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The exergy approach for evaluating and developing an energy system for a social dwelling

S.C. Jansen [a,*], J. Terés-Zubiaga [b], P.G. Luscuere [a]

[a] Technical University of Delft, Faculty of Architecture, Department AE+T, Section of Climate Design, The Netherlands
[b] ENEDI Group, Department of Thermal Engineering, Faculty of Engineering of Bilbao, University of the Basque Country UPV/EHU, Alda Urkijo S/N, Bilbao, Spain

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ABSTRACT

In this paper the energy and exergy performance of a social dwelling of a multi-family building from the 1960s in Bilbao (Spain) is presented and various improved energy concepts based on exergy principles are proposed and investigated. The aim of this paper is to explore and demonstrate the usefulness of the exergy approach in the assessment and development of an energy system for the dwelling under consideration. The total energy supply system is analysed, including the demand (space heating, domestic hot water and electricity), the system components (for conversion, storage and distribution) and the energy input from energy resources (primary energy and renewable resources). The study includes a comparison of the primary energy input of all cases considered and an analysis of the energy and exergy losses of each system component. The study has shown that the exergy analysis reveals thermodynamic losses that are not revealed using energy analysis and secondly, that the development of an improved energy system based on exergy principles has resulted in a significantly reduced primary energy input compared to the reference situation.

1. Introduction

The energy demand for heating and cooling in the built environment is mainly a demand for 'low quality' energy, due to the associated temperatures required. Exergy is a thermodynamic concept which indicates the 'quality' of the energy, by expressing the thermodynamic ideal work potential of a certain form of energy. The first law of thermodynamics states that energy cannot be destroyed, but exergy, according to the second law, can be destroyed. Explanations of the exergy theory can be found in many textbooks on thermodynamics, such as [1–3].

Thermodynamic ideal processes are reversible, which means no exergy is destroyed and the original situation can be re-obtained. In real processes, however, exergy is always destroyed, often even in large amounts. The exergy destruction of a process indicates the ideal thermodynamic improvement potential of this process. This improvement potential is not shown in energy analysis; exergy analysis therefore has an added value for the evaluation of the performance and improvement potential of a system [4].

The 'low exergy' heating and cooling demands in the built environment are generally met with 'high exergy' energy sources, such as gas or electricity and usually a lot of exergy is being destroyed in these systems. This means there is much room for improvement. Exergy analysis of heating and cooling systems in the built environment is an emerging field of science in recent decades, as is shown by a large number of publications and international research activities such as [5–7].

In this paper the exergy performance of a social dwelling of a multi-family building from the 1960s in Bilbao (Spain) is presented and improved energy concepts based on smart exergy use are proposed and investigated. The aim of this paper is to explore and demonstrate the usefulness of the exergy approach in the assessment and development of an energy system for the dwelling under consideration.

The following cases are studied and presented:

- Case I – original situation (no insulation, single glazing)
- Case II – case study assuming the usual retrofitting works
- Case III – improved cases based on exergy principles.

For the improved cases (Case III) six options have been developed based on exergy principles. These options are evaluated using steady state analysis of the energy system, but based on a dynamic energy and exergy demand calculation.

2. Methodology

This paper aims at demonstrating the usefulness of applying the exergy approach for the development of an efficient energy system for a dwelling of a social multi-family building located in

* Corresponding author.
E-mail address: s.c.jansen@tudelft.nl (S.C. Jansen).

