AN EXERGY-BASED SIMULATION STOCK MODEL: A NEW APPROACH FOR POLICY MAKING

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ABSTRACT

This article presents the use of an exergy-based bottom-up stock model to investigate the impact of large-scale energy retrofit scenarios in the English and Welsh (E&W) non-domestic sector, with a modelling projection to 2050. The model consists of a combination of EnergyPlus as a first law analysis tool and a dynamic exergy analysis method. The aim of the paper is to illustrate the potential of exergy analysis in improving efficiency at a sectoral level. This preliminary study is composed by 6 different large-scale retrofit scenarios including low carbon and low exergy approaches. The results show that current regulations can reduce carbon emissions by up to 50% but only reduce exergy destructions by 8%. On the other hand, a low exergy scenario based on low temperature district systems was able to reduce carbon emissions by 68% and exergy destructions by 26%.

INTRODUCTION

In the UK, the non-domestic sector (defined as buildings that are neither residential nor industrial facilities) is responsible for 17% of the country's total energy use, which is equivalent to an annual primary energy use of 1576.9 PJ (DECC, 2014); with a high dependency of high quality sources such as natural gas, oil, and off-site generated electricity. Among all economic sectors, the UK building sector has the highest potential to improve its thermodynamic efficiency (Figure 1), and among end-uses, space conditioning processes present the lowest efficiencies (>6.5%) (Gasparatos et al., 2009). These inefficiencies are related to the concept of exergy (energy quality or potential to do work), and where unlike energy which is conserved, exergy is exposed to destructions. This is supported by the second law of thermodynamics that states that *"in every process where energy or matter is dispersed, entropy is inevitable generated; leading to exergy destructions or irreversibilities*". Any real process is irreversible, which means that it cannot return to original conditions because of the constant increase of entropy in the environment.

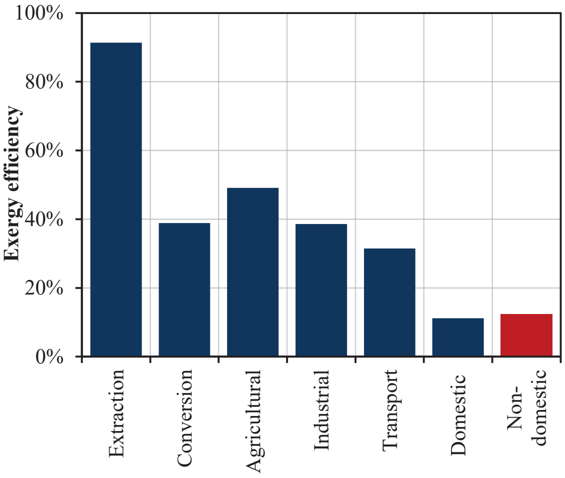

Figure 1 Exergy Efficiency in different UK sectors

The objective of any energy system is to obtain a desired product, where the product's exergy content will always be less than the exergy contained in primary source/fuel that entered the system. A typical example in the case of buildings is the thermal exergy content in the cool air or hot water that is finally delivered by space conditioning systems (at ~20°C), where the final exergy content is much less than the exergy contained in the primary energy source (e.g. gas, electricity). The irreversibilities or exergy destructions occur when the energy flow passes through the different subsystems of the energy supply chain, with large destructions in processes such as combustion and large temperature heat exchanging. By destroying exergy, useful work that could be useful for other higher quality processes (e.g. industrial, transport, and chemical) is wasted. Inefficient and unwise use of resources can significantly impact national energy security (Dincer, 2002); therefore, these irreversibilities give us a clear indication of the thermodynamic improvement potential of the sector. The application of exergy analysis has a significant potential in the identification of unconventional opportunities and the consequent reduction of dependency on high quality fuels. Jansen et al. (2012) demonstrated how primary energy input into buildings can be reduced by the application of different principles based on exergy, such as minimizing large temperatures differences, using renewable energy smartly, and considering appropriate passive design measures. However, complex exergy analysis methods show that energy systems have unavoidable exergy destructions, where techno-economic constraints still persist, making it impossible to achieve the maximum theoretical efficiency (Açıkkalp et al., 2015).

