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A better way of looking at energy systems

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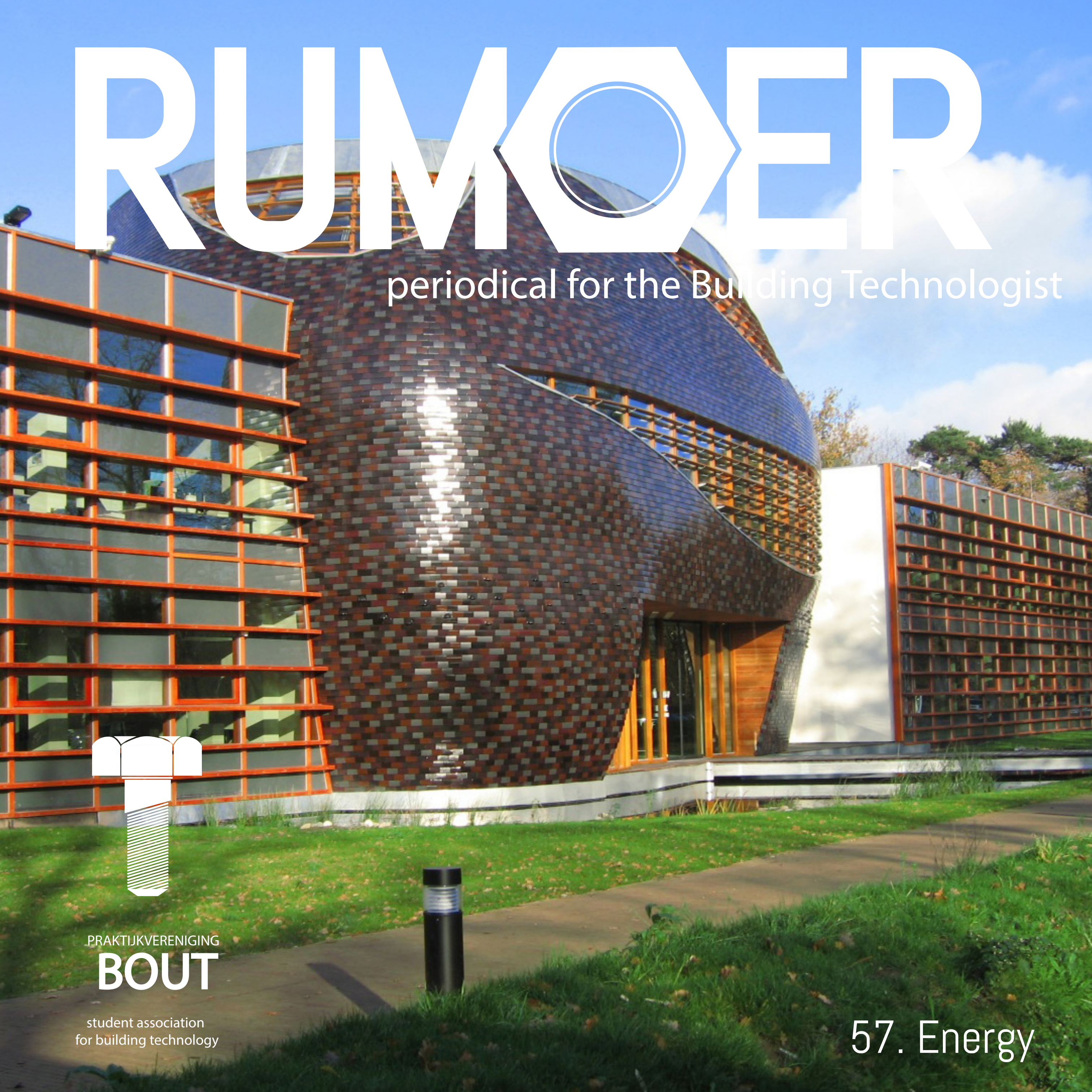

