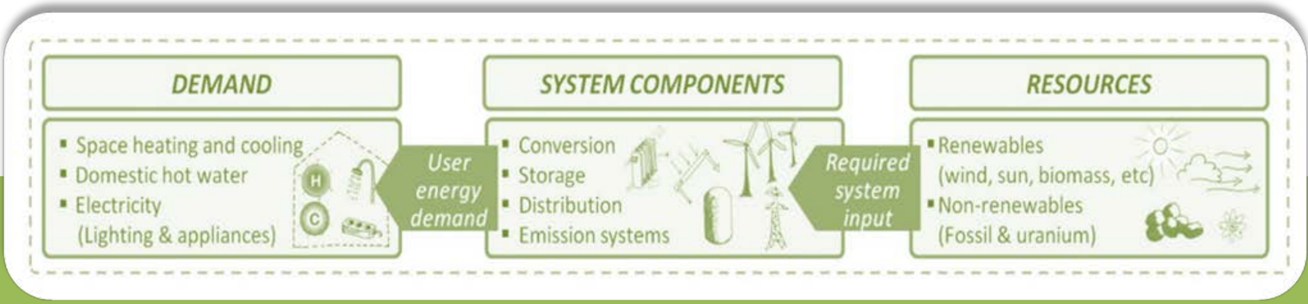
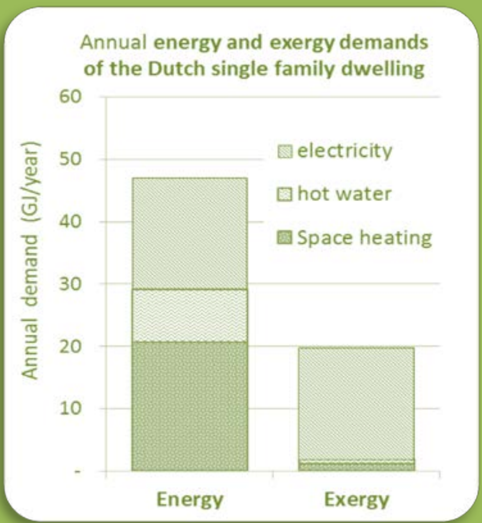
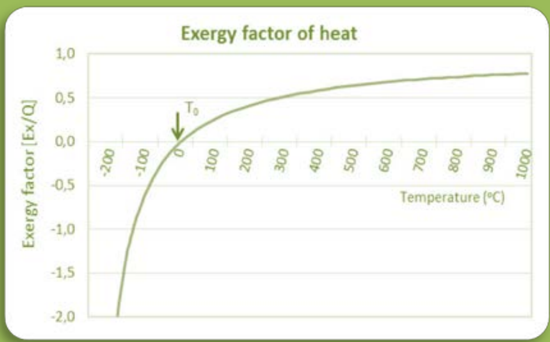
Exergy Guidebook for Building Professionals

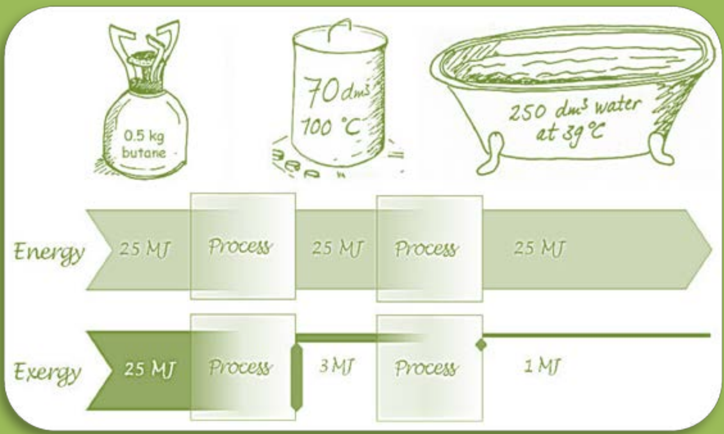
How to use exergy to analyse and develop energy systems for the built environment