Building simulation is commonly used to support the decision making process in the early energy design or to assess the impact of retrofit measures of individual buildings, with its most powerful potential being the support of building energy policy (Crawley, 2008). Comprehensive models are critical to help in the understanding of the current energy situation and possible future scenarios for adopting energy efficiency measures that ultimately can lead to the design of building energy policies. Swan and Ugursal (2009) identified two basic modelling approaches: top-down and bottom-up, being the latter more suitable for the exploration of "what-if" scenarios. The major drawback of top-down models is the lack of detail regarding the energy consumption of individual end-uses which eliminates the potential of identifying key areas for improvements. However, current bottom-up models are only based on the first law of thermodynamics which aims to reduce energy use and does not consider the efficient use of a resource. Adding exergy to the analysis can, therefore, provide an effective tool to improve resource utilisation and energy conservation at a national level.

Sectoral exergy models for buildings

Sectoral exergy research, including non-domestic sectors, has been undertaken sporadically in the past 40 years. Two main approaches are found in the literature: a) Reistad (1975), which considers energy quality of carriers for final energy uses, b) and Wall (1977), which accounts for exergy in energy flows for end-uses and material flows. In other sectoral exergy studies, authors typically provide measures that could lead to improvements but do not carry out further investigation of the impact of these solutions. To the authors' knowledge, no studies based on exergy analysis to understand future scenarios have been performed, especially in the non-domestic sector. This paper presents a novel modelling framework that assesses sectoral energy and exergy utilisation and investigates future scenarios based on large-scale energy retrofit measures.

METHODOLOGY AND CASE STUDY

The energy model is based on the study described by Griffith and Crawley (2006), with some modifications introduced in order to adapt the model to the limitations of current data available for the English and Welsh (E&W) case. This method consists of a model based on several building archetypes simulated in EnergyPlus (2012).

Data sources

A significant number of data sources were required for the specific task of constructing the representative models. Supported with the work from Pout et al. (2002) and combined with ASHRAE Standard 55 (2004) and CIBSE guide A (2006), the models were designed to generalise the most important characteristics and represent the variability in the stock based on technical factors such as floor and glazing area, elements U-values, occupancy, appliances, HVAC equipment, etc. Eight main end-uses categories were identified (Table 1).

Table 1 End-uses in the E&W non-domestic sector

Lighting	Catering
Internal equipment	Cooling
Motors and pumps	Domestic hot water (DHW)
Fans	Refrigeration

To represent the whole E&W non-domestic sector (excluding industrial buildings) data from three sources were inspected: a) DECC (2014), which shows data of national energy use by building type, end uses and by fuels, b) the *CaRB UK* stock model (Bruhns, 2007), which contains estimations on total energy use and national floor area by building type, and c) a database developed by Hong and Steadman (2013), which contains data on energy use of UK non-domestic buildings developed through a comprehensive statistical analysis of 73,160 Display Energy Certificates. After analysing this evidence, 80 principal types of non-domestic buildings were found, and through further scrutiny, 11 buildings were identified as having the most significant impact on sectoral energy use (Table 2). This simplification was undertaken to achieve uniformity within the DECC database, which differentiates the sector in these 11 buildings types. Table 2 also shows the baseline energy use obtained through the energy modelling. These indicators were calibrated using the aforementioned data sources.

Table 2 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**

By gathering information on total floor area by building, an extrapolation was performed to obtain the energy use at a stock level covering a total area of 665 million m².

$$E_{tot}\ [PJ] = \sum_n (EUI_n * m^2(n)) \quad (1)$$

To account for the majority of the stock (>70%) with only 11 types of buildings, the floor area of the buildings subtypes that were disregarded was designated accordingly to one of these 11 principal types. Future work will consider the expansion of the number of buildings to account for a larger variability.

