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The role of an exergy-based building stock model for exploration of future decarbonisation scenarios and policy making

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Abstract

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, demonstrating it to be the only rational basis for evaluation. After discovering the lack of thermodynamic integration into stock modelling, this paper presents the development of an exergy-based building stock model. The aim of this paper is twofold. Firstly, to investigate the impact of large-scale future energy retrofit scenarios in the English and Welsh (E&W) non-domestic sector, and secondly, to determine the potential of exergy analysis in improving sectoral efficiency and its potential implications on exergy-oriented policy making. The research explores seven different large-scale future retrofit scenarios that encompass typical, low-carbon, and low-exergy approaches. Modelling results show that by 2050, current regulations have the potential to reduce carbon emissions by up to 49.0 ±2.9% and increasing sector thermodynamic efficiency from 10.7% to 13.7%. On the other hand, a low-exergy oriented scenario based on renewable electricity and heat pumps is able to reduce carbon emissions by 88.2 ±2.4%, achieving a sectoral exergy efficiency of 19.8%. This modelling framework can provide energy policy makers with new insights on policy options based on exergy indicators and the assessment of their potential impact.

Keywords:
Energy conservation; Exergy; Stock model; Retrofit scenarios; Non-domestic; Low-exergy buildings

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1. Introduction

Following the industrial revolution, fossil fuels have been increasingly utilised to support the processes required to meet the requirements of modern societies. Energy represents the driver to move almost every activity in today's modern societies. The importance of ensuring energy generation and supply is a fundamental part to keep energy-consuming activities in the built environment at a rate that modern and future generations demand. Countries depend on this process on a daily basis to keep modern economy moving, provoking an irreversible environmental degradation.

In industrialized 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). As the issue of energy performance of the building sector has increased in significance, developing methods for designing efficient and cost-effective energy systems has become the main challenge for energy efficient buildings researchers. The non-domestic sector, despite of its high variability, represents a significant opportunity for GHG reduction. Recent energy policies and regulatory shifts have aimed to improve cross-sectoral efficiency including policies to drive down building energy demand and decarbonisation of the electricity and heating supply. The sector also holds opportunities to improve other parts of the supply chain. Shao et al. (2014) presented a system accounting method to calculate real energy consumption and carbon emission of material, equipment, energy and manpower in the office sector of Beijing. The authors found that 90% of the total energy use and carbon emissions are embedded into buildings' materials (mainly steel and concrete), being coal is the main energy source, accounting for 83.6% of the total energy utilisation.

The recent UK government low carbon strategic framework highlights the importance of considering the 'energy quality' or 'exergy' in the analysis for low carbon strategies (DECC, 2012), implying its importance for building energy efficiency design. Deriving from the Second Law of Thermodynamics principles and combining it with the First Law (energy balance), the concept of '*Exergy'* arises. Exergy unlike energy, which is always conserved, is exposed to consumption and destructions. 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. These irreversibilities give a clear indication of the thermodynamic improvement potential of the sector. Chen (2005) presented a systematic study on the earth's global exergy consumption adding a new approach for ecological modelling. The model is based on a thermodynamic abstraction of the earth working under a temperature difference between the sun and the cosmic background. The author provided a mechanism to illustrate the transformation process between exergy in space and the exergy entering the earth systems as well as an "exergy budget" demonstrating its implications on global sustainability. Inefficient and unwise use of resources can significantly impact sustainability and national energy security (Dincer, 2002). In addition, exergy analysis provides a viable link between demand and supply analysis, which is often performed separately. This disassociation has lead decisions makers to assume that systems such as electric-based heating are the most efficient way to deliver heat as it has an 'efficiency' of 100%. The problem is that the delivery of electricity to cover a low-quality demand such as space heating/cooling should be considered as irrational because the qualities of the demand and the supply does not match. This approach has cause that among all economic sectors in the UK, the building sector has the highest potential to improve its thermodynamic efficiency (Figure 1) (Gasparatos et al., 2009).

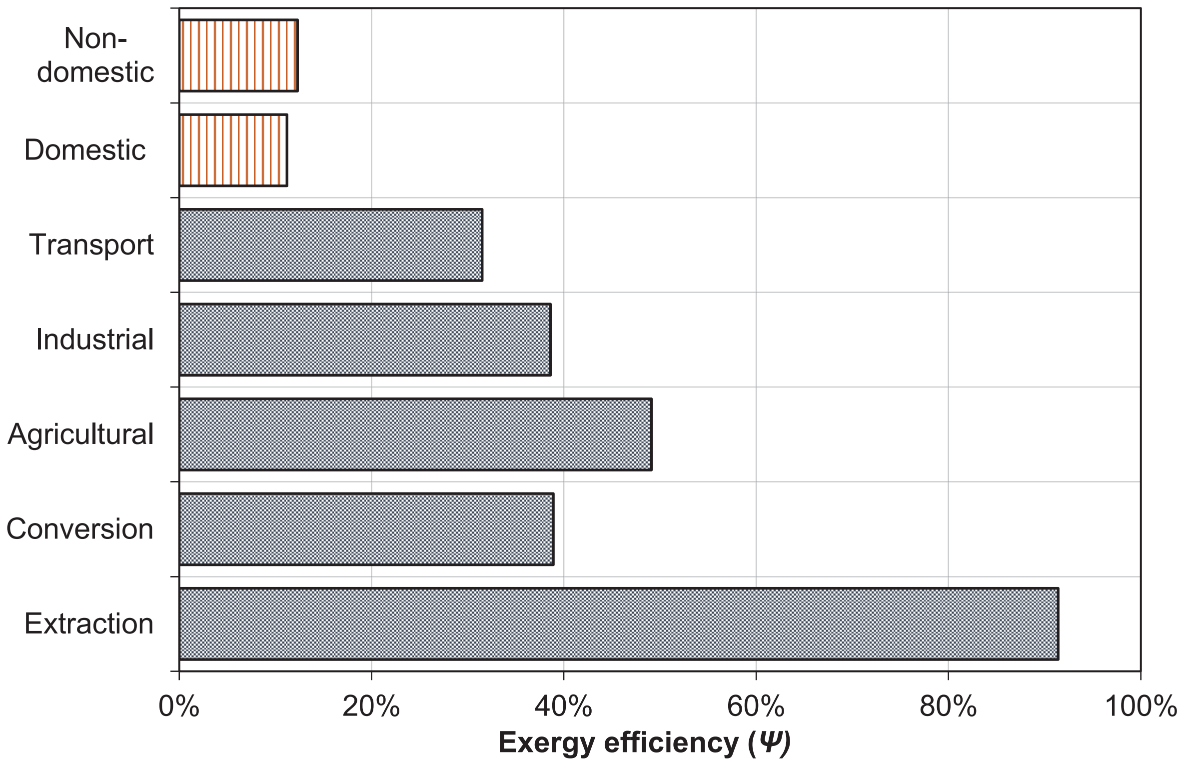

Figure 1 Exergy Efficiency in different UK sectors. Source: Gasparatos et al, 2009.

Improving current buildings energy performance with low environmental impact designs is crucial to meet the national emission reduction targets. However, by having a poor understanding of exergy utilisation in buildings, current policies produce a mistreatment of current physical resources. In the past decades, an increase in the utilisation of exergy analysis methods in the practice of real case scenarios 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, 2002).

Recently, retrofit-oriented stock modelling methods have received significant attention in building energy practice (Kavgic et al., 2010; Mata et al., 2013); however, exergy-based analysis have not managed to keep up with the same trend. By utilising popular building simulation tools as the foundation, practical exergy theory could become more accessible, reaching a wider audience of policy makers. Exergy analysis presents a perfect case for energy system renovation, where 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. For this purpose, new frameworks have to be investigated and developed to explore thermodynamic indicators under different future retrofit scenarios.

2. Background

2.1 Exergy and Buildings

The principles of the Second Law analysis have become popular in other sectors such as power generation and industrial processes. This happened through a research methodology switch from an entropy-based approach to an exergy-based approach, as exergy is a more tangible measure. However, exergy as a concept is arising among buildings' energy researchers, and most importantly, among policy makers. A great 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 a government report in order to establish a difference between 'energy' and 'energy quality'. The report considers exergy as a useful indicator in the development of low carbon systems. The report also mentions 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 Combined Heat and Power (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. This demonstrates that in some cases CHP performance can exceed Carnot theoretical performance of heat pumps, working under similar reference environment conditions, and can deliver from three to seven units of heat for each unit of electricity that is produced.

Nevertheless, despite the evidence, given the current energy prices, it is 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).

While the building sector holds potential for a significant thermodynamic improvement, exergy analysis could provide with a new insight for buildings energy systems improvement. The application of exergy analysis in existing buildings has a significant potential in the identification of unconventional opportunities and the consequent reduction of dependency on high quality fuels (Jansen et al., 2012). However, the majority of exergy research in the built environment dedicated to improve energy performance has been applied at large scale technologies, especially in the assessment of district networks and community supply power generation systems (Bagdanavicius et al., 2012; Li and Svendsen, 2012; Molyneaux et al., 2010; Nilsson, 1997; Rezaie et al., 2015; Verda et al., 2012a; Verda et al., 2001; Verda et al., 2012b). This previous research has mainly focused on defining criteria for network design and energy generation plant sizing.

As detailed in Torio (2012), exergy analysis methods among different energy processes are not completely transferable between them. For example, exergy analysis for retrofitting a power generation plant have different objectives than those found into building energy design. Conceptually, the main difference is that the objective of a power plant is to increase the (exergy) output of the product (e.g. electricity) by reducing thermodynamic losses, while in buildings it is to keep (or improve) occupant comfort conditions by decreasing thermodynamic losses and decreasing the exergy input. Some researchers have considered that exergy interactions at a building level play a fundamental part in improving exergy efficiency in the building sector.

2.2 Building stock models

As in any energy system, buildings are physically complex where interactions between the building, the occupants, the equipment, and the environment are poorly understood. In order to improve the selection of appropriate measures, practitioners and decision makers require robust tools for effective design, where building simulation play a major role in the design of energy efficient buildings (Siddharth et al., 2011). In addition, the most powerful potential of building performance simulation is the support of building energy policy (Crawley, 2008).

While extensive exergy-based research has been carried out at individual systems level, as a result of high energy use and natural resources at a regional level, exergy analysis has also been used to study sectoral energy use. Reistad (1975) and Wall (1977) were the first researchers to use exergy as a basis to account for thermodynamic flows at a sectoral level considering all economic sectors in a country. These approaches have been used for further studies and are mainly based on top-down econometric modelling. For example, in studies related to the building sector, Dincer et al. (2004) performed an analysis of sectoral energy and exergy use of Saudi Arabia between 1990 and 2001. Country's energy efficiency was found at 50.2%, while the exergy efficiency only at 31.3%. Saidur et al. (2007) made an energy and exergy analysis of the utility and commercial sector of Malaysia. For electrical efficiencies, although energy efficiency was found at 85.7%, the exergy efficiency was around 4.2%. The same results can be found with LNG consumption with an energy efficiency of 60 % and an exergy efficiency of 14.9%. Low exergy efficiency in the Malayan commercial sector is mainly due to the use of electricity to cover cooling demands. Kondo (2009), aiming to provide a correlation between available energy losses and current policies, estimated thermodynamic efficiency of Japan's commercial sector. Between the years 1990 and 2006, the author found that building's exergy efficiency was only 5.7%. Zhang and Chen (2010) applied a comprehensive exergy analysis to the Chinese society, where the building and the tertiary sectors (including construction) were found to be responsible of 20.4% and 9.0% of the country's total exergy consumption (94.6 EJ). The authors found an exergy conversion performance of 1.3% for households and 38.5% for the tertiary sector. In the past 20 years, several other exergy-based sectoral studies have been developed for countries such as the U.K. (Brockway et al., 2014; Gasparatos et al., 2009; Hammond and Stapleton, 2001), Italy (Wall et al., 1994), Norway (Ertesvåg, 2001), Turkey (Rosen and Dincer, 1997; Utlu and Hepbasli, 2003), China (Chen and Chen, 2006; Brockway et al., 2015), Mexico (García Kerdan, Morillón Gálvez et al., 2015), Jordan (Al-Ghandoor, 2013), U.S. (Reistad, 1980), Denmark (Bühler et al., 2016), and Canada (Rosen, 1992). Rosen (2013) described that exergetic-based sectoral analysis showed that actual efficiencies in the building sector are lower than the perceived inefficiencies commonly published in government annual reports, while in sectors such as the transportation and utility the efficiencies are higher than the perceived efficiencies.

