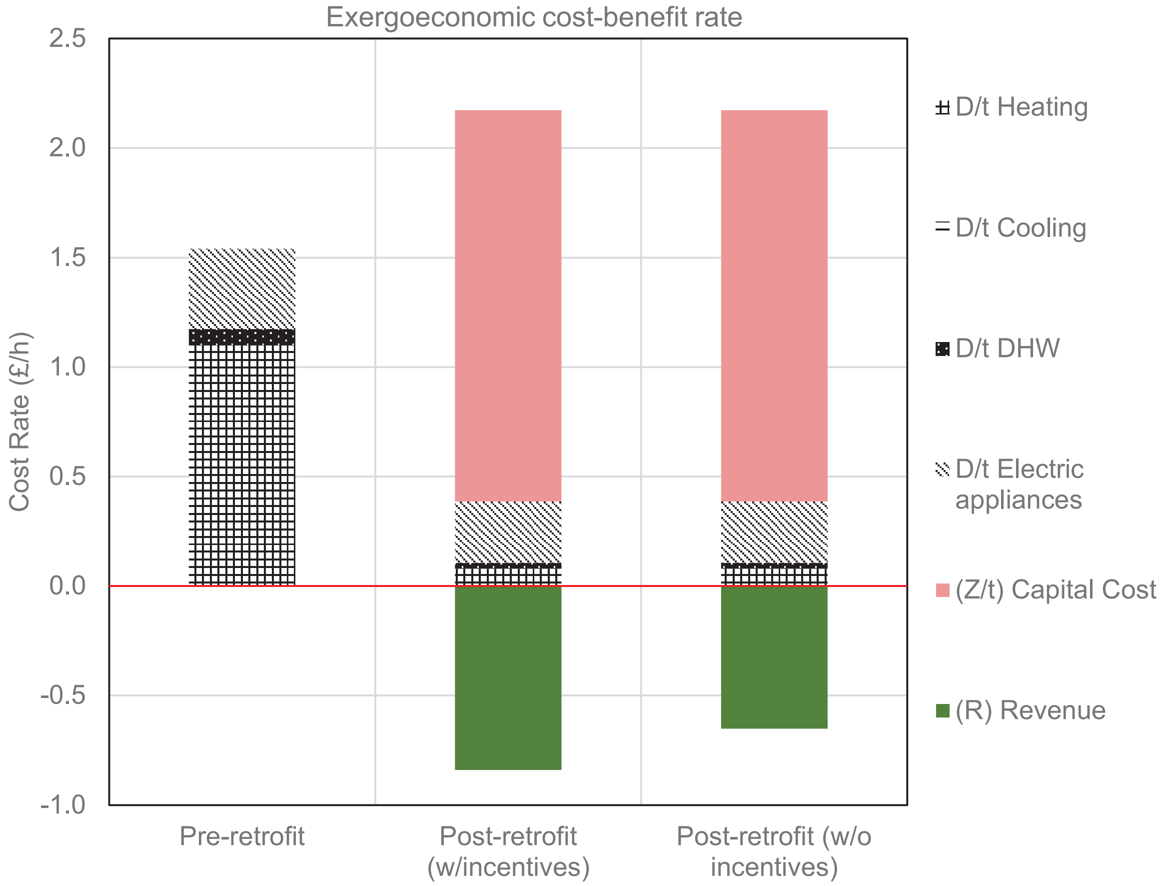


Fig. 16 A comparison of the exergoeconomic cost-benefit rate breakdown comparison between pre and post retrofit building

5. Conclusions

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. First, a comparison was made between the pre-retrofit building and the actual Passivhaus retrofit design. To accomplish this, two calibrated building models, using actual monthly data, were created using an exergy-based building simulation tool (ExRET-Opt). The tool was able to estimate the required investment 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 by 64.5%, seemed to provide a building with improved thermodynamic performance by reducing primary exergy input by 56.4%. Although just managing to reduce building exergy demand, switching it from space heating demand to electric-based equipment demand, the Passivhaus design significantly reduces overall exergy destructions by 60.4%, ultimately increasing building exergy efficiency from 9.8% to 18.0%. This was accomplished by a design based on a GSHP connected to medium temperature radiators and supported by a 90% efficient MVHR system.