Exergy analysis model

Later, the energy model was linked with a dynamic exergy method developed by the IEA ECB-Annex49 (2011). This method has the potential to analyse the whole building energy supply chain following an input-output approach based on seven different subsystems. This gives the possibility to determine the exergy use and destructions at different points of the building energy supply chain and, thus, find exact locations for improvement. For this study, the method was simplified by reducing the number of subsystems to four: 1) the Primary Energy Transformation subsystem, 2) The Generation and Storage Subsystem, 3) the Emission Subsystem, and 4) the Envelope Subsystem (Figure 2).

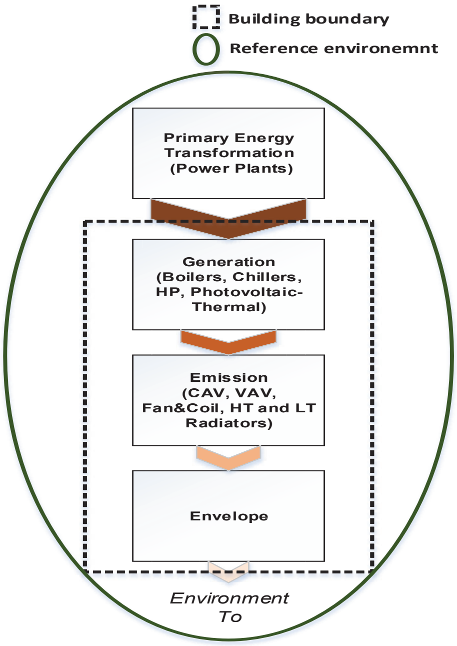

Figure 2 Exergy flow through the building energy supply chain

Firstly, to calculate the exergy demand for thermal-based end uses, the application of the second law and the Carnot formula* was required. By multiplying the energy demand for space conditioning by the quality factor (usefulness part of energy to produce work) the exergy demand can be obtained:

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

In a similar manner exergy demand for refrigeration, water heating, and cooking respectively can also be calculated:

$$Ex_{ref}(t_k) = Q_{ref}(t_k) * COP_{ref}(t_k) \left(\frac{T_0(t_k)}{T_{p_{refr}}(t_k)} - 1 \right) \quad (3)$$

$$Ex_{DHW}(t_k) = Q_{DHW}(t_k) * \frac{\eta_{WH}(t_k)}{q_{fuel}} * \left(1 - \left(\frac{T_0(t_k)}{T_{p_{WH}}(t_k) - T_0(t_k)} \right) * \ln\left(\frac{T_{p_{WH}}(t_k)}{T_0(t_k)} \right) \right) \quad (4)$$

$$\psi_{cooking} = \eta_{cooking}(t_k) * \left(1 - \frac{T_0\,(t_k)}{T_{p_{cook}}(t_k)} \right) \quad (5)$$

In the Carnot formulas, T_o represents the reference environment temperature (in absolute value [K]). 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 and therefore the same exergy consumption:

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

To obtain total exergy consumption at the building level, all the exergy consumption by end-use were added.

$$Ex_{bui} = \sum Ex_i \quad (7)$$

To analyse exergy destruction up to the primary generation subsystem and distinguish the impact of using different types of energy sources and the impact of renewables and low quality sources, the next equation was used:

$$\mathrm{Ex_{prim}} = \{\textstyle\sum_i [\frac{En_{\ gen,i}(t_k)}{\eta_{gen,i}\,(t_k)} * F_{p,source,i} * F_{q,source,i}]\} - \{F_{q,building} * \textstyle\sum_i\ [Q_i\,(t_k)]\} \quad (8)$$

Finally, total irreversibilities were given by subtracting the primary exergy supplied minus the exergy demanded by the building:

$$Ex_{dest} = Ex_{prim} - Ex_{bui} \quad (9)$$

These indicators were later used for extrapolation to obtain the sectoral baseline exergy utilisation. The London-Gatwick TMY2 weather file was used as the reference environment. Only thermal exergy was considered, disregarding the impact of mechanical and chemical exergy in the analysis.