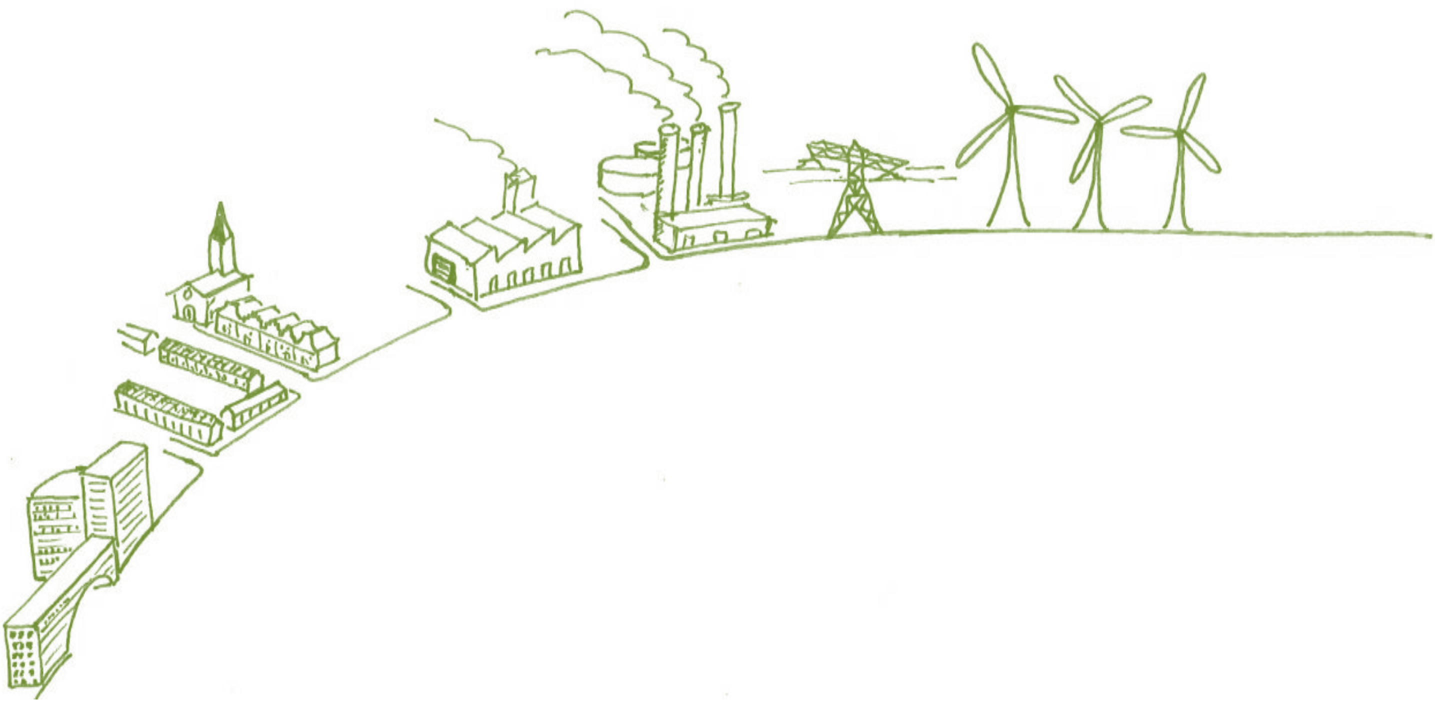
Sabine Jansen











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How to use exergy to analyse and develop energy systems for the built environment

Sabine Jansen

Delft University of Technology, October 2014, Delft

Based on the doctoral thesis 'Exergy in the built environment - The added value of exergy in the assessment and development of energy systems for the built environment' by Sabine Jansen. (2013).

This publication is realised with the financial support of RVO ('Rijksdienst voor Ondernemend Nederland', before named Senternovem), within the Long Term Energy Research Programme (EOS LT02003). This support is gratefully acknowledged.

Preface

Imagine a man who is going to an exchange office to convert 100 euros into Mexican pesos. The cashier gives him 98 Mexican pesos for this transaction, and the man is very happy, since this seems a very efficient deal...