The tool calculated a required investment for the Passivhaus retrofit of £417,028. Passive technologies account for 41% of the project, while the PV/T panels, comprised by 18 kWp of PV and 3 m^2 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 retrofit 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. It can be inferred that designers considered energy savings, aesthetics, and thermal comfort as main drivers, rather than the retrofit economics. Furthermore, the application of exergoeconomic analysis has demonstrated the poor overall performance of the actual design. On one hand, the product cost formation showed 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). Thanks to the calculation of the products' cost formation and the building's exergy destruction cost, the exergoeconomic cost-benefit indicator has been calculated. As aforementioned, the

Passivhaus design, while improving exergy efficiency, has also minimised exergy destruction cost rate, from a value of £1.54/h to £0.38/h. However, such good thermodynamic result has been achieved with a high capital investment. If accounting for capital and revenue cost rates, the Passivhaus design yields an exergoeconomic cost-benefit value of £1.33/h. As the improvement compared to the pre-retrofit exergy destruction cost is low ($\dot{C}_{D,pre-retrofit}$=1.54), this suggests that the design did not achieve an acceptable exergoeconomic performance and is far from the optimum solution. To lower the exergoeconomic cost-benefit index (as well as LCC), a design needs to have lower capital investment cost, lower exergy destructions, and an increase in revenue rates. In the analysed case study, this could come from reducing the investment for insulation and focusing more resources on improving building services.

The inclusion of a second law framework analysis, especially exergoeconomic analysis, provided more information than typical approaches as it pinpointed exact sources of inefficiencies and its cost implications. For example, for the pre-retrofit building, exergoeconomic analysis located large exergy destruction costs at the heating generation subsystem (due to the combustion process), followed by the distribution subsystem for electric appliances. As the building was retrofitted using the 1st law analysis only, results showed that the design was able to reduce exergy destruction costs of heating generation by 94.3%, but reducing only 23.3% for the electric equipment. By using exergoeconomic optimisation for the entire building energy system, a trade-off between subsystems' exergy destruction costs could be obtained, providing an appropriate balance between active and passive measures, focusing on improving subsystem thermodynamic and cost performance.

The outputs demonstrated that although the Passivhaus retrofit provided good energy and exergy performance, the approach was neither an economically nor exergoeconomically-attractive solution for the specific case study. In this sense, the Passivhaus approach may well be a tempting individual solution due to its exceptional energy performance, but it was not an appropriate cost-effective solution due to the building's pre-retrofit low energy bills combined with the high capital investment required for the specific design. Nevertheless, the evaluation presented in this paper neglected the quantification of other non-energy related benefits, such as indoor air quality, thermal comfort and building aesthetics improvement; if appropriately quantified, it could enhance the financial viability of the actual retrofit design. For future work, with the aim to find alternative cost-effective designs, a multi-objective optimisation study is being prepared by the authors. The study will consider exergy/exergoeconomic as well as non-thermodynamic variables such as occupant thermal comfort and carbon emissions as objective functions. As has been demonstrated by other sectors (e.g. industrial processes and power generation), the application of exergoeconomic optimisation could complete a robust methodology that might be useful for future building retrofit practice.

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Nomenclature

ach	air change rates (1/h)
$\dot{C}_D$	exergy destruction cost (£)
c_f	average cost of fuel (£/kWh)
c_p	average cost of product (£/kWh)
COP	coefficient of performance (W/W)
CRF	capital recovery factor (-)
DHW	domestic hot water
$dest$	destructions or irreversibilities (kWh)
$dist$	distribution
DPB	discounted payback (years)
EPS	expanded polystyrene
EUI	energy use index (kWh/m²-year)
En	energy (kWh)
Ex	exergy (kWh)
$\dot{E}x_D$	exergy destructions (kWh)
$Exec_{CB}$	exergoeconomic cost benefit factor (£/h)
f_k	exergoeconomic factor (-)
f_q	quality factor (-)
FiT	feed-in-tariff (£)
$GSHP$	ground source heat pump
$HVAC$	heating, ventilation, and air conditioning
LCC	life cycle cost (£)
$MVHR$	mechanical ventilation heat recovery
MBE	mean bias error (%)
NPV	net present value (£)
PET	primary energy transformation
PW	power factor (-)
q_{fuel}	fuel quality factor (-)
R	annual revenue (£)
r_k	relative cost difference (-)
ref	refrigeration
ret	return
RHI	renewable heat incentive (£)
$RMSE$	root mean squared error (%)
$strg$	storage
SV	savage factor (-)
T	temperature (K)