Retrofit and future scenarios module

In addition to adapting the exergy method for the bottom–up model, a comprehensive energy retrofit module was also developed. This includes several low-carbon and low-exergy technologies as well as future information on construction and demolition rates and future energy emissions factors. Several scenarios were created to understand energy use, carbon emissions and most importantly exergy utilisation. By reviewing different current building energy codes, low carbon policies, financial mechanism, and exergy research, six different retrofit scenarios were developed. In all cases, new

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[*] The Carnot formula sets the limiting value on the fraction of the heat which can be used.

buildings were modelled in accordance with the latest national energy regulations.

Scenario 1: Pessimistic scenario

This scenario considers that no retrofit measures are applied to the existing stock. Carbon reductions in the sector are only obtained by the decarbonisation of the power sector (reduction of the carbon emissions per unit of energy generated), expected to be achieved by increasing the share of renewable energy and/or nuclear energy into the energy supply matrix, which currently is made mostly by fossil fuels such as gas and coal.

Scenario 2a: Low uptake of common retrofits

Low deployment of retrofit measures (building type dependant) based on the latest UK energy regulation Part L2B. This considers minimum U-values for the building's envelope and minimum efficiency for the HVAC systems. The generation systems are based on condensing boilers and high efficient chillers. The emission systems are based on CAV with working temperatures of 12°C for cooling and 60 °C for heating. Heat recovery is also considered.

Scenario 2b: High uptake of common retrofits

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

Scenario 3: Use of high quality sources

This scenario represents technology that makes use of high-grade sources, such as electricity, and the use of renewable environmental sources. The HVAC system is based on air to air heat pumps with a nominal COP of 3.6. The emission systems are based on Fan Coil units with working temperatures of 14 °C for cooling and 48 °C for heating.

Scenario 4: Renewables and storage

This scenario considers the installation of photovoltaic thermal hybrid solar collectors (PV/T systems) to supply on-site electricity, hot air and hot water. Electrical heaters are used as backup when renewable energy is not sufficient. PV/T systems convert the solar radiation (a high exergy source) into electricity and thermal energy. This allows having larger exergetic efficiencies than single PV or PT panels. The emission system is based on CAV systems with DX cooling and electric heating coils. Also on-site electric storage devices and hot water tanks are modelled.

Scenario 5: Low Temperature District Systems

This scenario is based on the development of low temperature district systems assuming that the energy is produced by a single-effect indirect-fired absorption chiller with a COP of 0.7. The idea behind this scenario is to close the quality levels gap between the supply and demand by supplying low temperature heating and high temperature cooling. To achieve this, the emission system is assumed to work at low supply/return temperatures of 16/20 °C for cooling and 40/30 °C for heating.

Scenario 6a: Ambitious scenario based on Renewables

This scenario is a combination of Scenario 2b and Scenario 4; where high insulation levels for the building's envelope is assumed in combination with PV/T systems and on-site storage. This scenario also considers the implementation of these systems measures for new buildings.

Scenario 6b: Ambitious scenario based on Low Temperature technologies

This is similar to Scenario 6a but combines low temperature district systems instead of PV/T systems.

Simulation

To build the necessary database, all the possible combinations were simulated. In total, 88 detailed simulations were performed, where hundreds of parameters were modified for each simulation. This data was then used to populate the future scenarios module.

Stock's future growth and retrofit deployment rates

Projections for growth (construction and demolition rates) in the non-domestic building stock were taken from recently published study by ARUP (2013). The largest growth is found in A/C offices (2.6% annually) and the lowest in warehouses (-0.6% annually) (Figure 3). It is expected that by 2050 the considered building stock will grow from 665 million m² to 870 million m², an increase of 30%. Also, this particular projection shows that by 2050, 80% of current buildings will still be in use, representing 62% of the future stock.