These analyses have provided an understanding of true efficiencies and potentials for energy and resource utilisation, and valuable information that is useful to governments and policymakers. However, none of this research investigates the impact of future possible scenarios, providing just recommendations for action. One study that stands out is Motasemi et al. (2014). The authors applied an energy and exergy analysis for the Canadian transport sector covering the period 1990-2035. The study predicts future exergy performance (2013-

2035) based on previous years' data. From the outputs, the research suggests a fuel-based retrofit to improve sectoral exergy efficiency, by switching the transport sector from gasoline and diesel to natural gas. Depending on the replacement rate, results showed an improvement in exergy efficiency in the order of 0.53-3.73% compared to the baseline scenario. Such efforts should be extended to cover economic and environmental factors, increasing benefits of exergy methods to societies. For example, several authors have proposed exergy losses and irreversibilities as a basis for energy taxation (Hirs, 1993; Massardo et al., 2003; Szargut, 2002).

Despite the potential benefits of using exergy methods, the implications of exergy assessments are often ignored for the building sector. To the authors' knowledge, no bottom-up building stock models based on exergy analysis to explore future scenarios have been published so far. The main aim of this research is to develop a novel modelling framework that integrates dynamic exergy analysis into a building energy bottom-up stock model, with the capabilities to investigates future large-scale energy retrofit scenarios. The development of such framework and model could lead to the support of programmes and incentives focusing on building thermodynamic performance improvement, by providing specific subsidise, funding, and taxation relief to exergy efficient technologies. This would encourage the building industry to provide more low-carbon and exergy-efficient designs.

3. Methodology

The developed model is based on that described in García Kerdan, Morillón Gálvez et al. (2015) study, with a number modifications included in order to adapt the model to the limitations of current data available for the English and Welsh (E&W) case and to add the possibility to explore future retrofit scenarios. A preliminary model within the E&W context using steady-state exergy calculations within spreadsheets has been presented before (García Kerdan, Raslan et al., 2015). However, in this paper, the modular-based dynamic energy/exergy analysis tool was developed through embedding dynamic exergy equations in a typical open-source building simulation tool – EnergyPlus (2012). This novel dynamic modelling tool reads outputs from EnergyPlus containing key energy balance information such as energy, mass, enthalpy, and temperatures of any energy stream located in the building energy supply chain. Then with the aid of Python scripts, the exergy balance is performed (García Kerdan et al., 2017). The following section details the model presenting data sources, assumptions, modules, and subroutines used for its development.

3.1 Data sources and archetype development

According to DECC (2014) non-domestic building classification, which shows data of national energy use by building type, end uses and by fuels, eleven building types can be identified as having the most significant impact on sectoral energy use. In addition, Table 1 shows the average floor area (Bruhns, 2007), and the mean value baseline energy use (Hong and Steadman, 2013) for each of these buildings.

Table 1 E&W non-domestic building types and energy use

Building activity	**Average floor area (m²)**	**Baseline EUI (kWh/m²-year)**
Air Conditioned (A/C) Office	2,700	270
Primary and Secondary School	2,180	577
Hospital	20,000	265
Food shop (Supermarket)	6,000	159
Non-food shop (Retail store)	1,500	329
Pub and Restaurant	400	427
Hotel and Catering	4,900	251
Church	800	574
Warehouse	2,100	196
Leisure Club with pool	3,500	305
University	3,888	408

Moreover, eight main end-uses categorised by electric-based and thermal-based were identified (Table 2).

Table 2 End-uses in the E&W non-domestic sector

Electric-based	**Thermal-based**
Lighting	Catering
Internal equipment	Cooling
Motors and pumps	Domestic hot water (DHW)
Fans	Refrigeration

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. 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., 2013). In this research, several data sources were required (Pout et al., 2002; ASHRAE Standard-55, 2004; CIBSE Guide F, 2012; and CIBSE Guide A, 2015) to construct and calibrate representative building models. The calibration process within the model is explained in Appendix A.

After the building model is calibrated, and to account for national energy utilisation, an extrapolation by building type is performed.

$$E_{tot} = \sum_n [EUI_n * A_n] \quad (1)$$

where EUI is the energy use index, A is the total floor area, and *n* is the building type. The model covers an area of 665 million m^2.

3.2 Exergy analysis model

This module represents a novel approach as there is a lack of joint dynamic exergy analysis in current building energy performance simulation tools. To cover this gap, a link between EnergyPlus and a holistic building exergy method covering all end-uses (e.g. heating, cooling, electricity, DHW, catering, etc.) was implemented.

3.2.1 Thermal exergy demands

The selected thermal exergy method, which has the potential of analysing the whole building energy supply chain, is based on the model first developed by Schmidt (2004) and Torio (2012) that was further improved in the IEA ECB-Annex49 (2011). According to the authors, 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. However, the methodology was created to account for exergy use at a single building level. To account for thermal exergy within the stock, the method was simplified by reducing the energy supply chain abstraction to four subsystems (Figure 2), resulting in a framework with some similarities to the one presented by Favrat (2008): 1) Primary Energy Transformation subsystem, 2) Generation and Storage Subsystem, 3) Emission Subsystem, and 4) Envelope Subsystem.

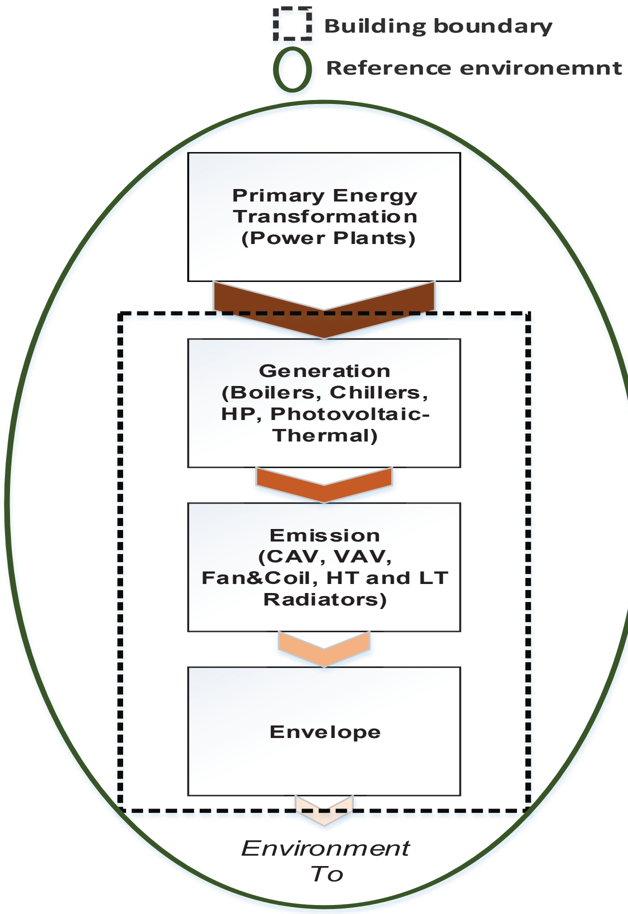

Figure 2 Exergy flow through the building energy supply chain

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.

$$Ex_{dem,HVAC}(t_k) = (1 - \frac{T_0\,(t_k)}{T_i\,(t_k)}) * Q_{HVAC}(t_k) \quad (2)$$

where $T_0\ (t_k)$ is the outdoor temperature, $T_i\ (t_k)$ the indoor temperature and $Q_{HVAC}(t_k)$ the energy use by the HVAC equipment.

In a similar manner to heating and cooling processes, exergy demand for refrigeration $Ex_{dem,ref}$, domestic hot water $Ex_{dem,DHW}$, 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 (Figure 3).

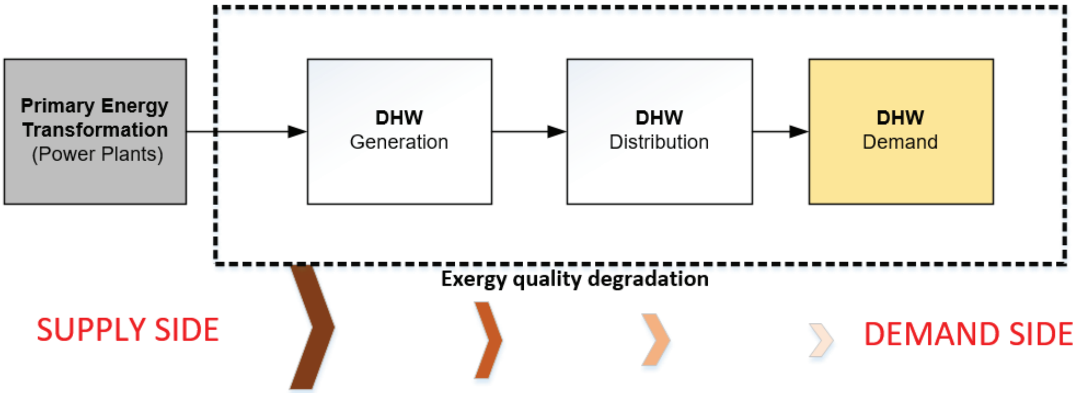

Figure 3 Energy supply chain for DHW processes

Generation and distribution is calculated similarly to the HVAC processes; however, exergy demand is calculated differently.

$$Ex_{dem,DHW}(t_k) = Q_{DHW}(t_k) * \frac{\eta_{WH}(t_k)}{q_{fuel}} * \left(1 - \left(\frac{T_0(t_k)}{T_{pWH}(t_k) - T_0(t_k)}\right) * \ln\left(\frac{T_{pWH}(t_k)}{T_0(t_k)}\right)\right) \quad (3)$$

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_{pWH} 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 $T_0(t_k)$.

$$Ex_{dem,ref}(t_k) = Q_{ref}(t_k) * COP_{ref}(t_k)\left(\frac{T_0(t_k)}{T_{p_{refr}}(t_k)} - 1\right) \quad (4)$$

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 solar-based, the following formula is used:

$$Ex_{dem,cook}(t_k) = Q_{cook}(t_k) * \frac{\eta_{cook}(t_k)}{q_{fuel}} * \left(1 - \frac{T_0\,(t_k)}{T_{p_{cook}}(t_k)}\right) \quad (5)$$

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.

