Energy Policy 105 (2017) 467–483

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

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

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ARTICLE INFO

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

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.

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

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http://dx.doi.org/10.1016/j.enpol.2017.03.020
Received 8 September 2016; Received in revised form 13 February 2017; Accepted 9 March 2017

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/m^2-year)
Ex	exergy (kWh)
$\dot{E}x_D$	exergy destructions (kWh)
Ex_{dem}	exergy demand (kWh)
Ex_{prim}	primary exergy (kWh)
Ex_{sun}	solar exergy (kWh)
F_p	primary energy factor (dimensionless)
F_q	quality factor (dimensionless)
G	incident solar radiation, (W/m^2)
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 (dimensionless)
ψ	exergy efficiency (dimensionless)

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

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 (Fig. 1) (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

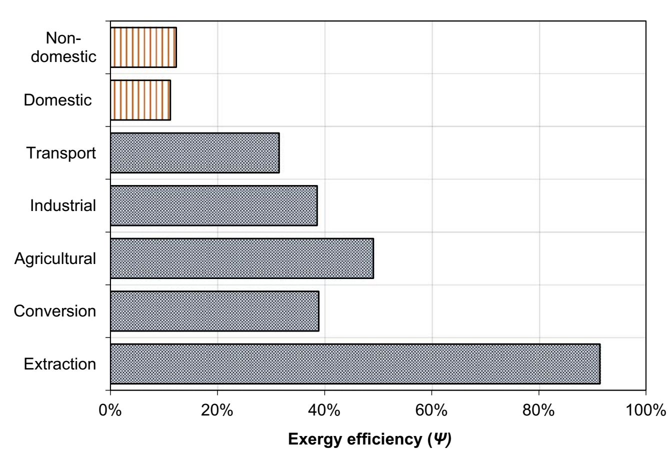

Fig. 1. Exergy efficiency in different UK sectors.
Source: Gasparatos et al. (2009).