At home, his wife is heating their home using a very efficient condensing boiler. In this boiler 100 Joules of chemical energy (contained by natural gas) are converted into 98 Joules of heat to supply to their floor heating systems. She is also very happy, since this seems a very efficient process.

Now, the husbands holidays are cancelled and he wants his euros back for his 98 Mexican pesos. So he returns to the exchange office. But this time, he only gets 5 euros back… Now he gets really upset! He only gets back a fraction of his input!

Most people reading this preface will think the man is not very clever. He should have checked the value of his currency before going to the exchange office, in order to know the value of his currency and ideal exchange rate for the desired conversion[1].

Almost nobody will consider the wife to be silly, since boilers are generally believed to be highly energy efficient, as almost all the chemical energy is converted into heat.

However, after reading this book, you will consider the wife to be equally stupid.

You will learn that by neglecting the difference between various forms of energy and the ideal convertibility of one form of energy into another, the energy concept does not give a full representation of the energy performance of a process or conversion. The exergy concept, which is the topic of this book, provides a much better and more meaningful representation. In fact, the exergy concept can determine the 'ideal exchange rate' of one form of energy into another. It can therefore compare a conversion with the ideal conversion, which is a good measure of its performance. A better insight into the performance also provides a better insight into further improvements. Therefore, this book will hopefully support a better use of the potential of our resources.

[1] Exchange rate of Mexican pesos for euro's dd. October 2014: 100 Mexico Peso = 5,91 Euro.

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Summary

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.

Why use 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 0-1 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. The red bars in this figure represent the exergy losses of each process.

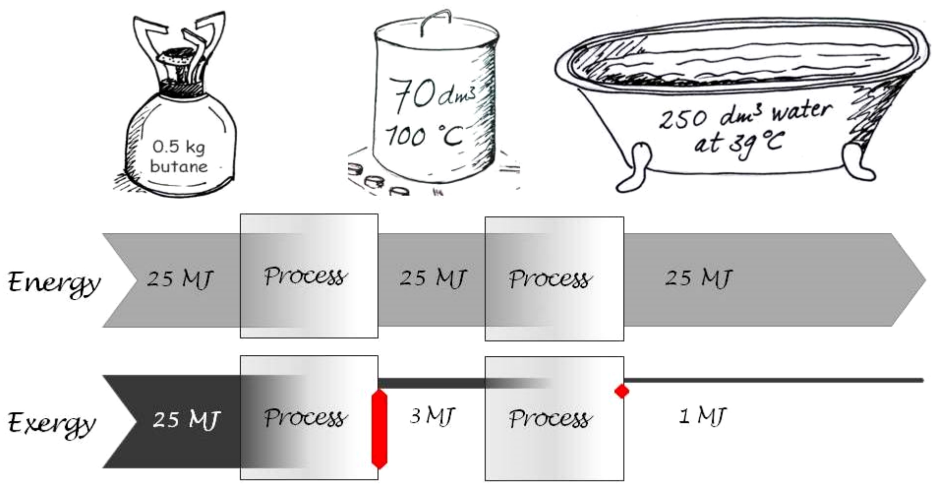

Figure 0-1: Energy and exergy values of three different forms of energy.

This example clearly shows that the *energy quantity* is not the only relevant information when evaluating the performance of an energy process: also the *form of energy* is very important. However, the form of energy is usually not regarded in the analysis of energy systems. As can be seen from figure 0-1, important information is missing when looking only at energy: the fact that something is lost.

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?

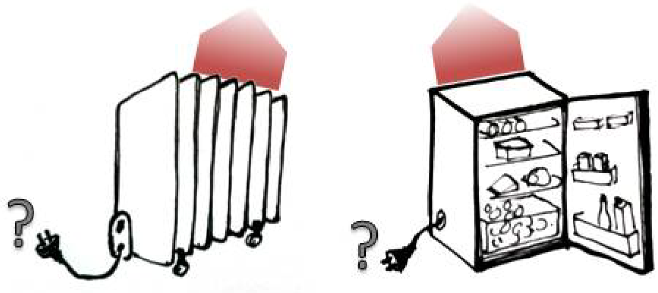

Figure 0-2: Which device is more efficient for heating a room: an electrical heater or a refrigerator?