3.2.2 Electric-based exergy demand

Electric based equipment, either used to support HVAC systems or other appliances are not usually regarded in building exergy assessments. However, exergy demand of 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. In buildings a wide range of equipment can be found. An abstraction of electric-based energy supply chain can be seen in Figure 4:

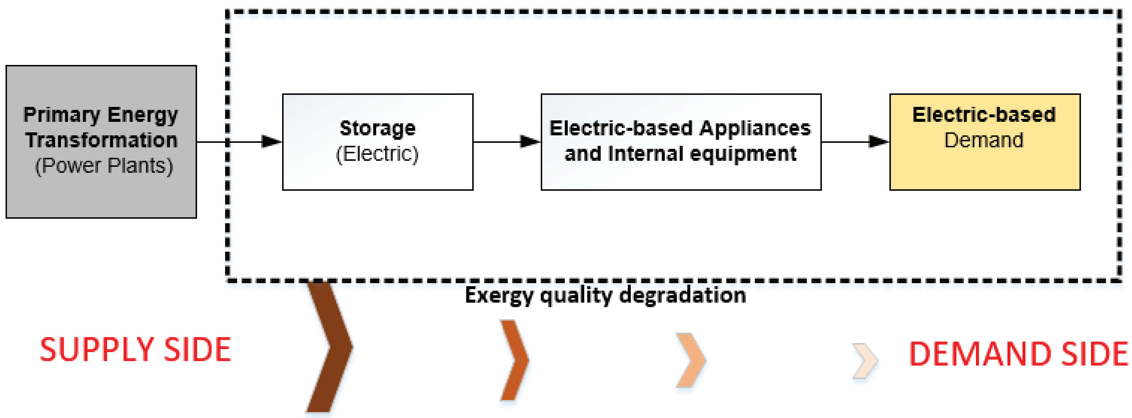

Figure 4 Energy supply chain for an electric-based process

As electricity has similar energy and exergy contents, all electric equipment such as fans, pumps, lighting, computers, and motors were considered to have the same exergy efficiency as their energy counterpart:

$$\psi_{elec} \approx \eta_{elec} \quad (6)$$

Exergy efficiency of electrical equipment shows insights into inefficiencies, providing with information to improve overall system performance. Hence, to calculate the electrical exergy demand $Ex_{dem,elec,ith}$ the following formula can be used:

$$Ex_{dem,elec,ith}(t_k) = En_{dem,elec,ith}(t_k) * F_{q,elec} \quad (7)$$

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. Table 3 presents energy and exergy efficiency values for the most common end-use equipment found in buildings.

Table 3 Exergy efficiency values for electric-based devices (Rosen and Bulucea, 2009)

Equipment	Energy Efficiency (%)	Exergy efficiency (%)
Motors	80-87	80-87
Fuel cell system	33	33
CHP	74	31
Solar photovoltaic	6-25	6-25
Solar thermal	10-30	10-30
Wind turbine	20-40	19-29
Electric battery (lead-acid)	75-85	75-85
Pumps	60-70	58-67
Fans	55-80	50-68
Resistance space heater	99	6
Lighting fluorescent and LED	20	20
Electric-based catering	85	50
Internal/office equipment	70	70

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

$$Ex_{dem,bui} = \sum Ex_{dem,end\ use,ith}$$

$$= Ex_{dem,HVAC}(t_k) + Ex_{dem,DHW}(t_k) + Ex_{dem,ref}(t_k) + Ex_{dem,cook}(t_k) + En_{dem,elec,ith}(t_k) \quad (8)$$

In this study some renewable technologies have been considered, however these require a different exergy analysis from conventional systems. Exergy analysis for renewable technologies is explained in Appendix B.

3.2.3 Primary exergy input and exergy destructions

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. 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, next equation has to be applied:

$$Ex_{prim}(t_k) = \sum_i \left(\frac{Q_{gen,i}(t_k)}{\eta_{gen,i}(t_k)} * F_{p,source,i} * F_{q,source,i}\right) + \left(Ex_{dem,elec,ith}(t_k) * F_{p,elec}\right) \quad (9)$$

where, Q_{gen} is the total energy used by the building HVAC/DHW generation systems (boiler, heat pumps, etc.), η_{gen} is the system efficiency, $F_{p,source}$ and $F_{q,source}$ is the is the UK primary energy factor (Pout, 2011) and fuel quality factor (IEA ECB-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.

Table 4 Primary energy factors and quality factors by energy sources

Energy source	Primary energy factor	Quality factor
Natural gas	1.11	0.94
Electricity (grid supplied)	2.58	1.00
District energy[1]	1.11	0.94
Oil	1.07	1.00
Biogas (Wood pellets)	1.20	1.05
Coal	1.01	1.04

[1] 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.

It is possible to distinguished many sources (e.g. electricity, natural gas, and district energy), and external supplies (gas, oil, renewables) within the proposed framework, which gives a more robust understanding of the impact of different primary energy sources used for buildings and their systems. This indicator is important as it is often used as one of the optimisation objectives when retrofitting power plants. To calculate the destructions at building level, the following formula is used:

$$Ex_{dest,bui}(t_k) = Ex_{prim}(t_k) - Ex_{dem,bui}(t_k) \quad (10)$$

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*:

$$Ex_{dest,sys\ ith}(t_k) = Ex_{in,ith}(t_k) - Ex_{out,ith}(t_k) \quad (11)$$

This is useful in locating components with higher destruction rates, and therefore considering its replacement or improvement. These indicators were later used for extrapolation to obtain the sectoral baseline exergy utilisation

3.2.4 Exergy efficiency and other indexes

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

$$\Psi_{bui}(t_k) = \frac{Ex_{dem,bui}(t_k)}{Ex_{prim}(t_k)} = 1 - \frac{Ex_{dest,bui}(t_k)}{Ex_{prim}(t_k)} \quad (12)$$

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

$$\Psi sim_{sys,ith}(t_k) = \frac{Ex_{out,ith}(t_k)}{Ex_{in,ith}(t_k)} \quad (13)$$

$$\Psi rat_{sys,th}(t_k) = \frac{Ex_{dest,out,ith}\,(t_k)}{Ex_{in,ith}(t_k)} \tag{14}$$

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 ECB-Annex 49, 2011). In this research, we used the rational exergy efficiency. The integration of the presented exergy analysis into the stock model is explained In Appendix C.

3.3 Simulation process

As shown throughout the last sections and Appendices A-C, the model relies on a composition of several modules; therefore, to automate the whole process, soft-linking of different software environments was necessary. After individual building models are constructed with its corresponding retrofit measures including its physical and technical characteristics, the post-retrofit performance and prediction is performed. Once energy and exergy outputs are defined for each subsystem, the annual inefficiency of the building and the building system components can be calculated with its correspondent errors range. Then to build the necessary database, these outputs are exported to the stock model module that has embedded demolition and construction rates, retrofit deployment rates, emission factors, etc. The data is then extrapolated depending on the total surface share by building type and is then used to populate the future scenarios module. Figure 6 shows the simulation process of the model.

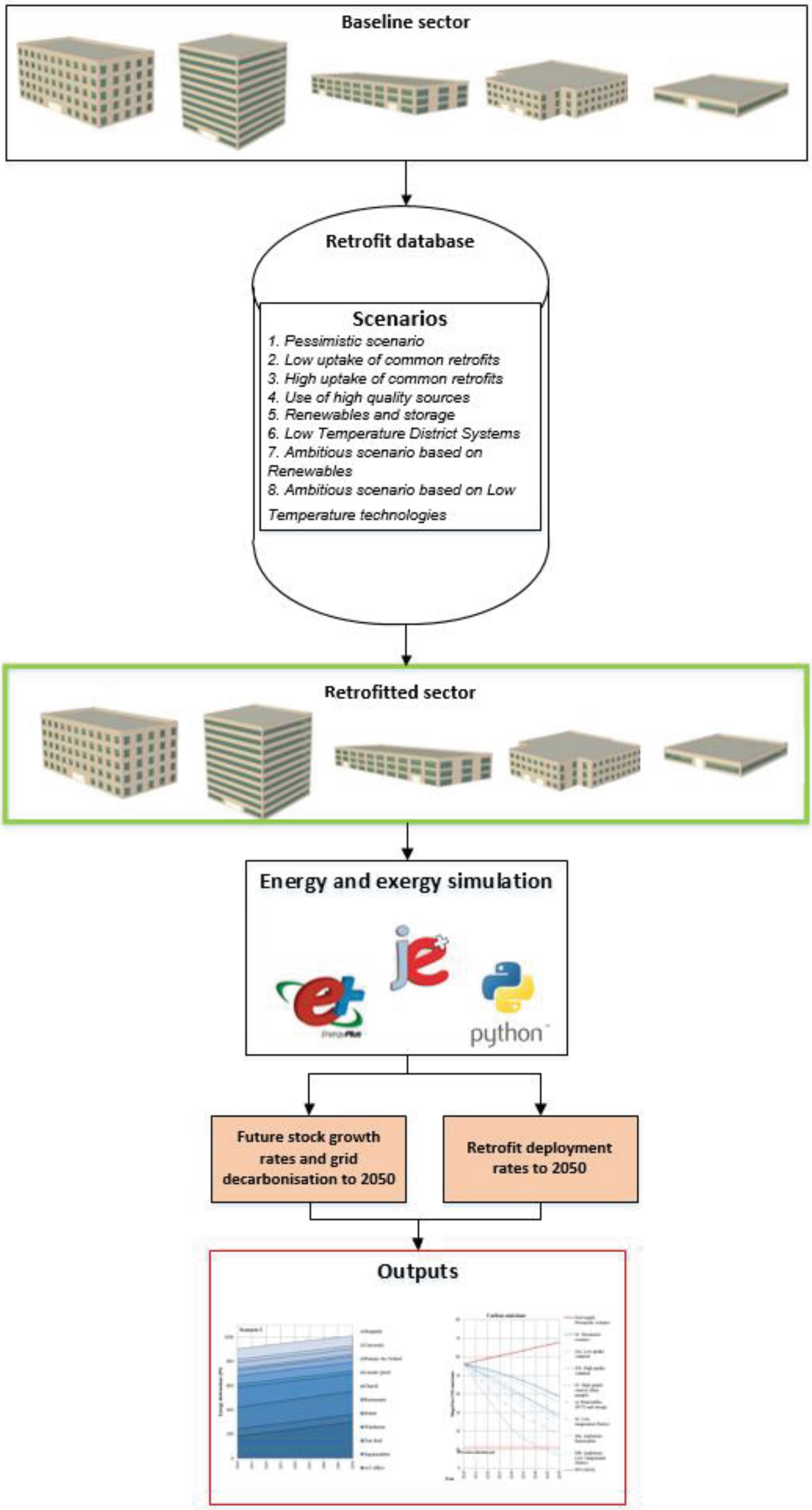

Figure 5 Simulation process of the propsed exergy stock model

4. Case study

4.1 Retrofit future scenarios

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). For this specific research, several scenarios based on the authors engineering judgement were designed. The scenarios included several low-carbon and low-exergy technologies as well as future information on construction and demolition rates as well as future energy emissions factors. Based on current building policies, codes, and academic research, seven main different retrofit scenarios were developed:

- ***Scenario 1: Pessimistic scenario***

No retrofit measures are considered. Therefore, sector's carbon emissions reductions are only achieved through decarbonisation of the power sector by assuming an increase of renewable and nuclear energy the into the energy supply matrix.

- ***Scenario 2a: Low uptake of common retrofits***

Low deployment of typical retrofit measures. Buildings going through a refurbishment process have to comply with minimum U-values for the building's envelope and minimum efficiency for the HVAC systems (Part L2B). HVAC systems are based on condensing boilers and high efficient chillers working with high temperature heating (60 °C) and low temperature cooling (12°C).

- ***Scenario 2b: High uptake of common retrofits***

This is similar to scenario 2a but includes a wider deployment of retrofit measures.

- ***Scenario 3: Air Source Heat Pumps***

The scenario is based on a wide installation of air source heat pumps (ASHP) with a nominal COP of 3.6, working at temperatures of 14 °C for cooling and 48 °C for heating. HP requires use of high-quality sources, such as electricity, to lift (or drop) temperatures from environmental sources.