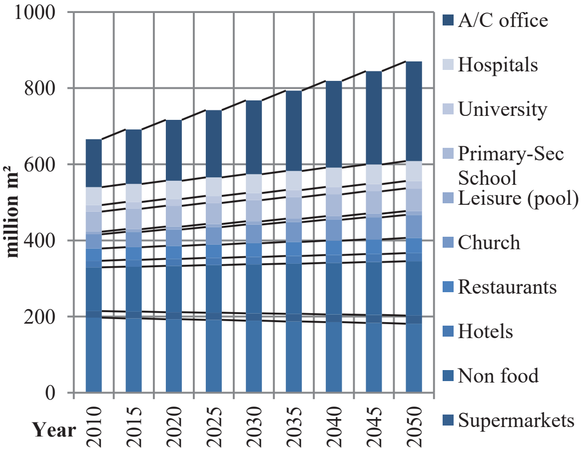

Figure 3 Total growth projection of the E&W sector

Future grid decarbonisation (assumptions)

Emission factors of different fuels are typically expressed in $kgCO_2/kWh$. In this research a moderate future electricity decarbonisation was considered, going from the current value of 0.50 $kgCO_2/kWh$ to 0.20 $kgCO_2/kWh$ by 2050. The quality factors of the other fuels were assumed to remain constant (Table 3).

Table 3 Future carbon emission factors considered

Year	Electricity (kgCO2/ kWh)	Gas (kgCO2/ kWh)	DistrictEnergy (kgCO2 /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

Model limitations

The model does not enable the undertaking of economic analysis such as including cost of measures, return of investments, fuel process, and/or market penetration. Furthermore, only the London weather file is used to represent the entire E&W stock. For future work more data will be needed to present a model differentiated by climatic regions. Also, no climate change forecast was considered

RESULTS AND DISCUSSION

Energy and Exergy Baseline (2010)

The base case shows an energy use in the sector of 622 PJ, where A/C Offices, Retails, Warehouses and Hospitals are the four largest consumers representing 66% of the total sector energy use. Figure 4 shows the total energy use by building type and end use. If the whole energy supply chain is considered, in 2010 an input of 1035 PJ of primary energy was required, resulting in a sectoral energy efficiency of 60.1%. Carbon emissions were found to be in the range of 56.2 MTon CO_2.

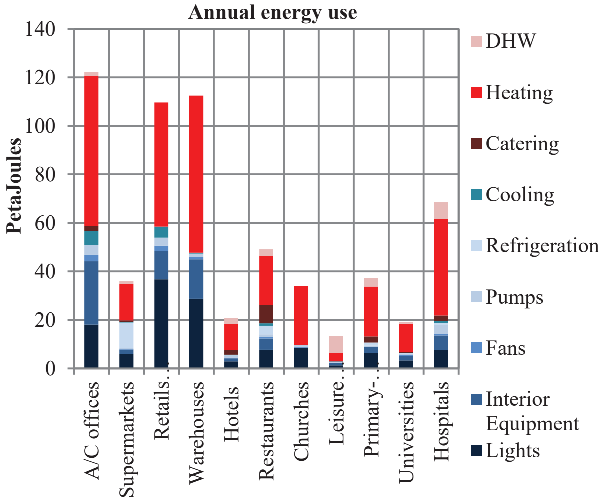

Figure 4 Baseline total energy utlisation by building and end uses

To validate baseline outputs, information from the previously mentioned CaRB model and UK DECC statistics were used. Some modifications such as removing the energy share of Scottish buildings by considering the country population size (8.4% of the UK) had to be made. In addition, statistics on subsectors that weren't modelled were removed (e.g. "Industry" and "Transport and Government"). This results in a prediction error of 0.3%.

From the exergy analysis, annual exergy input at building level was found to be 600.4 PJ, with annual irreversibilities of 491.9 PJ. This represents a total building exergy efficiency of 18.1%. If we consider the exergy content of the primary fuels, the exergy input increases to 1012.4 PJ, resulting in a total exergy efficiency of the sector of 10.7%. By building type, A/C offices represent 18% of the national exergy destructions followed by retail buildings and warehouses. The sector exergy flows through the energy supply chain are illustrated in Figure 5:

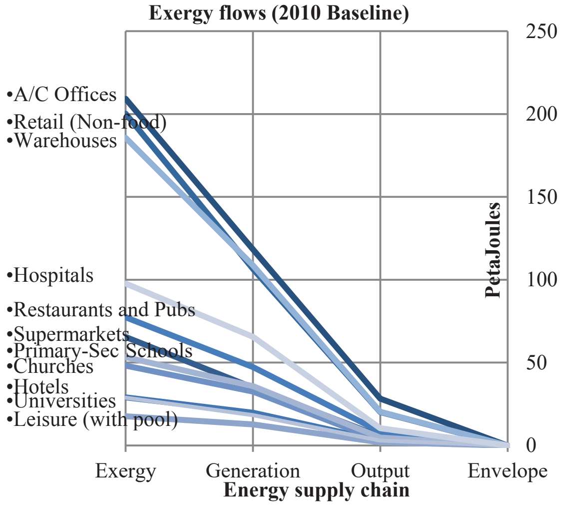

Figure 5 Sectoral exergy flows for the English and Welsh non-domestic sector

Future scenarios results (2050)

The overall results for sectoral energy use are presented in Figure 6. The pessimistic scenario (S1), where no retrofit measures were considered, will cause an increase in annual energy use of 10%. On the other hand, scenario 6a, based on an ambitious renewables target represents an energy reduction of 81% by 2050.

Sectoral Exergy Improvement

Table 4 shows the impact of each scenario on the national exergy destructions. Unlike the previous energy analysis, exergy analysis shows that the measures did not significantly reduce exergy destructions as expected. An interesting result from scenario 3, based on the use of high quality sources by air/air heat pumps, is that it will result in an increase in sectoral exergy destruction of 4% by 2050. Finally, both ambitious scenarios were able to minimise destructions above 25%.

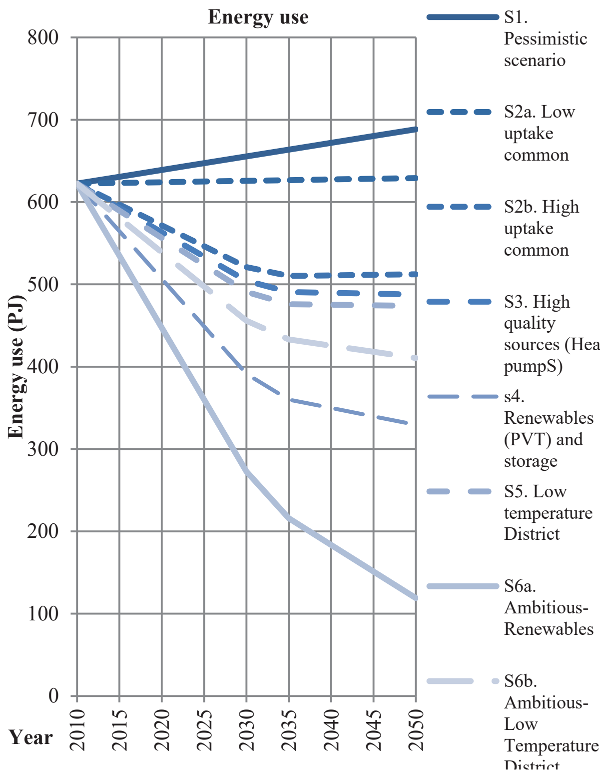

Figure 6 Sectoral energy use and impact of different large-scale energy retrofit scenarios

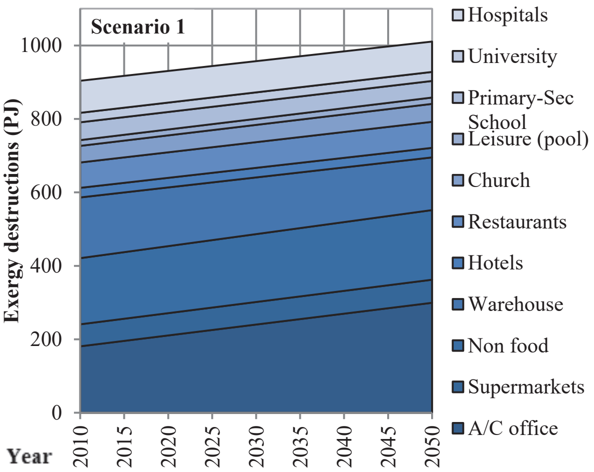

Figure 7 Stacked exergy destructions by building type of Scenario 1. Pessimistic (no retrofits)