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57. Energy

Exergy

A better way of looking at energy systems

Written by: Sabine Jansen

Sabine Jansen studied at the Faculty of Architecture of Delft University of Technology and received her master's degree within the Building Technology master programme in 2002. After her studies she moved to Barcelona, Spain, where she worked at Aiguasol Enginyeria as a consultant on building physics and energy use in buildings. In 2004 she returned to the Netherlands where she worked for Deerns Consulting Engineers and Cauberg-Huygen Consulting Engineers.
In December 2006 she started her PhD research on the application of exergy in the built environment, supervised by Professor Peter Luscuere and Professor Andy van den Dobbelsteen. She successfully defended her thesis entitled "Exergy in the built environment: The added value of exergy in the assessment and development of energy systems for the built environment" on November 5th 2013.

The law of conservation of energy, stating that energy cannot be created nor destroyed, is inadequate to measure the performance of energy systems in the built environment: Even though energy figures suggest differently, these systems generally present a very poor performance, as they achieve only a fraction what is theoretically possible. By looking at exergy a much more meaningful insight into the performance of energy systems is obtained, which can greatly support the development of energy systems with a reduced need for high quality energy.

What is exergy ?

Most people, including engineers, look at energy systems through 'first law' spectacles: the amount of energy going into a system is equal to the amount going out. The fact that the energy has changed from one form to another (for example from chemical energy contained by gas into thermal energy contained by hot water) is obviously important, since it is the objective of the process in the first place, but no further analysis of this change is considered. However, we know from experience that processes always take place in a certain direction: it is possible to heat up water in a pan by using butane gas and to use the pan of hot water to heat up cold water in a bathtub, but the reverse process is not possible. In these two processes the energy may not be lost, but something must be lost since we cannot re-obtain the original situation without adding new energy. What is lost in this process is the 'exergy' of the energy, which is often referred to as the 'quality' of energy. Figure 1 shows a sketch of this process, which in fact is very similar to the traditional way of heating our homes by using a condensing boiler. The energy efficiency of this process is 100%, but the exergy efficiency certainly is not.

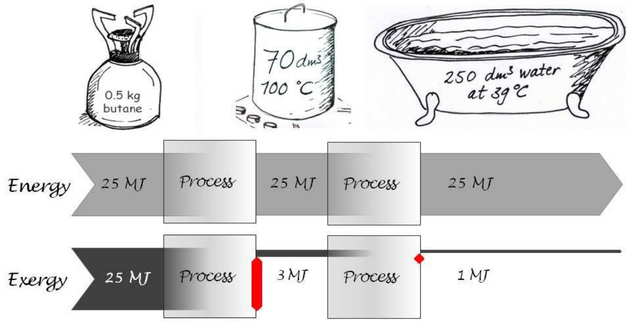

Figure 1. Energy and exergy values of three different forms of energy

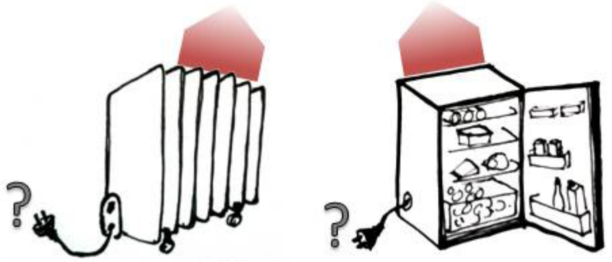

Figure 2. Which device will be more efficient for heating a room: an electrical heater or a refrigerator?

Now let's have a look at another example: Suppose we can choose between an electrical heater and a refrigerator for heating a room. Which device will be the best option for heating the room?

Both devices use electricity as input and both devices have to obey the law of energy conservation. The electrical heater converts all electricity into heat, which means the energy efficiency is 100%. The refrigerator on the other hand 'produces' cold: It extracts heat from the inside of the fridge and emits heat at the back of the fridge. In fact, it transfers heat from the colder to the warmer side by using electricity. In order to obey the energy conservation law the amount of heat emitted at the back must equal the amount of electricity plus the amount of heat extracted from the inside of the fridge. As a net heat 'producer' the fridge therefore also has an energy efficiency of 100%.
This fact will not be new to people familiar with heat pump systems, as will be the fact that you can choose to put only one side of the fridge to the room and the other to the outside. This way the resulting heating (or cooling) can exceed the required electricity input. The efficiency of heat pumps or refrigerators can thus exceed 100% and is therefore usually referred to as the 'coefficient of performance' or COP. Naturally, the process still obeys the first law, due to the intake of 'free' heat at the cold side of the device.