- ***Scenario 4: Renewables, storage and GSHPs***

This scenario considers the installation of photovoltaic thermal hybrid solar collectors (PV/T systems) to supply on-site electricity, hot air and hot water. In this scenario, surplus electricity not needed to cover non-HVAC electric equipment is then used to run a ground source heat pumps (GSHP). In addition, on-site electric storage devices and hot water tanks are modelled.

- ***Scenario 5: Low Temperature District Systems***

The scenario considers low temperature district heating/cooling systems assuming that the energy is produced by a single-effect indirect-fired absorption chiller with a COP of 0.7. The working supply/return temperatures are assumed to work at 16/20 °C for cooling and 40/30 °C for heating.

- ***Scenario 6: micro Combined Heat and Power (mCHP)***

This scenario considers the installation of gas fuelled Stirling engine micro CHP systems providing heat and electricity in-site. The scenario also considers a natural gas boiler if the mCHP is incapable of covering the heat and DHW demand.

Scenario 7a: Ambitious scenario based on Renewables and GSHPs

This scenario is a combination of Scenario 2b and Scenario 4. It considers systems based of PV/T – GSHP systems and on-site storage connected to buildings with high insulation levels.

- ***Scenario 7b: Ambitious scenario based on Low Temperature technologies***

This is similar to Scenario 7a but includes low temperature district systems instead of PV/T systems.

- ***Scenario 7c: Ambitious scenario based on mCHP***

This is similar to Scenario 7a but includes a gas fuelled micro CHP and a natural gas condensing boiler.

4.2 The future growth of the non-domestic building stock and grid decarbonisation

To further reduce uncertainty in the results, construction and demolition rates in the E&W non-domestic building stock were also considered. These were taken from a recently published study by ARUP (2013) (Figure 6). The report suggests that by 2050 the E&W stock will grow from 665 million m² to 870 million m², where 80% of current buildings will still be in use (representing 62% of the future stock).

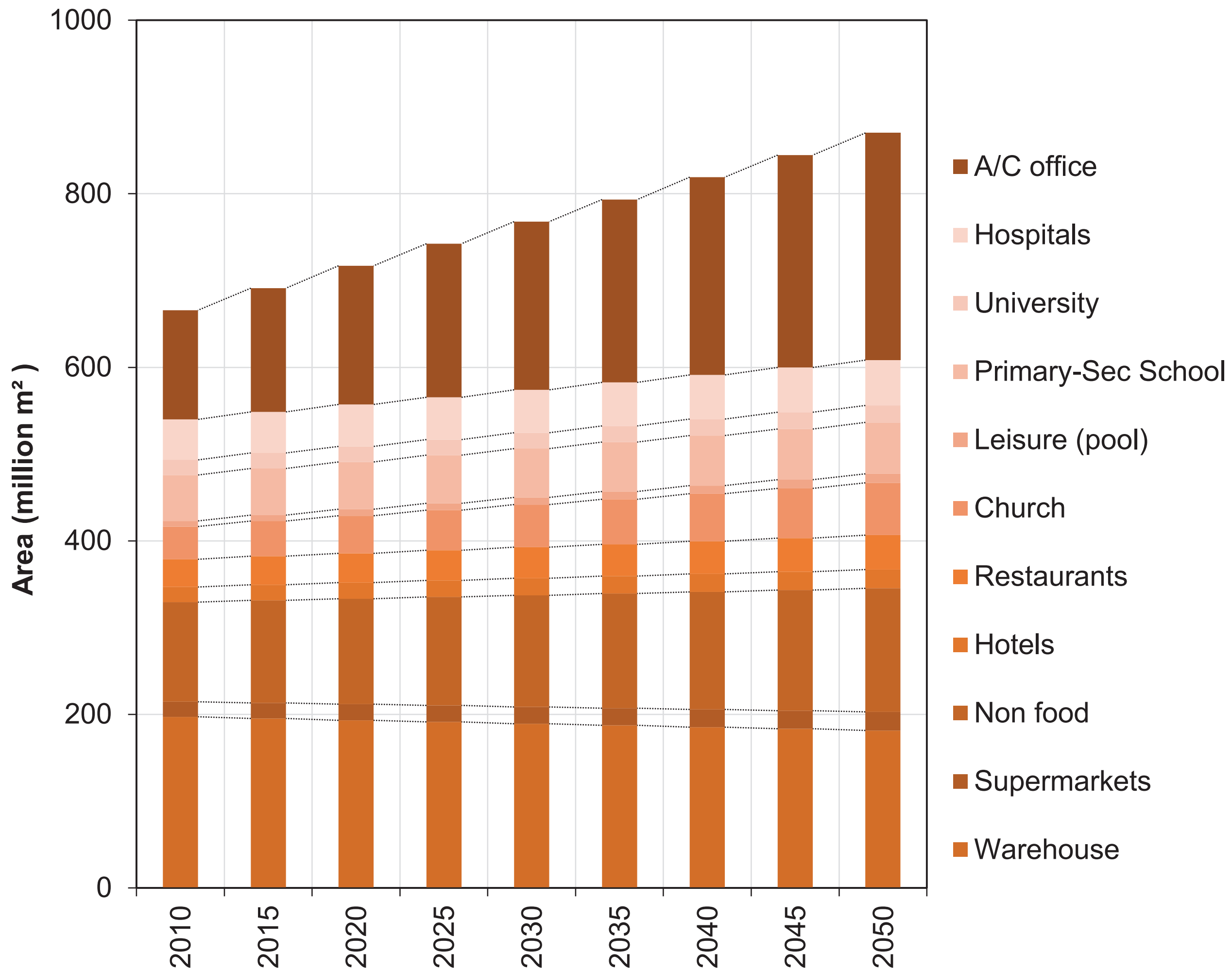

Figure 6 Total growth projection of the E&W sector (Label positioning as stacked in the bar chart)

Meanwhile, the future carbon emission factors used in the model are shown in Table 5.

Table 5 Future carbon emission factors considered

Year	Electricity ($kgCO_2/kWh$)	Gas ($kgCO_2/kWh$)	District Energy ($kgCO_2/kWh$)
2010	0.502	0.202	0.184
2015	0.464	0.202	0.184
2020	0.427	0.202	0.184
2025	0.389	0.202	0.184

2030	0.351	0.202	0.184
2035	0.314	0.202	0.184
2040	0.276	0.202	0.184
2045	0.238	0.202	0.184
2050	0.200	0.202	0.184

4.3 Uncertainties and model limitations

Due to scarce available data and inherent limitations in the modelling process, outputs are exposed to some degree of uncertainty. The error range that will be presented throughout the paper's outputs are mainly due to uncertainties in input data into the model. Values regarding to the envelope characteristics (e.g. thermal conductivity, thickness, U-values) and occupancy behaviour are highly uncertain. Additionally, information on the technical characteristics on building systems is scarce as several assumptions has to be made. Other information that is limited is the fuel share along the sector. Although DECC provides important information, some subsectors lack detailed information. Additionally, only the London-Gatwick weather file (.epw) is used as reference environment. As with the differences in exergy analysis encountered in power plants or chemical processes, the selection of the reference environment in buildings is of vital importance because buildings work to the temperatures tht are very close to the environment temperatures.

5. Results and Discussion

5.1 Energy baseline (2010)

Considering primary energy, in 2010 an input of 1035 ±32 PJ of energy was calculated. Carbon emissions were found to be in the range of 56.2 ±1.7 MTon CO_2 per year. On the other hand, the sectoral final energy use was found at 622 ± 22 PJ (resulting in a mean sectoral energy efficiency of 60.1%). Statistics from DECC suggest an actual energy demand of 620.9 PJ. This value is obtained by removing statistics on subsectors that were not modelled (e.g. “Industry” and “Transport and Government”). Therefore, the modelling outputs results in a prediction error of 0.3 ± 3.5%.

In the model, the top five consumers are: A/C Offices, Retails, Warehouses, Hospitals, and Restaurants and Pubs, representing 74% of the total sector energy use. Figure 7 illustrates the mean values of total energy use by building type and end use.

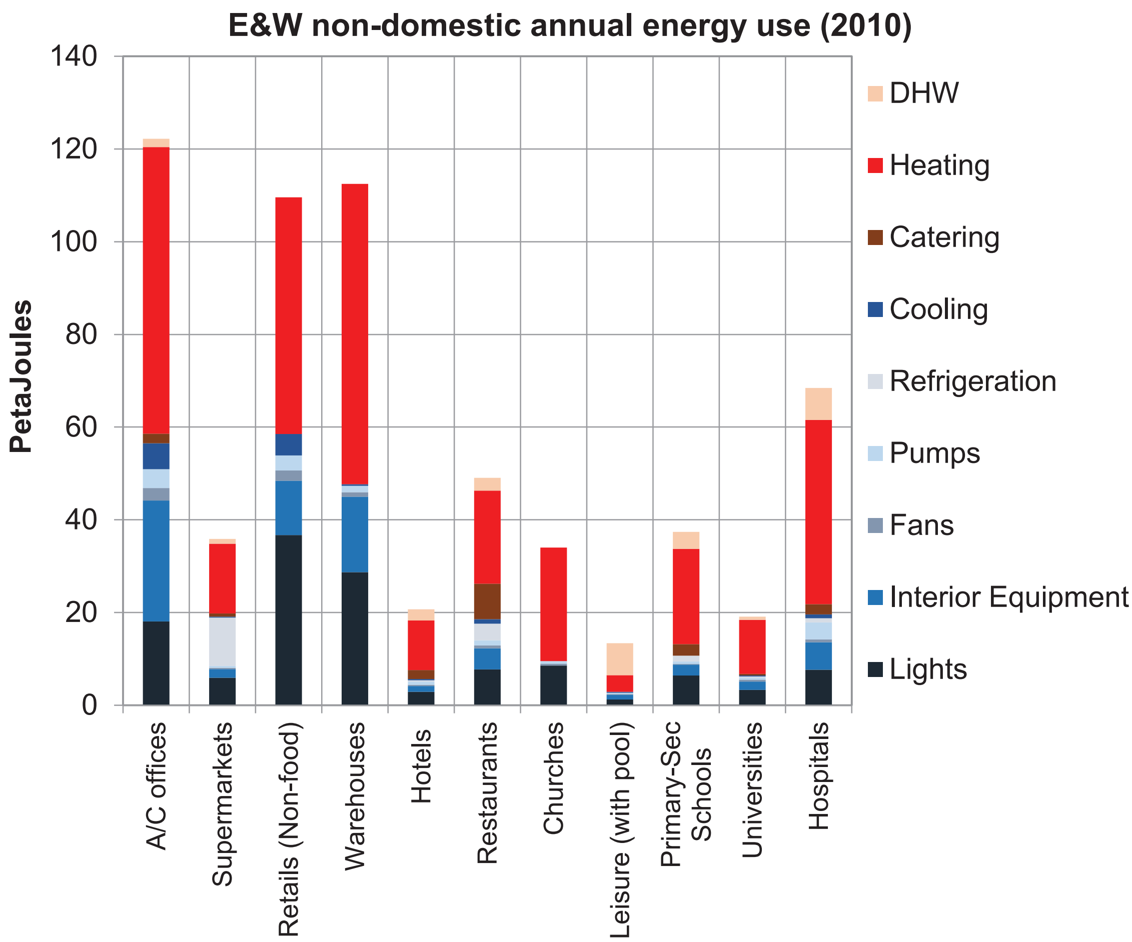

Figure 7 Mean baseline total energy utlisation by building and end uses

5.2 Exergy baseline (2010)

Considering the exergy analysis outputs, the primary exergy input was found at 1012.4 ±35.6 PJ, with an annual exergy input at building level at 600.4 ±21.3 PJ. The annual exergy destructions were calculated at 491.9 ±17.5 PJ, thus representing a baseline exergy efficiency at building level of 18.06 ±5.15%. However, if the exergy content of the primary energy fuels is considered, this results in a total exergy efficiency of the sector of 10.71 ± 4.06%. This result is similar to the data provided by Gasparatos et al. (2009), who calculate a sectoral efficeicny of 12.3%.