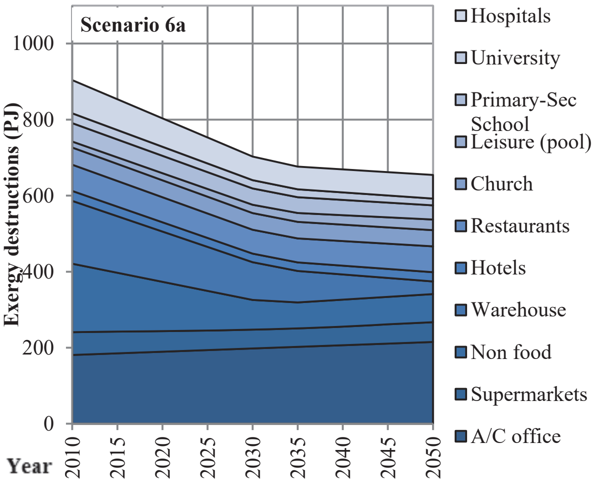

Figure 8 Stacked exergy destructions by building type of Scenario 6a Ambitious Renewables

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). For the purpose of comparison, Figure 7 and 8 show a detailed analysis (differentiated by building type) of the worst and the best exergy scenarios.

Table 4. National Exergy destructions of different large-scale retrofit measures

Scenarios	2010	2015	2020	2025	2030	2035	2040	2045	2050	Improvement
S1. Pessimistic scenario	904	917	931	944	957	971	984	997	1011	-12%
S2a. Low uptake of common retrofits	904	910	916	922	928	934	940	946	951	-5%
S2b. High uptake of common retrofits	904	884	864	844	824	819	825	831	837	7%
S3. Smart use of high quality sources (Heat pumps)	904	902	901	899	897	903	914	926	937	-4%
S4. Renewables (PVT) and storage	904	860	817	773	730	708	704	700	695	23%
S5. Low temperature District Systems	904	873	843	812	782	770	772	774	776	14%
S6a. Ambitious-Renewables	904	854	803	753	703	676	669	662	655	28%
S6b. Ambitious-Low Temperature District	904	860	815	771	727	701	691	680	670	26%

Carbon reductions

Figure 9 shows the carbon emission pathway for all six scenarios. An extra scenario was added to represent what would happen if the carbon emission factor for electricity remains constant for the next 35 years. As can be seen, carbon emissions will dramatically increase if no measures at the power sector are applied. This also shows the significant uncertainty of this analysis due to modelling assumptions and therefore demonstrates that exergy analysis may become a viable option for policy-making as quality factors (being a physical property) will remain constant. Nevertheless, the results show that scenario S1 (pessimistic) achieves reductions of 32% solely based on the decarbonisation of the electricity grid (considering the factors from Table 2). Still the best results are obtained based on exergy efficient renewables technologies, achieving reductions up to 88%.