The fact that heat pumps perform better than electrical heaters is also not new, but the shortcomings of the energy approach become very clear when evaluating these devices: If the energy efficiency of an electrical (resistance) heater is 100%, while we know we can use the same electricity plus an additional input of 'free' energy with no value to produce more heat, what is the significance of this 100% energy efficiency? It does not mean the process cannot be better. We know it can be better. Common heat pumps have COP's around 4, meaning 4 times as much heat can be produced with the same amount of electricity.

That's much better, but still these values are no indication of how much heat (or cold) could ideally be obtained with the same electricity.

This is why exergy has such a great added value in addition to energy: While an energy efficiency of 100% does not necessarily mean the process cannot be improved, the ideal and therefore maximum exergy efficiency is always 100%, since in thermodynamic ideal processes no exergy is lost. All real exergy efficiencies are below this value and

Energy form	***Exergy factor f_{ex} (Exergy/Energy)***
Kinetic energy	1
Potential energy	1
Electrical energy	1
Solar radiation	0.9336 [a]
Chemical exergy of some fuels:	
Coal	1.03 [b]
Wood	1.05 [b]
Natural gas	0.94 [b]
Exergy of heat (for T_0= 5 °C):	
at 1600 °C	0.85
1000 °C	0.78
200 °C	0.41
100 °C	0.25
60 °C	0.17
20 °C	0.05

[a]= Szargut, 2005, p.39

[b] = ratio of chemical exergy of the fuel to the higher heating value (Szargut 2005)

Figure 3. Exergy factors of various forms of energy and fuels

the distance from 100% quantifies the exergy losses and thereby the ideal improvement potential. Exergy therefore does not only indicate where but also quantifies how much an energy conversion could be improved. This information cannot be obtained with an energy analysis.

Thermodynamic definition of exergy and the exergy factor

In thermodynamics, exergy is defined as 'the maximum amount of work obtainable from a system as it comes to equilibrium with the environment'. The reference environment is the surrounding environment that is unlimitedly available and unaltered as a result of a process; the environment can thus be used as an unlimited energy source (as is the case with the heat pump example) or sink of a process.

The exergy factor f_{ex} is defined as the amount of exergy per unit energy. Energy with a high exergy factor can be called 'high-exergy' or 'high-quality' energy; energy with a low exergy factor can be called 'low-quality' or 'low-ex'

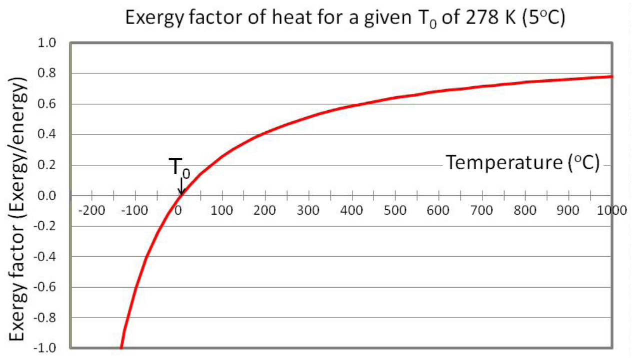

Figure 4. Exergy factor of heat according to equation f_{ex}=exergy/energy=(1-T_0/T) (in Kelvin)

energy. In figure 3 the exergy factors of various forms of energy are listed. The exergy factor of heat depends on the temperature according to the formula (1-T_0/T), where T_0 is the temperature of the environment (T in Kelvin). In figure 4 a graph of the exergy factor of heat is shown.