By building type, A/C offices, Retails, and Warehouses represent 58.2% of the national total exergy destructions (526.0 ±16.5 PJ). The sector exergy flows through the whole energy supply chain is illustrated in Figure 8. Building types are ranked by total primary exergy input.

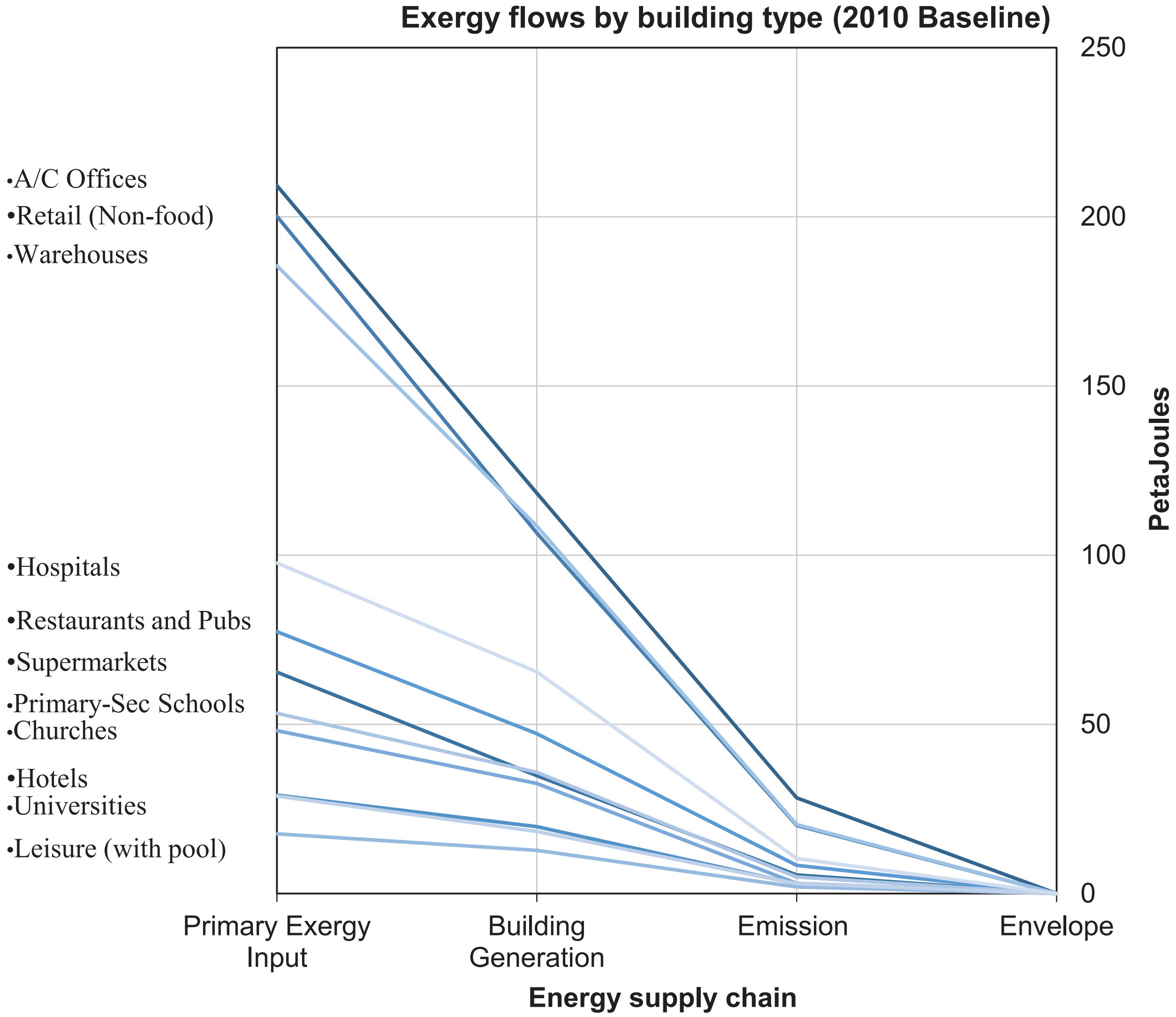

Figure 8 Mean sectoral exergy flows for the English and Welsh non-domestic sector

However total destructions are highly related to total floor area. To understand the thermodynamic performance for each building type, an individual analysis has to be done. The results show that by building type, A/C Offices present the best thermodynamic behaviour, with an exergy efficiency of 13.5%, while the lowest are found in Supermarkets (Ψ=8.4) and Churches (Ψ=6.2).

5.2.1 Comparison with other studies

The baseline indicators obtained were compared against other similar studies. A similar comparison can already be found in García Kerdan, Morillón Gálvez et al. (2015). Table 6 shows a comaprison among regions. Altough studies difer in methodological approaches, outputs suggest that Asian countries tend to have lower thermodynamic efficiency in the building sector. Specially, this can be observed in the south-east region. This poor perfromance could be due a combination of modern architecture (e.g glass buildings) in hot and humid climates, where the use of air-conditioning is necessary to provide comfortable conditions and represnts one of the major energy end-uses. In thermodynamic terms, an artifical cooling process is intrinscally low exergy efficient due to the use of electricity to run compressors in refrigeation systems. In this case, large irreversibilities could be reduced by the application of natural ventilation and other passive systems. A similar phenomenon occurs in Brazil and some areas of Mexico. For the European and North American countries, largest irreversibility rates arise from the utilisation of fossil fuels to cover space heating and DHW demands, where the high detsructions are located in combustion processes by burning oil, gas and biomass. Optimisation of building envelope combined with a large scale implementation of district systems, GSHP, and CHP systems hold great potential for thermodynmamic improvement in countries with high heating demands.

Table 6 Building sector exergy efficiency of different countries

Region	Country	Exergy	Year	Study
Europe	United Kingdom	10.7 ± 4.1	2016	
	United Kingdom	12.3	2004	Gasparatos et al. (2009)
	Sweden	13.0	1994	Ertesvåg (2001)
	Norway	11.0	1995	Ertesvåg (2001)
Asia	Japan	5.8	2009	Kondo (2009)
	Singapore	3.4	1999	Saidur et al. (2007)
	Thailand	7.5	1999	
	Indonesia	4.8	1999	
	Malaysia	4.3	1999	
	Saudi Arabia	8.1	2001	Dincer et al. (2004)
Americas	Mexico	19.7	2014	García Kerdan et al. (2015)
	Brazil	12.0	1987	Ertesvåg (2001)
	Canada	14.0	1986	Rosen (2013)
	USA	14.0	1970	Reistad Gordon (1980)

5.3 Future energy and exergy scenarios (2050)

Figure 9 presents the mean values for the sector's energy utilisation forecast under the different designed retrofit scenarios. Results show that by 2050, the pessimistic scenario (S1) will cause an increase in annual energy use of 10.60 ±6.00 %, mainly due to the increment of floor area within the sector. However, this is considered that all new buildings are being constructed under current (2015) regulations; however, it is expected that these regulations will be tightened and thus provide building designs with better energy performance. On the other hand, scenario 7a, based on an ambitious smart use of renewables and high envelope quality, represents an energy reduction of 80.89 ±6.49% by 2050. The second best is Scenario 4 with reductions of 47.06 ±6.97%, followed by scenario 7c (ambitious micro-CHP) with reductions of 34.34 ±7.16%. However, these scenarios will almost certainly require high capital expenditure with poor return on investment (although this mainly depends on factors such as technology prices and energy source costs). Although not simulated, Scenario 5 and 7b (District Systems) have the potential to reduce energy use even further if system designs based on waste-heat sources are considered.

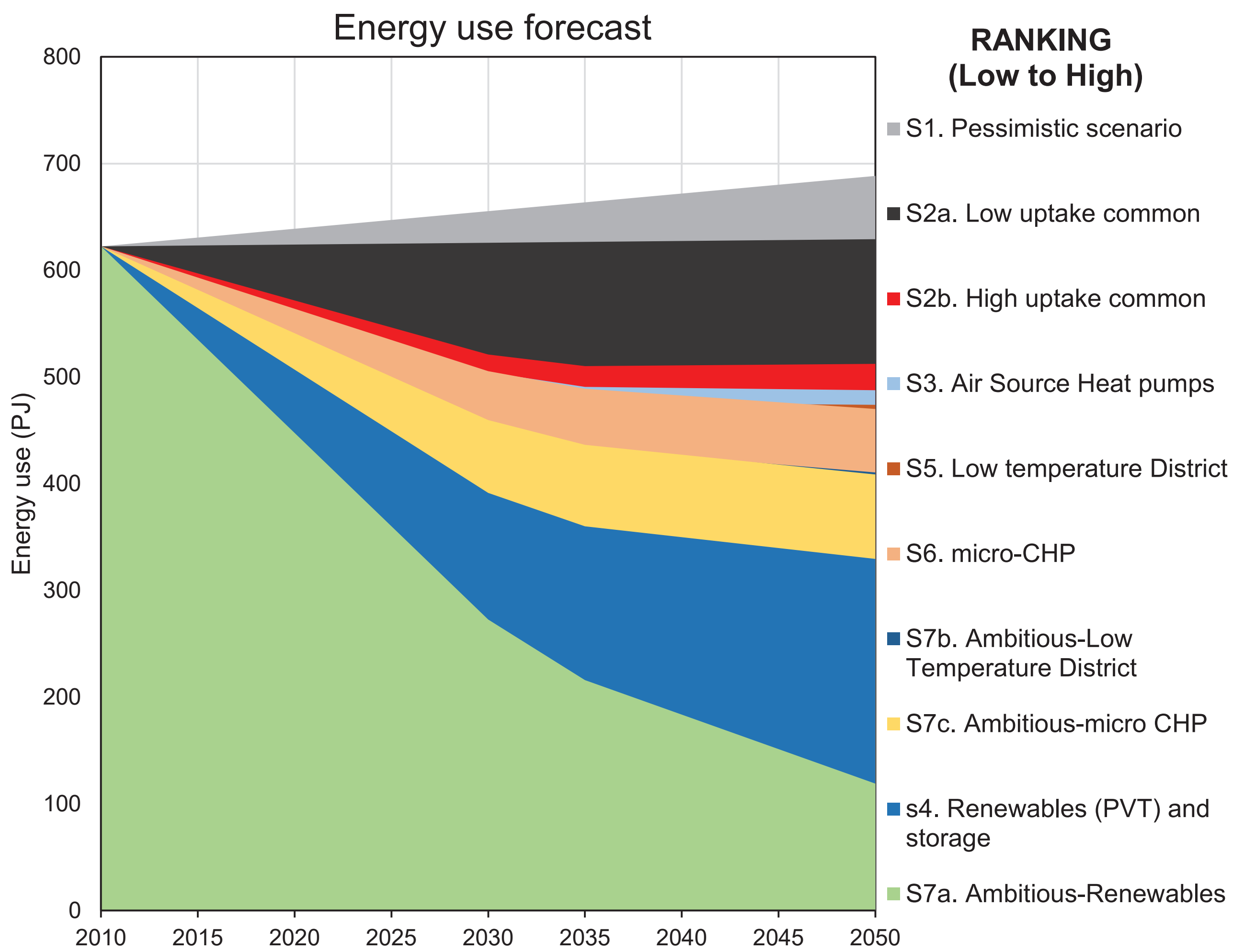

Figure 9 Sectoral energy use and impact of different large-scale energy retrofit scenarios (mean values)

Table 7 shows he national exergy destructions under each scenario. In this case, it can be noticed that unlike the energy savings forecast, thermodynamic improvements from some considered 'efficient' scenarios did not significantly reduce irreversibilities as expected. This is more noticeable for Scenario 2a and 3, where results show that by 2050 an increase in sectoral exergy destructions of 5.26 ±3.79% and 3.66 ±3.73% respectively, is expected. The former is due to high utilisation of conventional energy conversion systems based on gas boilers, where large irreversibilities are found in the combustion processes (generation subsystem) and high temperature drop within the distribution-emission subsystems. The high irreversibilities of Scenario 3 is due to buildings poor fabric conditions resulting in high demand rates of electricity for the air source heat pump compressors. On the other hand, all three ambitious scenarios based on a combination of good envelope thermal quality and low-exergy systems could minimise destructions above 25%, being renewable-based technologies and micro CHP with the most potential. Specially, the ambitious case of micro-CHP (S7c) has the potential to reduce baseline year irreversibilities to up to 35.23 ±2.36%.