T_0 reference temperature (K)
τ equipment annual working hours
TCI total capital investment (£)
U_{value} thermal transmittance (W/m^2-K)
XPS extruded polystyrene
$\dot{Z}_{sys}$ capital investment rate (£/h)

Greek symbols
ψ_{tot} exergy efficiency (-)

Appendix A. Exergy/exergoeconomic calculation framework

A.1 Exergy analysis

A.1.1 HVAC exergy stream

a) Detailed thermal exergy demand (heat and matter):

$$Ex_{dem,therm,zone\ i}(t_k) = \sum_{i=1}^{n}\left(En_{dem,therm\ ith}(t_k) * \left(1 - \frac{T_0\ (t_k)}{T_i\ (t_k)}\right)\right) \quad \text{(A.1)}$$

$$Ex_{dem,vent,zone\ i}(t_k) = \sum_{i=1}^{n}\left(En_{dem,vent\ ith}(t_k) * \left(1 - \frac{T_0\ (t_k)}{T_i\ (t_k) - T_0\ (t_k)} ln \frac{T_i\ (t_k)}{T_0\ (t_k)}\right)\right) \quad \text{(A.2)}$$

b) Room air subsystem:

$$F_{q,room}(t_k) = 1 - \frac{T_0\ (t_k)}{T_{emission}\ (t_k)} \quad \text{(A.3)}$$

Therefore, the exergy load of the room is:

$$Ex_{room}(t_k) = F_{q,emission}(t_k) * Q_{emission}\ (t_k) \quad \text{(A.4)}$$

c) Emission subsystem:

Referencing to the inlet and return temperature of the system, the exergy losses of the emission system are calculated as follows:

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

(A.5)

Therefore, exergy load rate of the heating system is:

$$Ex_{emission}(t_k) = Ex_{room}(t_k) + \Delta Ex_{emission}(t_k) \quad \text{(A.6)}$$

d) Distribution subsystem:

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:

$$\Delta Ex_{dist}(t_k) = \frac{Q_{loss,dist}(t_k)}{\Delta T_{dist}(t_k)} * \left\{(\Delta T_{dist}(t_k) - T_0(t_k)) * \ln\left(\frac{T_{dist}(t_k)}{T_{dist}(t_k) - \Delta T_{dist}(t_k)}\right)\right\} \quad \text{(A.7)}$$

Hence, the exergy load of the distribution system is:

$$Ex_{dist}(t_k) = Ex_{emission}(t_k) + \Delta Ex_{dist}(t_k) \quad \text{(A.8)}$$

e) Storage subsystem:

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

$$\Delta Ex_{strg} = \frac{Q_{loss,strg}(t_k)}{\Delta T_{strg}(t_k)} * \left\{(\Delta T_{strg}(t_k) - T_0(t_k)) * \ln\left(\frac{T_{dist}(t_k) + \Delta T_{strg}(t_k)}{T_{dis}(t_k)}\right)\right\} \quad \text{(A.9)}$$

And the exergy load is calculated as follows:

$$Ex_{strg}(t_k) = Ex_{dist}(t_k) + \Delta Ex_{strg}(t_k) \quad \text{(A.10)}$$

A.1.2 DHW exergy stream

Exergy demand for domestic hot water is calculated as follows::

$$Ex_{dem,DHW}(t_k) = Q_{DHW}(t_k) * \frac{\eta_{WH}(t_k)}{q_{fuel}} * \left(1 - \left(\frac{T_0(t_k)}{T_{p_{WH}}(t_k) - T_0(t_k)}\right) * \ln\left(\frac{T_{p_{WH}}(t_k)}{T_0(t_k)}\right)\right) \quad \text{(A.11)}$$

Distribution and storage subsystem in the DHW stream is calculated similar to the HVAC stream.

