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Dynamic exergy analysis of energy systems for a social dwelling and exergy based system improvement

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ABSTRACT

This paper presents a study of the usefulness of the exergy approach in the development of energy systems for the built environment. The energy and exergy performance of five different energy systems for a social dwelling in a multifamily building from 1960s in Bilbao (Spain) are studied; two reference cases as well as three improved options. The total energy chain is considered from the energy demand to the energy resources and the analyses are performed using dynamic simulations. The exergy losses of energy system components are identified and quantified and efficiency values in terms of energy and exergy are evaluated. Based on an analysis of the exergy losses further improvements are investigated. This study has shown the exergy concept to be a useful addition to the energy concept, giving a more rational analysis than an analysis solely based on the energy concept. It has also shown that identification and quantification of exergy losses can support the further improvement of energy system configurations, leading to a further reduction of exergy losses and thus a further reduction of high quality energy use.

1. Introduction

Developing sustainable energy systems is becoming more and more important in today's world due to the depletion of fossil energy resources and the global warming problems related to the use of these resources. Reducing the need for energy sources is a key factor in the development towards a sustainable energy future [1]. The built environment uses more than 40% of the total final energy consumption in the European Union [2]. A significant share of the energy use in buildings is related to heating and cooling and thus to near-environmental temperatures at around 20 °C. Due to this temperature level, the energy demand for heating and cooling in the built environment is mainly a demand for "low quality" energy. However, this demand is usually met by high quality energy carriers, such as fossil fuels or electricity. The building sector has a high potential for improving the quality match between energy supply and demand and thereby reducing the required input of high quality energy sources.

Exergy is a thermodynamic concept which can be regarded as the quality of a form of energy, by expressing the maximum theoretical work that can ideally be obtained from it in a given reference environment. In ideal energy conversion processes no exergy is lost, but in any real process exergy destruction takes place; exergy is therefore a more rational measure of the performance of an energy conversion process than energy [3]. Originally the concept was primarily applied to chemical processes and thermal plant analysis [4]. An extensive number of studies has been carried out in the last decades in this field, such as [5–8].

The exergy approach in the built environment is relatively new but may be considered an emerging field of science. The concept has been used in building efficiency studies with several international research projects, such as IEA ECBCS Annex 37 [9] and Annex 49 [10]. Also several studies on energy systems used in the built environment can be found in the last years, such as [11–20], to name but a few. Most exergy studies in the built environment are based on steady state calculations. Exergy analysis may also be fruitfully applied to renewable energy-based systems in order to identify the optimal use of the available renewable sources [21].

This paper applies the exergy approach to the assessment and development of (more efficient) energy systems for a social dwelling located in Bilbao, Spain. The exergy approach used in this study consists of two steps of which this paper describes the second one. In the first step promising energy scenarios were developed based on exergy principles and a steady state evaluation has been performed, as described in a previous research article [22]. In the present paper more detailed dynamic calculations are performed for the two reference cases and the three most promising solutions presented in [22]. In addition the analysis of exergy losses occurring in each energy system component is used to assist the

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Nomenclature

A	Area (m^2)
c_p	Isobaric heat capacity ($J\,kg^{-1}\,K^{-1}$)
D	Annual exergy destruction (MJ/y)
E	Electricity (MJ/y)
F	Exergy factor
L	Annual exergy losses (MJ_{ex}/y)
m	Mass (kg)
$\dot{m}$	Mass flow rate (kg/s)
PE	Primary energy
PEF	Primary energy factor
Q	Heat and sensible heat (MJ/y)
T	Air temperature (°C)
U	Heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
V	Volume (m^3)
x	Exergy (MJ_{ex}/y)

Greek symbols

ψ	Exergy efficiency
η	Energy efficiency

Subscripts

CHP	Related to co-generation system
DHW	Related to domestic hot water
del	Delivered
dem	Demand
E	Related to electricity
exp	Exported
H	Related to heating system
HR	Related to heat recovery
i	Stream
in	Indoor
inl	Inlet
inf	Infiltrations
Inp	Input
int	Internal gains
op	Operative (Temperature)
out	Outdoor
outl	Outlet
outp	Output
ret	return
sp	Set-point (Temperature)
sol	Solar gains
ST	Related to solar thermal
sup	Supply
TES	Related to thermal energy storage system
TESHT	Related to thermal energy storage system (High Temp.)
TESLT	Related to thermal energy storage system (Low Temp.)
trans	Transmission
vent	Ventilation
X	Related to exergy
0	Reference

further improvement of the promising solutions, aiming at a further reduction of exergy losses.

2. Methodology

Like many exergy studies applied in buildings, this work was also carried out using an input–output approach, described in [11] and [23]. The energy chain considered consists of the energy demand of the users of the building (heating, domestic hot water and electricity – cooling is not considered), the energy transformation components for conversion, storage and distribution of energy, and finally the resources. A scheme of the energy chain is shown in Fig. 1.

2.1. Dynamic energy simulation

The analysis was performed using dynamic simulations by means of the well-known transient energy simulation software TRNSYS (V17). The energy demands for space heating were modelled using TRNSYS type 56. The study cases and related systems components, described in Section 3, were modelled and simulated according to the parameters presented in Appendix A. The weather data used for the city of Bilbao are obtained from the Meteonorm database available within TRNSYS.

2.2. Exergy calculation

The exergy values are calculated for each time-step (1-h) of the simulation, based on the energy values and the relevant temperatures. This means the exergy calculations are in fact semi dynamic. Only sensible heat is taken into account in accordance with [24]. The reference environment is therefore simplified to the reference temperature T_0 only, for which the varying outdoor temperature at each simulation time-step is taken, as recommended in [23].

The exergy of an amount of energy is calculated by multiplying the energy with its related exergy factor (F). For heat at constant temperature T this can be calculated by means of Eq. (1); for sensible heat of an amount of matter Eq. (2) can be used (see also [11,22,25]).

$$F(Q) = 1 - \frac{T_0}{T} \tag{1}$$

$$F(Q_{sens}, T_2 - T_1) = \left(1 - \frac{T_0}{T_2 - T_1} \cdot \ln \frac{T_2}{T_1}\right) \tag{2}$$

The Exergy factors of inputs and outputs of the energy system components and of used fuels used are given in the Appendix A. For Primary Energy the exergy content equals the energy content, since an exergy factor of 1 is assumed for the primary energy as is further explained in the Appendix A.

2.3. Electricity Production and calculation of the net primary energy input

In some energy system solutions presented electricity is produced at building level (e.g. by solar PV panels). No electricity storage is considered and therefore in each simulation time step there can be either a need for additional electricity supply from the grid or an overproduction at building level which has to be sent back to the grid. This means on an annual basis the sums of all electricity balances at each time-step results in:

- An annual amount of electricity input delivered by the grid, (E_{del});
- An amount of electricity exported to the grid (E_{exp}).

In order to evaluate the performance of the energy systems components these values are presented separately. However, in order to compare the different case studies the required primary energy input for the same output has to be compared and therefore the “Net primary energy input” (NPE) is calculated using Eq. (3), according to [26].

$$\mathrm{NPE} = \sum \left(E_{del,i} \cdot \mathrm{PEF}_{E,del,i}\right) - \sum \left(E_{exp,i} \cdot \mathrm{PEF}_{E,exp,i}\right) \tag{3}$$