Table 7 Sectoral exergy destructions and mean exergy efficiencies (italic) under different large-scale retrofit scenarios

Scenarios	2010	2015	2020	2025	2030	2035	2040	2045	2050	Irreversibilities improvement
S1. Pessimistic scenario	904 ±32	917 ±32	931 ±33	944 ±33	957 ±33	971 ±34	984 ±34	997 ±34	1011 ±35	-11.80 ±4.08%
	10.7%	*11.0%*	*11.2%*	*11.4%*	*11.6%*	*11.8%*	*12.0%*	*12.2%*	*12.4%*	
S2a. Low uptake of common retrofits	904 ±32	910 ±32	916 ±32	922 ±32	928 ±32	934 ±32	940 ±32	946 ±33	951 ±33	-5.26 ±3.79%
	10.7%	*11.0%*	*11.3%*	*11.5%*	*11.8%*	*12.1%*	*12.3%*	*12.6%*	*12.8%*	
S2b. High uptake of common retrofits	904 ±32	884 ±31	864 ±30	844 ±29	824 ±29	819 ±28	825 ±28	831 ±29	837 ±29	7.36 ±4.02%
	10.7%	*11.2%*	*11.6%*	*12.1%*	*12.6%*	*13.0%*	*13.2%*	*13.5%*	*13.8%*	
S3. Air Source Heat Pumps	904 ±32	902 ±32	901 ±32	899 ±31	897 ±31	903 ±32	914 ±32	926 ±32	937 ±32	-3.66 ±3.73%
	10.7%	*10.9%*	*11.2%*	*11.4%*	*11.6%*	*11.8%*	*12.0%*	*12.2%*	*12.4%*	
S4. Renewables (PVT) and storage	904 ±32	860 ±30	817 ±29	773 ±27	730 ±26	708 ±25	704 ±25	700 ±24	695 ±24	23.06 ±3.06%
	10.7%	*11.9%*	*13.1%*	*14.4%*	*15.9%*	*16.9%*	*17.4%*	*18.0%*	*18.6%*	
S5. Low temperature District Systems	904 ±32	873 ±31	843 ±29	812 ±28	782 ±27	770 ±27	772 ±27	774 ±27	776 ±27	14.20 ±2.97%
	10.7%	*11.2%*	*11.8%*	*12.3%*	*12.9%*	*13.4%*	*13.7%*	*14.0%*	*14.3%*	
S6. micro-CHP	904 ±32	860 ±30	817 ±29	774 ±27	730 ±26	706 ±25	697 ±24	687 ±24	678 ±24	24.97±2.74%
	10.7%	11.4%	12.2%	13.0%	13.9%	14.6%	15.2%	15.7%	16.3%	
S7a. Ambitious-Renewables	904 ±32	854 ±30	803 ±28	753 ±27	703 ±25	676 ±24	669 ±23	662 ±23	655 ±23	27.59±2.67%
	10.7%	*11.9%*	*13.3%*	*14.8%*	*16.4%*	*17.6%*	*18.3%*	*19.1%*	*19.8%*	
S7b. Ambitious-Low Temperature District	904 ±32	860 ±30	815 ±29	771 ±27	727 ±25	701 ±24	691 ±24	680 ±24	670 ±23	25.90±2.69%
	10.7%	*11.3%*	*12.0%*	*12.7%*	*13.5%*	*14.1%*	*14.6%*	*15.2%*	*15.7%*	
S7c. Ambitious-micro CHP	904	843 ±30	782 ±28	721 ±26	660 ±23	626 ±22	612 ±22	599 ±21	585 ±21	35.23±2.36%
	10.7%	*11.8%*	*13.0%*	*14.4%*	*16.0%*	*17.2%*	*18.0%*	*18.8%*	*19.7%*	

If no retrofit measures are delivered for existing buildings (S1), it is expected exergy destructions to increase 11.80 ±4.08% by 2050. Nevertheless, exergy efficiency will still rise from an average of 10.7% to 12.4%, mainly due to the efficiency improvement of power generation plants. Figure 10 show a detailed analysis (differentiated by building type) of the sector behaviour under this scenario.

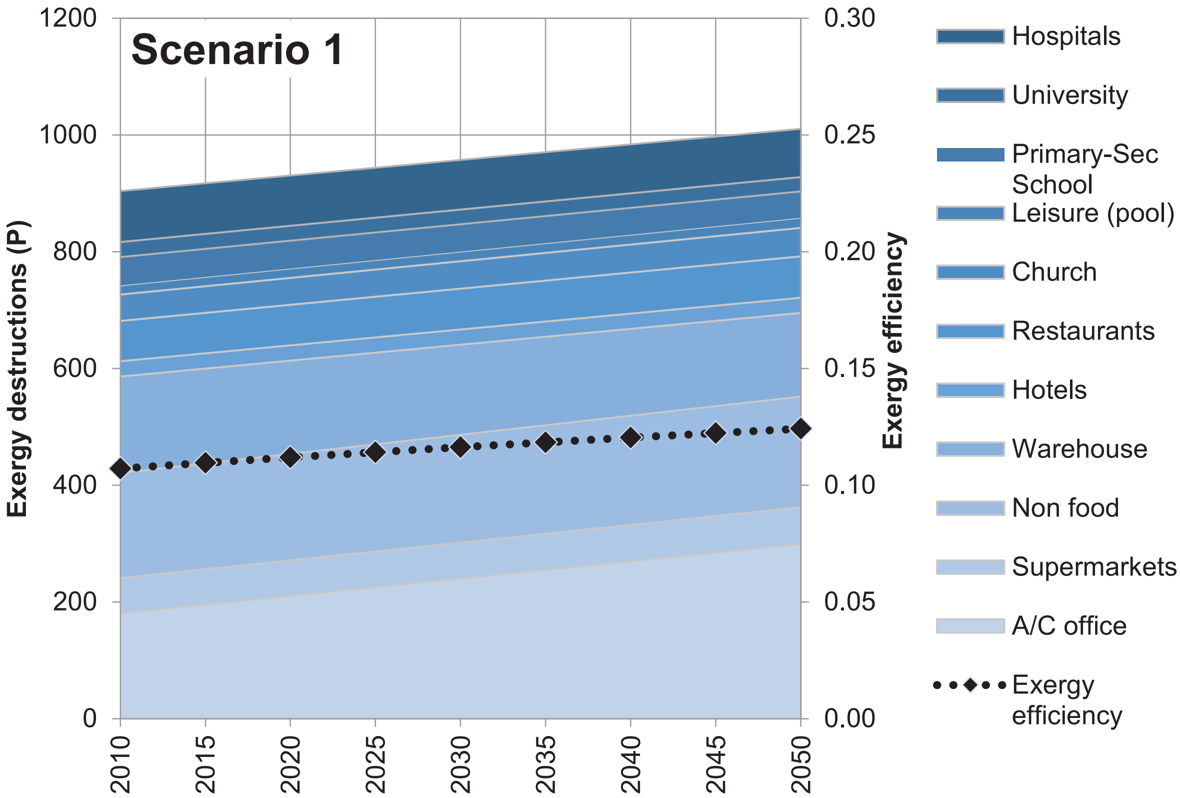

Figure 10 Cumulative mean exergy destructions by building type of Scenario 1: Pessimistic (no retrofits)

Scenario 7a presents a decrease of 27.59±2.67% of exergy destructions by 2050, thanks to an exergy efficiency improvement of almost double, from an average of 10.7% to 19.8% (Figure 11). This higher exergy efficiency is achieved thanks to quality a match between the supply and demand, where renewable electricity is rationally used, by directing it to drive heat pumps equipment.

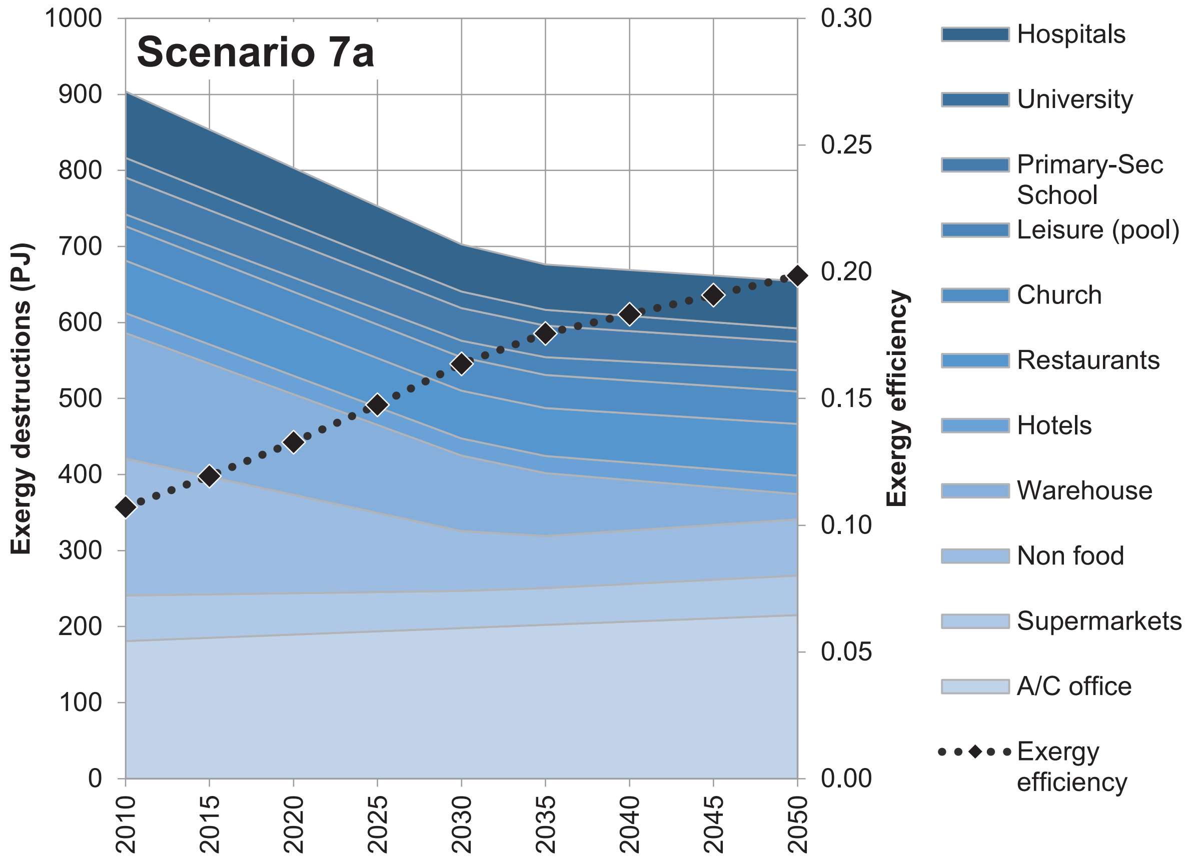

Figure 11 Cumulative mean exergy destructions by building type of Scenario 7a: Ambitious Renewables

Scenario 7c presents a decrease of 35.23±2.36% of exergy destructions by 2050. Similar to scenario 7a, sectoral exergy efficiency improve potential is from 10.7% to 19.7% (Figure 12). If sized correctly, CHP are high efficient systems capable to deliver a combined production of low-carbon heat and electricity at cheaper prices compared to conventional grid supply (Campos-Celador et al., 2012).