A.1.3 Electric-based exergy stream

Electric-based equipment such as fans, pumps, lighting, computers, and motors were considered to have the same exergy efficiency as their energy counterpart ($\psi_{elec} \approx \eta_{elec}$) and therefore the same exergy consumption.

$$Ex_{dem,elec,i}(t_k) = En_{dem,elec,i}(t_k) * F_{q,elec} \quad \text{(A.12)}$$

A.1.4 Other end-use streams

Exergy demand for cooking equipment (gas based):

$$Ex_{dem,cooking} = Q_{cook}(t_k) * \frac{\eta_{cook}(t_k)}{q_{fuel}} * \left(1 - \frac{T_0\,(t_k)}{T_{p_{cook}}(t_k)}\right) \quad \text{(A.13)}$$

Exergy demand for refrigeration:

$$Ex_{dem,ref}(t_k) = Q_{ref}(t_k) * COP_{ref}(t_k) \left(\frac{T_0(t_k)}{T_{p_{refr}}(t_k)} - 1\right) \quad \text{(A.14)}$$

A.1.5 Primary Exergy Input

For primary exergy input, the following formula is used:

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

(A.15)

Fuel primary energy factors and quality factors used in this study are shown in Table A.1

Table A.1 Primary Energy Factors and Quality Factors by energy sources

Energy source	Primary energy factor (F_p) (kWh/kWh)	Quality factor (F_q) (kWhex/kWhen)
Natural gas	1.11	0.94
Electricity (Grid supplied)	2.58	1.00

A.1.6 Exergy destructions and exergy efficiency

Exergy destructions is obtained by subsystems or whole building is obtained as follows:

$$Ex_{dest,i} = Ex_{IN,i} - Ex_{OUT,i} \quad (A.16)$$

Therefore, a building's exergy efficiency Ψ_i is obtained as follows:

$$\Psi_{sys,i}(t_k) = \frac{Ex_{out,i}(t_k)}{Ex_{in,i}(t_k)} \quad (A.17)$$

A.2 Economic/Exergoeconomic analysis

A.2.1 Economic analysis

NPV and DPB are calculated as follows:

$$NPV_{Nyears} = -TCI + \left(\sum_{n=1}^{N} \frac{R}{(1+i)^n}\right) + \frac{SV_N}{(1+i)^N} \quad (A.18)$$

$$DPB = -\frac{\ln\left[\left((1-(1+i)) * \left(\frac{TCI}{R}\right)\right) + 1\right]}{\ln(1+i)} \quad (A.19)$$

The energy prices and subsidies considered in this study are presented in Table A.2.

Table A.2 UK energy prices and government subsidies

Prices and Incentive Schemes	Prices (£/kWh)

Natural gas (supplied)	0.030
Electricity (Grid supplied)	0.121
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

A.2.1 Exergoeconomic analysis (SPECO)

An exergy cost stream associated with the corresponding stream *i* is calculated as follows:

$$\dot{C}_i = c_i Ex_i \tag{A.20}$$

where c_i and Ex_i are the streams' specific cost and exergy, respectively. a general cost balance expression is expressed as follows:

$$\dot{C}_{p,k} = \dot{C}_{D,k} + \dot{Z}_k \tag{A.21}$$

In addition, the exergy destruction cost of a component is defined as:

$$\dot{C}_{D,k} = c_{f,K} \dot{Ex}_{D,k} \tag{A.22}$$

To obtain building total exergy destruction cost, a sum of all subsystems' components is needed:

$$\dot{C}_{D,sys} = \sum_{k=0}^{n} (c_{f,K} \dot{Ex}_{D,k}) \tag{A.23}$$

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

$$\dot{Z}_k = \frac{PW \cdot CRF}{\tau} \tag{A.24}$$

PW and *CRF* are obtained as follows:

$$PW = TCI - \frac{SV_N}{(1+i)^N} \tag{A.25}$$

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{A.26}$$

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

- *Relative cost difference*

$$r_k = \frac{c_{P.k} - c_{F,k}}{c_{F,k}} \tag{A.27}$$

- *Exergoeconomic factor*

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + c_{F,k}(\dot{E}x_{D,k})} \tag{A.28}$$

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Highlights

- Assessment of a Passivhaus retrofit design under both thermodynamic laws
- The Passivhaus case study design improves building's exergy performance (Ψ_{bui}=18%)
- Passivhaus presents the highest exergy destruction rates at electric appliances
- High exergy destructions and capital investment costs harms project's profitability
- The design presents a capital cost rate of £1.78/h with a revenue rate of £0.84/h