The exergy performance of current energy systems

Now let us have a look at the performance of current energy systems for the built environment. The doctoral study by the author (Jansen, 2013) presents a detailed study of the exergy performance of several current energy systems for a Dutch single family dwelling. In this article the results of the following three cases are briefly described:
Case 1) using a radiator and a condensing boiler.
Case 2) using a radiator and a small-scale unit for combined heat and power production (micro CHP)
Case 3) using a heat recovery unit, floor heating and a heat pump.

All cases are based on the same type of single family terraced dwelling ('Senternovem referentie tussen woning' in Dutch) with an equal demand for space heating. The energy and exergy demand of this dwelling are displayed in figure 5, together with the energy and exergy input of these three cases. For all cases the electricity is assumed to be supplied by a best practice gas power plant, which means the input of all cases consists of natural gas only. By assuming an exergy factor of 1 for gas, the exergy value of the input equals the energy value of the input.

As can be seen the exergy values of the electricity demand are equal to the energy values, but the exergy demand for heating (both space heating and domestic hot water) is much smaller than the energy demand. The energy efficiency of the system (defined as the energy demand divided by the energy input) seems quite good – especially of case 3 where the 'free' outdoor air is not included in the input – but the exergy efficiency (exergy demand divided by exergy input) is relatively low. This means that in theory there is a large room for improvement, which cannot be concluded from the energy figures.

In figure 6 the energy and exergy losses occurring at each system component of the cases studied are shown. This chart shows two bars for each case study: one bar for the energy values and another for the exergy values. The first item on each bar represents a copy of the energy or exergy demand; the subsequent stacked items represent the energy or exergy losses occurring in each system component. The demand and losses together equal the total input as shown in figure 5.

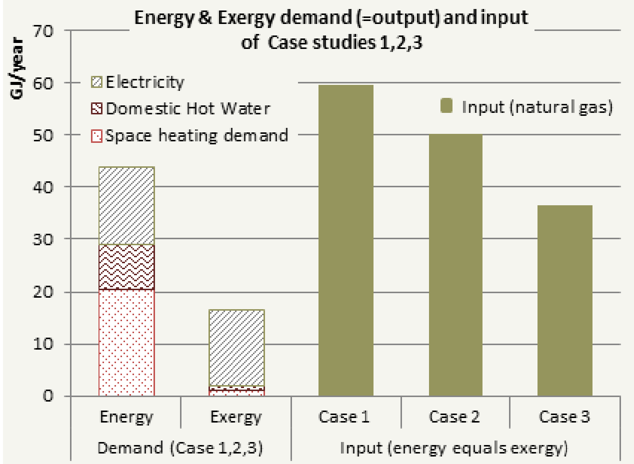

Figure 5. Energy and exergy demand of cases 1, 2 and 3.