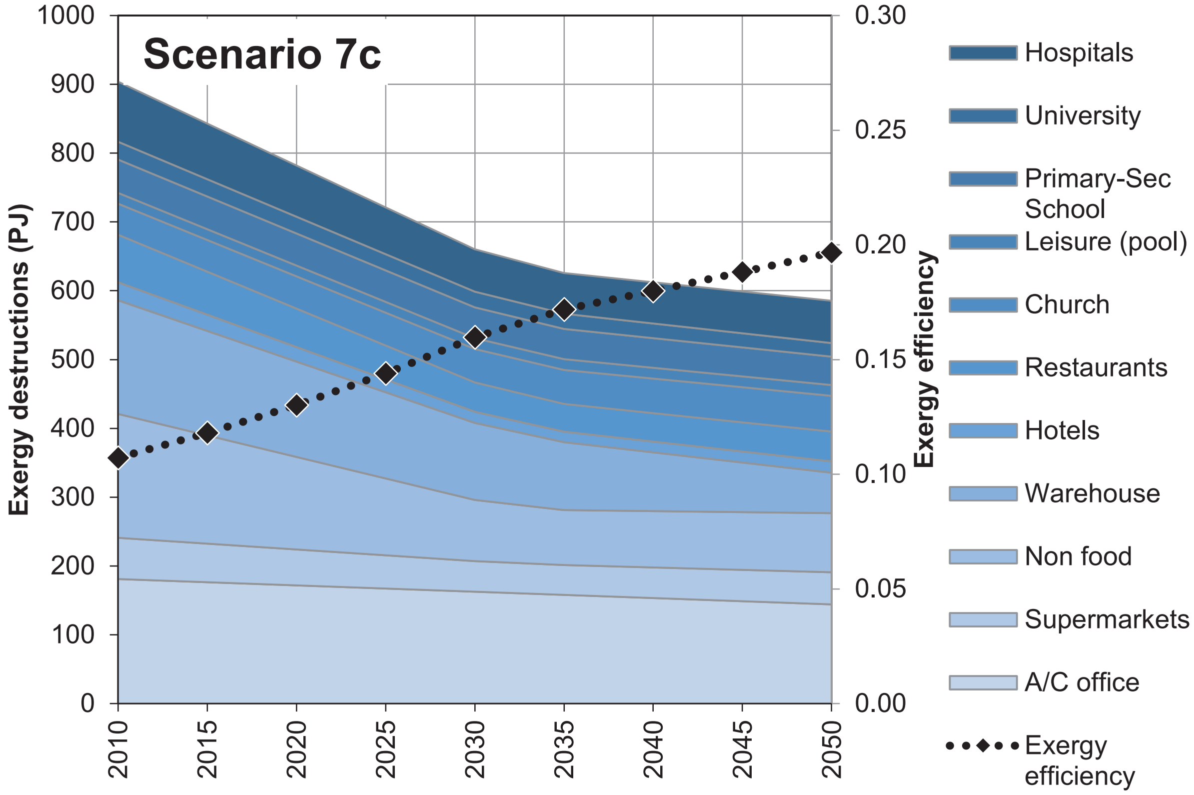

Figure 12 Cumulative mean exergy destructions by building type of Scenario 7c: Ambitious micro CHP

5.4 Future carbon emissions scenarios (2050)

Finally, Figure 13 shows the carbon emission pathway for all seven scenarios. An extra scenario has been added to represent what would happen if the carbon emission factor for electricity remains constant for the next 35 years (‘*Grid supply pessimistic scenario*’). In this unlikely scenario where no building retrofit measures are considered and where the energy matrix remains constant, results show a dramatic increase in carbon emissions from 56.2 ±1.7 to 67.9 ±3.5 MTon CO_2/year, representing an increase of 20.8 ±5.1 %. The results also show that scenario S1 achieves reductions of 31.5 ±2.5% solely based on the decarbonisation of the electricity grid (considering the factors from Table 5). If the current common approach of insulation-oriented retrofit is undertaken at a fast rate (S2b), emissions could be reduced to 28.6 ±1.6 MTon CO_2/year (49.0 ±2.9%). Although this scenario doesn’t represent a terrible outcome, modelling results suggest that if the typical approach is keep being considered, even under extreme installation rates, outputs will fell short compared to the 80% target imposed by the government. In this context, it was expected that Scenario 7b and 7c, would reach carbon emission reduction targets by 2050; however, model outputs show that it only reduced emissions by 59.8 ±2.2% and 56.3 ±2.3% respectively, due to a continuous demand for natural gas. Although gas is considered to have less environmental impact than other fossil fuels such as oil and coal, is still regarded as a transitional fuel to reach emissions reductions. As shown, just one of the scenarios developed in this research was able to achieve the carbon emissions reduction target set by the UK government. According to the model, it is expected that by 2043 ±3 years, a scenario such as Scenario 7a (renewable generation, low exergy system and good quality envelope) will achieve a sector decarbonisation of 80%, and by 2050 it will reach up to 88 ±2.4% (6.6 ±1.3 MTon CO_2/year).

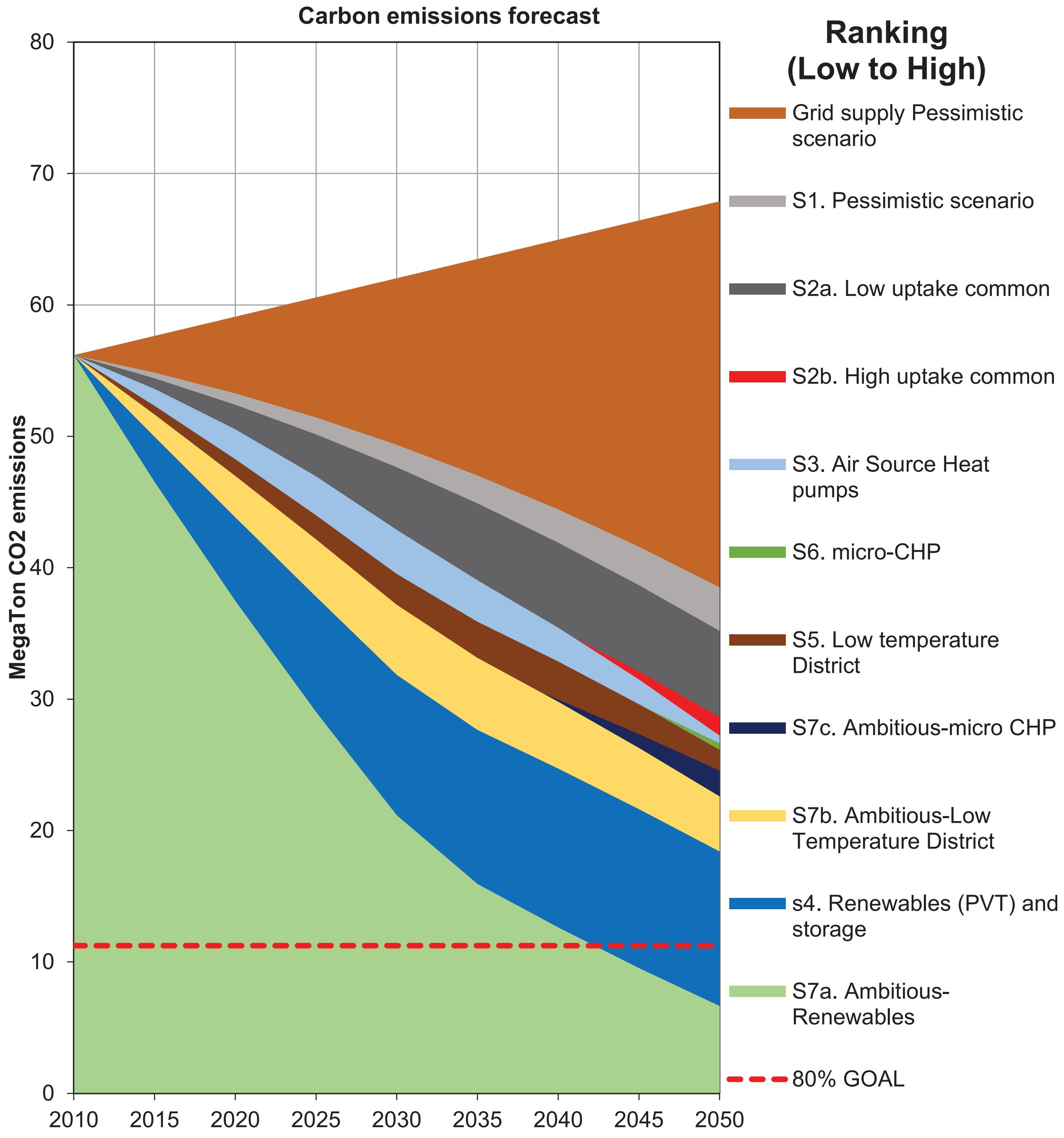

Figure 13 Sectoral carbon emissions (mean values) and impact of different large-scale energy retrofit scenarios

Although initial results suggest that both approaches (energy and exergy) could be related, the inclusion of exergy as objective functions into the modelling procedure has resulted in retrofit scenarios with better overall performance and optimised strategies. As shown in the results, some technologies that are traditionally considered 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 and carbon emissions due the high electricity demand. Therefore, decarbonisation of these scenarios highly depends on the supply side. Nevertheless, in an ideal thermodynamic scenario, the retrofit scenarios would be based on either a high efficient low temperature lifting heat pumps or on a waste-heat or low-carbon-based district system network based on CHP systems, with medium levels of envelope's thermal insulation combined with an energy matrix composed mostly by low carbon energy generation technologies. However, to achieve more detailed results, optimisation procedures are required.

6. Conclusion and Policy Implications

In addition to the development of energy and exergy data of the E&W non-domestic sector, the application of an exergy-based stock model to explore thermodynamic improvements at a sectoral level was demonstrated. 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. In addition, exergy analysis has the potential to provide a significant complementary perspective to typical energy analysis and can therefore provide a powerful tool to support building energy policy making. Reducing exergy destructions or irreversibilities 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. When exergy analysis differentiates between fossil and renewable destructions, it allows better building systems designs and the utilisation of more efficient energy conversion technologies.

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 a decrease in primary energy consumption and reduction of carbon emissions in existing buildings. The outputs of this study show the potential of the proposed model in locating these inefficiencies and unlocking unconventional strategies for the sector's thermodynamic improvement. Results also show that by following exergy indicators, scenarios with better thermodynamic performance also were able to provide significant reduction of carbon emissions. Exergy analysis provide a means to optimise renewable generation, low-exergy and high-quality envelope systems. The study shows that the E&W non-domestic sector has a potential to reduce the exergy destructions footprint by almost a third while achieving reductions in carbon emissions up to 88.2 ±2.4% compared to baseline values.