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Nomenclature

A	area [m^2]
c_p	isobaric heat capacity [J kg^{-1} K^{-1}]
E	electricity [J]
En	energy [J]
Ex	exergy [J]
F	Exergy Factor (exergy to energy ratio) [–]
H	(space) heating [J]
Q	heat [J]
Q_{sens}	sensible heat [J]
T	temperature (°C if explicitly mentioned) [K]
U	heat transfer coefficient [W m^{-2} K^{-1}]
V	volume [m^3]

Greek symbols

Ψ	exergy efficiency [–]
η	energy efficiency [–]

Subscripts

0	reference
dem	demand
e	outdoor
i	indoor
inl	inlet
op	operative (temperature)
outp	output
ret	return
sp	set-point (temperature)
sup	supply

Abbreviations (also used as subscript)

CHP	combined heat and power (cogeneration)
DHW	domestic hot water
H.R.U.	heat recovery unit
H.T.	high temperature
L.T.	low temperature
NG	natural gas
P.E.C.	primary energy conversion
P.E.F.	primary energy factor
PV	photo voltaic (energy)
S.T.	solar thermal (energy)
TES	thermal energy storage
V.L.T.	very low temperature

Bilbao (Spain). It presents the evaluation of two reference cases and the development of improved cases applying exergy principles is described. The energy and exergy performance is evaluated, based on dynamic exergy demand calculation and steady state analysis of the total energy system.

The following relevant methodology aspects for this study are described in this chapter: (1) the analysis framework according to the input–output approach; (2) the energy calculation method used; (3) the exergy calculation approach and (4) the exergy principles used for the development of exergetically improved options.

2.1. Analysis framework

In this study the total energy chain is analysed, which is composed of the energy demand, the energy system components (conversion, distribution and storage) and the energy resources. These are analysed according to the input–output approach described in [8] and [9]. The demand is the start of the analysis and for all subsequent energy system components the required input of the component equals the output of the next component. This way all energy and exergy losses are assigned to a component. In this study the demand for space heating, domestic hot water (DHW) and electricity for lighting and appliances are considered. A scheme of the framework is shown in Fig. 1.

2.2. Calculation method

The analysis of the cases has been performed using dynamic simulations for the calculation of the energy and exergy demand of the building and using a simplified steady state approach for the energy performance of system components, as described below.

2.2.1. Dynamic energy and exergy demand calculation

The energy and exergy demand calculations are performed using the internationally well-known transient energy simulation software TRNSYS (V 17). An annual simulation has been carried out using a 1-h time-step. The energy demand for space heating for the different scenarios studied here are modelled using TRNSYS type 56. Only sensible heat is taken into account, in accordance with [10]. Cooling is not treated in this study as it does not usually exist in residential buildings in this area. The exergy demand is not a standard output of the TRNSYS software and is calculated for each time step according to the method explained in Section 2.3.1. The demands for domestic hot water (DHW) and electricity for lighting and appliances are included as a schedule based on the literature, as is further explained in the Appendix. The detailed building properties and operation schedules can be found in the Appendix.

2.2.2. Steady state energy system analysis

The energy inputs and outputs of the subsequent energy system components for conversion and storage are calculated in a simplified way using a steady state approach, based on the component efficiencies described in the Appendix. The analysis has been performed for the heating season (October until March) and the summer season (April until September). For this steady state analysis the total seasonal demands resulting from dynamic simulation have been used.

2.3. Exergy analysis approach

The exergy of an amount of energy can be calculated by multiplying this amount of energy with its exergy factor (F), which is defined as the exergy to energy ratio. This approach is used for calculating the exergy of the inputs and outputs of all energy system components as well as of the resources. The exergy factor of the fuels used is given in the Appendix. The exergy factor of heat is based on temperatures. In this paper the outdoor temperature is considered as the reference temperature as recommended by [9]. The seasonal average is calculated by weighting the outdoor temperature by the heat demand per 1 h time step; in this way the – steady state – exergy calculations are more correct than when using the straight average outdoor temperature [11]. The exergy factor of heat at constant temperature can be calculated using Eq. (1), while the exergy factor of sensible heat of an amount of matter ($m \cdot c_p \cdot (T_2 - T_1)$) can be calculated using Eq. (2) [8,9,12,13]. Eq. (1) is thus used to calculate the exergy of heat transfers across a system boundary, while Eq. (2) is used to calculate the exergy of the sensible heat transferred by a flow of matter such as ventilation air or water.

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

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