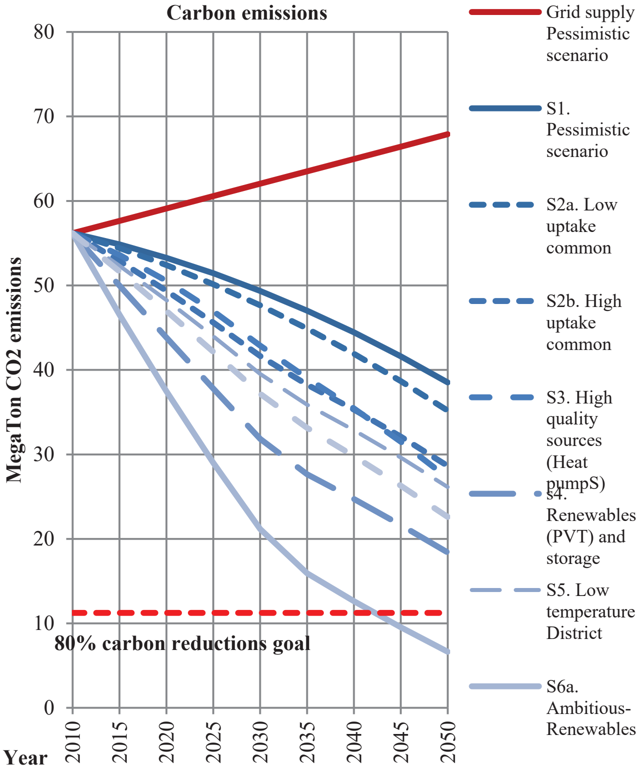

Figure 9 Sectoral carbon emissions and impact of different large-scale energy retrofit scenarios

DISCUSSION

As shown in the results, some scenarios that are typically believed to be efficient and provide large reductions in carbon emissions (e.g. air/air heat pumps) struggle to reduce exergy destructions at a sectoral level because of the high electricity demand. This means that these scenarios waste a large amount of useful work that could be used in other sectors. Low quality energy scenarios, such as those represented by low temperature district systems, can achieve better efficiencies if more low quality sources such as biomass or waste heat are introduced into the production of district energy. From an economic perspective, low exergy sources (low temperature water, ground source) may be cheaper than high exergy sources (gas and electricity), but 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. Lowering prices for low-exergy technologies would have a greater economic impact than for high exergy technologies (e.g. electric heater) as the first option currently has higher capital costs and lower operating costs. A high exergy scenario (e.g. all electric buildings) would be viable only if electricity prices go down significantly. 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 in a district 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. 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.

CONCLUSION

In addition to the development of energy and exergy data of the E&W non-domestic sector, the application of the exergy method to explore thermodynamic improvements at a sectoral level was demonstrated. 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. The outputs of this study show the potential of the proposed model in locating inefficiencies and unlocking unconventional strategies for the sector's thermodynamic improvement, combined with a significant reduction of carbon emissions. Minimizing exergy destructions at a national level provides greater energy security for the country as high quality sources can be used more efficiently in sectors with high exergy demand, such as the industrial and the transport sector. The study also shows that the E&W non-domestic sector has a potential to reduce exergy destructions by almost 30% while achieving important reductions in carbon emissions; although with the current market prices for these technologies it would make it difficult to implement these scenarios at a large scale.

Future studies

To reduce model uncertainties, future work will address the aforementioned limitations as follows:

- Data collection on buildings floor areas by regions. The lack of adequate and detailed data prevented the differentiation of climatic regions in the modelling, where the reference temperature has a significant impact on exergy results.
- Expansion of the number of archetypes to account for variability between similar buildings subtypes.
- Further analysis of the scenarios listed in this paper will be conducted as well as the development of other unconventional scenarios. The aim is to link the model with a global optimisation module to achieve optimal scenarios based on the parallel improvement of energy, exergy, carbon emissions and economic objectives.
- It is considered the inclusion of exergy analysis for energy storage systems. This will be based on the dynamic model developed by the IEA Annex 49 (the model has the potential to analyse charging, storing and discharging periods under dynamic ambient temperature).
- Finally, as current economic analysis favours low efficient exergy systems such as cheaper high-temperature heat exchangers, a comprehensive thermoeconomic model will be developed to allow the consideration of the cost of energy saving, cost of exergy destructions as well as life cycle analysis. Future work will also include the development of a larger retrofit database

NOMENCLATURE

E	Energy (J)
EUI	Energy use index (kWh/m²-year)
Ex	Exergy (J)
Q	Energy demand (J)
COP	Coefficient of performance (J/J)
F_p	Fuel Primary Energy Factor (-)
F_q	Fuel Quality factor (-)
T	Temperature (K)
ψ	Exergy or second law efficiency (-)
η	Energy efficiency
Ex_{total}	Total exergy supplied to the system (J)

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