Although not treated in this research, from an economic perspective, low exergy sources such as waste heat, may be cheaper than high exergy sources such gas or electricity; however, the current high capital costs that is associated with technologies that are able to use low exergy sources (e.g. a heat pump and floor heating system) prevents a more wide-spread installation. As market penetration of a particular technology is based on current policies, an exergy-based policy may also promote a price reduction in PV and battery technologies, but only if the systems design is appropriate, meaning that the electricity produced is only used to cover a high-exergy demand (such as lighting, appliances and cooking), and is never used to cover low-exergy demands such as space conditioning and DHW. Another possibility is to use the generated electricity for a district-scale heat pump system (research has shown good energetic and exergetic efficiencies on large-scale ground based heat pumps), to provide a low-exergy product at much lower energy and economic expenditure.

From a policy perspective, a well-grounded energy/exergy policy could speed up the development towards a more sustainable society by ensuring the exergy of the sources, rather than focus only on the energy use. The introduction of a tax based on exergy may provide a valid measure to improve energy systems in buildings where it can be used as a tool to identify and "penalize" inefficient systems with big exergy destructions. However, the scenarios presented in this study are just a limited configuration of possible designs. In the future, as economic appraisal is going to be included, comprehensive scenarios that are energy/exergy efficient and cost-efficient has to be designed. IT is considered the inclusion of exergy analysis for energy storage systems.

Acknowledgments

The first author acknowledges support from The Mexican National Council for Science and Technology (CONACyT) through a scholarship to pursue doctoral studies with a CVU: 331698 and grant number: 217593.

Nomenclature

A	area (m^2)

COP	coefficient of performance (W/W)
c_{Pheat}	specific heat capacity (J/K)
En	energy (kWh)
EUI	energy use index (kWh/m²-year)
Ex	exergy (kWh)
$\dot{Ex}_D$	exergy destructions (kWh)
Ex_{dem}	exergy demand (kWh)
Ex_{prim}	primary exergy (kWh)
Ex_{sun}	solar exergy (kWh)
F_p	primary energy factor (-)
F_q	quality factor (-)
G	incident solar radiation, (W/m²)
m	mass flow rate (kg/s)
T	temperature (K)
T_0	reference temperature (K)
T_i	room temperature (K)
W	Work (kWh)
Greek symbols	
η	energy efficiency (-)
ψ	exergy efficiency (-)
Subscripts and superscripts	
col	collector
cook	cooking
dem	demand
DHW	domestic hot water
elec	electricity
gen	generation system
HVAC	heating, ventilation, and air conditioning
HP	heat pump
i	i zone, equipment or energy source
prim	primary energy
PV	photovoltaic
ref	refrigeration
sun	sun
t_k	time step
therm	thermal demand

Appendices

Appendix A. Calibration process in the model

The tool is based on ExRET-Opt simulation tool (García Kerdan et al., 2017). The dynamic simulation tool has embedded a calibration where a three software process is necessary. Apart from EnergyPlus, both SimLab 2.2 (SimLab, 2011) and jEPlus 1.6.0 (jEPlus_1.6, 2016) are required. 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. Therefore, by coupling these three software, the calibration modelling process is comprised of four steps (Figure A.1):

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)

D. model selection based on ASHRAE 14-2002

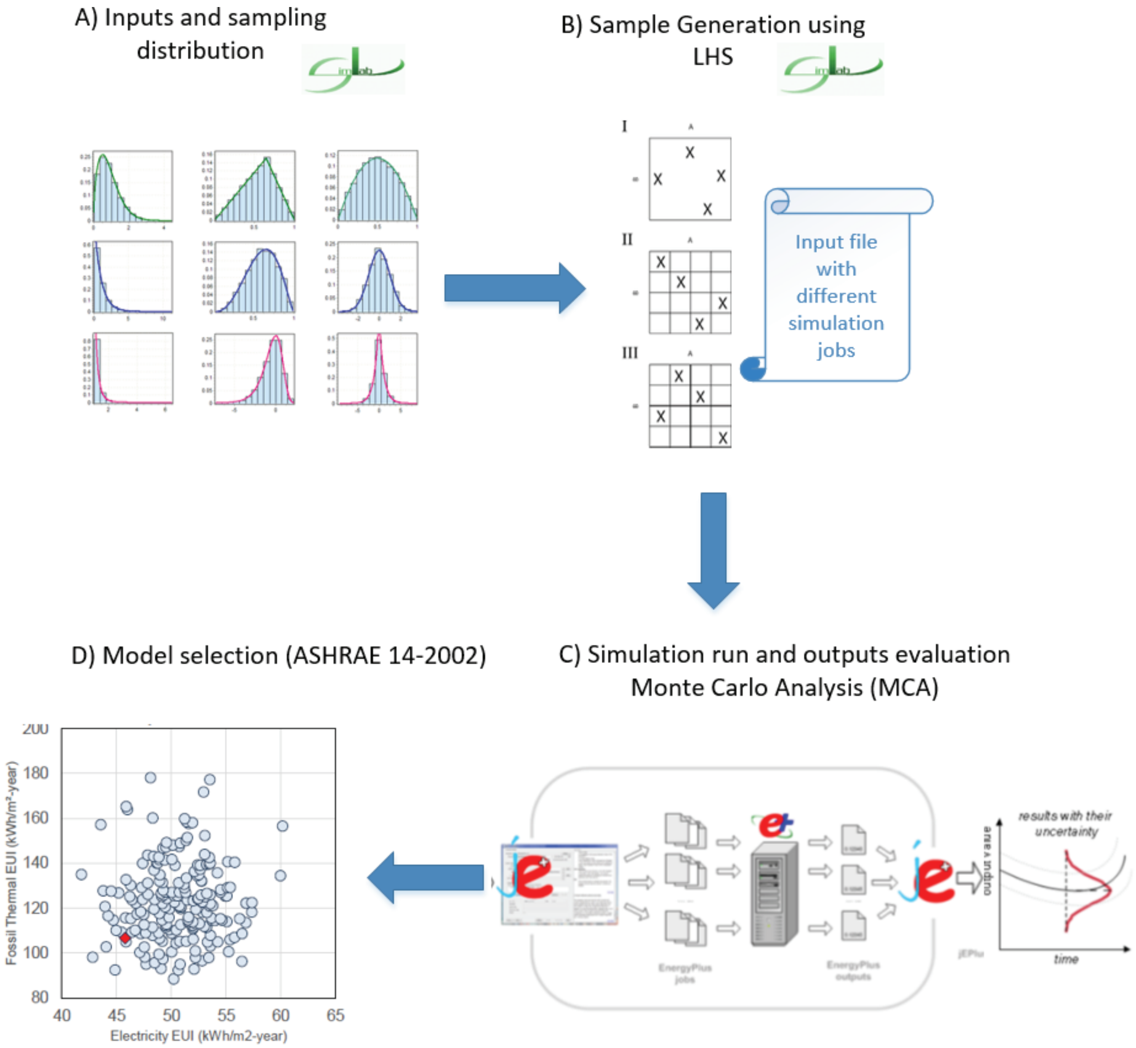

Figure A.1 Calibration process within ExRET-Opt using SimLab, jEPlus, and EnergyPlus (García Kerdan et al., 2017)

Appendix B. Exergy analysis for renewable generation

The following equations used in this model were taken from Torío et al. (2009), who undertook a comprehensive review of exergy analysis for renewable-based systems.

Solar collectors and PV systems: To calculate the exergy of the incoming solar radiation Ex_{sun} to the equipment the following formula is used:

$$Ex_{sun}(t_k) = G(t_k) * A_{col} * \left(1 - \frac{T_0(t_k)}{T_{sun}}\right) \quad \text{(A.1)}$$

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 (6000 K). Hence, the output of the collector Ex_{col} is the generation subsystem output and is calculated as follows:

$$Ex_{col}(t_k) = \dot{m}(t_k) * c_{Pheat} \left[(T_{out}(t_k) - T_{in}(t_k) - T_0(t_k) * ln\left(\frac{T_{out}\ (t_k)}{T_{in}\ (t_k)}\right)\right] \quad \text{(A.2)}$$

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:

$$\Psi_{col}(t_k) = \frac{Ex_{col}(t_k)}{Ex_{sun}\ (t_k)} \quad \text{(A.3)}$$

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

$$\Psi_{PVT}(t_k) = \frac{E_{PV}(t_k)+Ex_{col}(t_k)}{Ex_{sun}\ (t_k)} \quad \text{(A.4)}$$

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.

<u>Heat Pumps:</u> For heat pumps, we have to account for the electricity exergy content needed to operate the compressors and the evaporators, where the exergy content of the reservoir source (water, air, or ground) is considered as free exergy. Therefore, the efficiency Ψ_{HP} is calculated as follows:

$$\Psi_{HP}(t_k) = \frac{Ex_{th.dem}}{W} = \frac{\sum_{i=1}^{n}\left(En_{th,dem\ i}(t_k)*\left(1-\frac{T_0\ (t_k)}{T_i\ (t_k)}\right)\right)}{W\ (t_k)} = COP_{HP}\ (t_k) * \left(1 - \frac{T_0\ (t_k)}{T_i\ (t_k)}\right) \quad \text{(A.5)}$$

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

Appendix C. Integration of exergy analysis into EnergyPlus

The calculations presented in Section 3.2 were programmed using Python scripts. To integrate Python subroutines into EnergyPlus, jEPlus software (jEPlus 1.6, 2016) was 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 between EnergyPlus, Python, and jEPlus. 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 the exergy subroutine is called, a new spreadsheet version is obtained with all the new outputs. The simulation process is shown in Figure A.2.

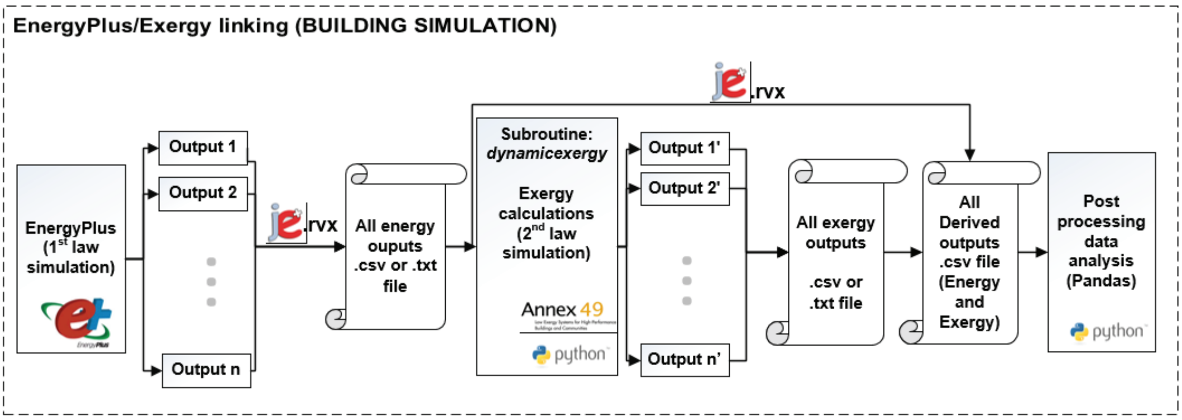

Figure A.2 Flow of Energy/Exergy co-simulation using EnergyPlus, Python scripting and jEPlus

As the manual evaluation of retrofit measures is infeasible, the model uses parametric simulation to manipulate models, modify building model code, and simulate them. The scenarios presented in Section 4.1 were implemented by developing individual stand-alone code ('*.idf* files') recognisable by EnergyPlus. By using the EP-Macro function within EnergyPlus and coupling the process with jEPlus, is possible to handle this 'pieces of code' an introduce them into the main building model and thus represent a future building scenario.

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