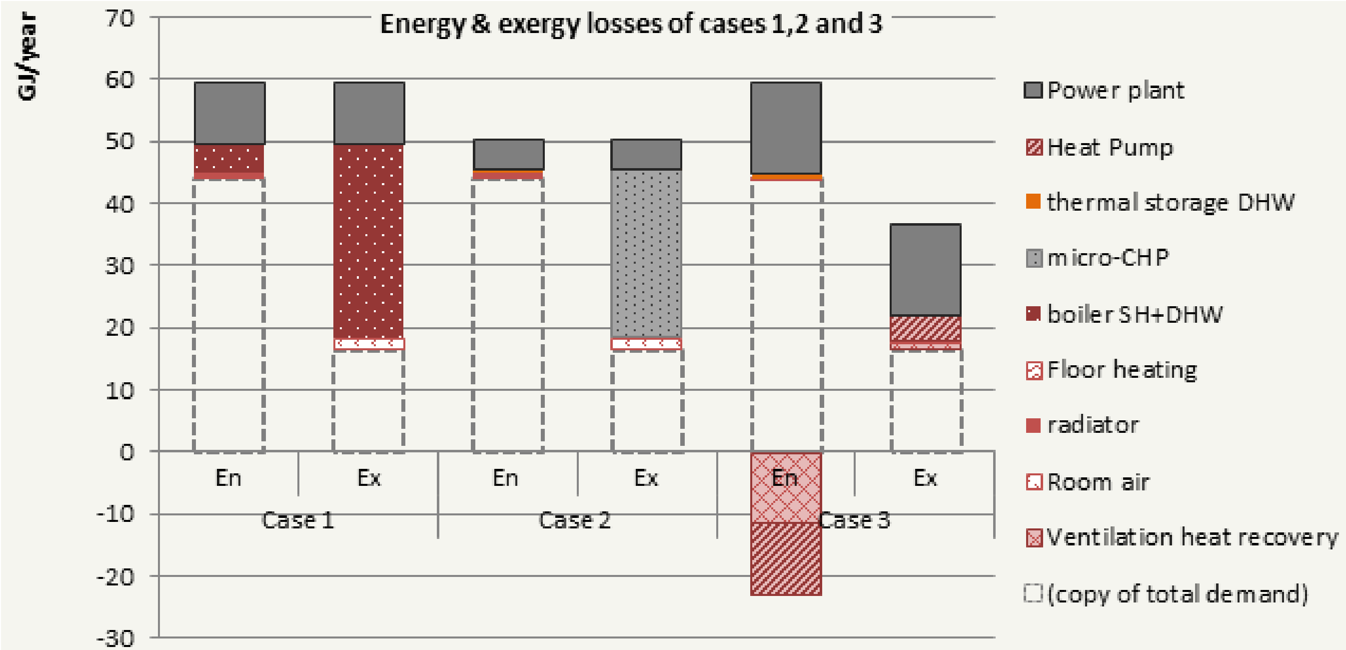

Figure 6. Energy and exergy losses of cases 1, 2 and 3.

The exergy losses (referring to both losses and destruction) offer a totally different insight than the energy losses: The first losses are introduced in the 'room air' component, presenting the losses between the demand (at indoor temperature) and the emission system. These losses are nonexistent in the energy approach. Furthermore major exergy destruction takes place in the boiler, as is almost commonly known. Also significant exergy destruction takes place at the Micro CHP, while the energy efficiency is 100% (80% heat and 20% electricity). Moreover, the heat pump and the heat recovery system present exergy losses, even though the energy losses are considered negative as a result of disregarding the input of free environmental or waste heat. It can also be concluded that the main losses take place in the components used for space heating and domestic hot water; the exergy efficiencies for providing heating are therefore particularly poor.

These results show that exergy analysis points in a totally different direction for improving these systems than energy analysis. While the energy figures suggest that the only way to reduce the required high-quality energy input is to (further) reduce the demand, the exergy figures show that the heating demand is actually low-ex energy and that avoiding exergy destruction can also reduce the input significantly. An energy approach leads to concepts such as the passive house concept (i.e. a drastic reduction of the demand), while an exergy approach shows it can be equally beneficial to develop a smarter and exergetically more efficient system.

Closure: What to expect from the exergy approach?

From the introduction to exergy and the case studies presented in this article it can be concluded that:

- Exergy offers a different and more meaningful insight into the performance and improvement potential of energy systems than energy.
- Our current energy systems have a very poor performance when compared to the ideal, which means theoretically there is much room for improvement

In Jansen (2013) several guidelines are given to use the exergy concept for developing systems with minimized exergy losses and thus reduced input of high-quality energy, including the use of exergy principles and the use of quantitative analysis of exergy losses. Further research is required to investigate the maximum efficiency obtainable in practice. As explained in this article exergy is a better tool for this investigation than energy. The more you know about exergy, the stranger it seems not to use it.

The application of the exergy concept to energy systems in the built environment is relatively new but it received growing interest in the last two decades. Much literature can be found on the topic and two related international research projects have taken place: IEA ECBCS Annex 37 (www.lowex.net) and IEA ECBCS Annex 49 (www.annex49.com).
This article is partly based on the authors' doctoral study, which is mentioned in the biography.