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, and thus also produces heat. 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 a COP 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 do not indicate how much heat (or cold) could ideally be obtained with the same electricity.

The added value of exergy & ideal improvement potential

As shown in the examples on the previous two pages, energy efficiencies are incapable of indicating how far a process is from the ideal conversion of the energy in the form of an available input into the form of the desired output. The ideal energy efficiency can be either below 100% (when converting low-quality energy into high-quality energy), or above 100% (when converting high-quality energy into low-quality energy, as is the case with the fridge).

This is why exergy has such a great added value in addition to energy: According to second law of thermodynamics no exergy is lost in a thermodynamically ideal process, which means the ideal exergy efficiency is always 100%. In all real processes however exergy is lost, often even in large amounts as is shown in the example of figure 0-1. All real exergy efficiencies are thus below 100%, and 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 is not 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.'* In short, exergy is the '*ideal work potential*' of an amount of energy. 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 to supply energy or sink to receive energy.

To express the 'quality' or 'work potential' of a certain form of energy often the exergy factor (f_{ex}) is used, which is defined as the amount of exergy per unit energy. 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 0-3 the exergy factors of various forms of energy are listed; in figure 0-4 a graph of the exergy factor of heat according is shown. 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' energy.

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 0-3: Exergy factors of various forms of energy and fuels

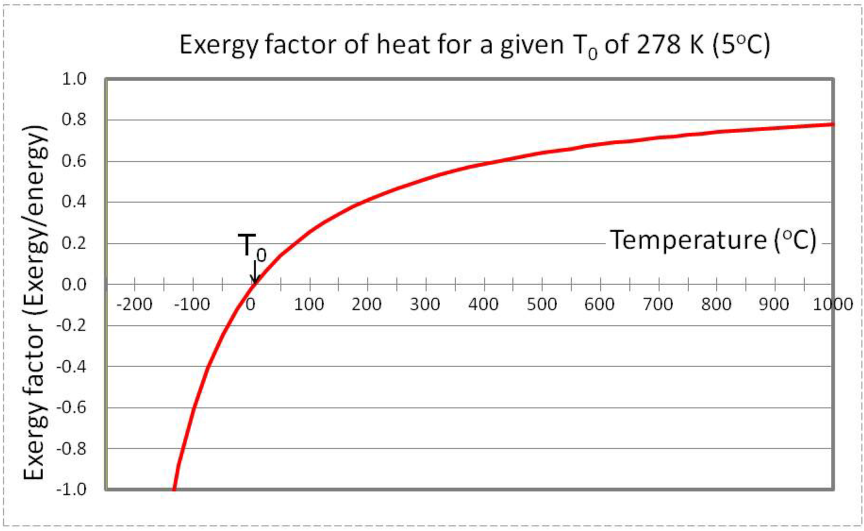

Figure 0-4: Exergy factor of heat according to equation f_{ex}=exergy/energy =(1-T_0/T) (in Kelvin)

Exergy performance of current energy systems

Now let us have a look at the performance of some current energy systems for the built environment. The following three case studies are discussed in chapter 3 of this book and the results are briefly discussed below:

Case 1) system with a radiator and a condensing boiler.
Case 2) system with a radiator and a micro CHP (combined heat and power)
Case 3) system 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 0-5, together with the energy and exergy input of these three cases. For all cases the only primary energy input is in the form of natural gas: electricity is assumed to be supplied by a best practice gas power plant, the boiler and micro CHP are directly supplied with natural gas. Since gas is a high-quality energy input with an exergy factor of approximately 1, the exergy value of the input equals the energy value of the input.

As can be seen the exergy demand for heating (both space heating and domestic hot water) is much smaller than the energy demand, while the value of the exergy demand for electricity is equal to its energy value. The low exergy demand for heating is due to the low quality of this demand, as can be seen in figure 0-4: the exergy factor of the heat demand of the built environment is below 10%, meaning that in an ideal case only 10% of high quality input is required.

The energy efficiency of the system (defined as the energy demand divided by the energy input) is 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, an insight that cannot be obtained from the energy figures.

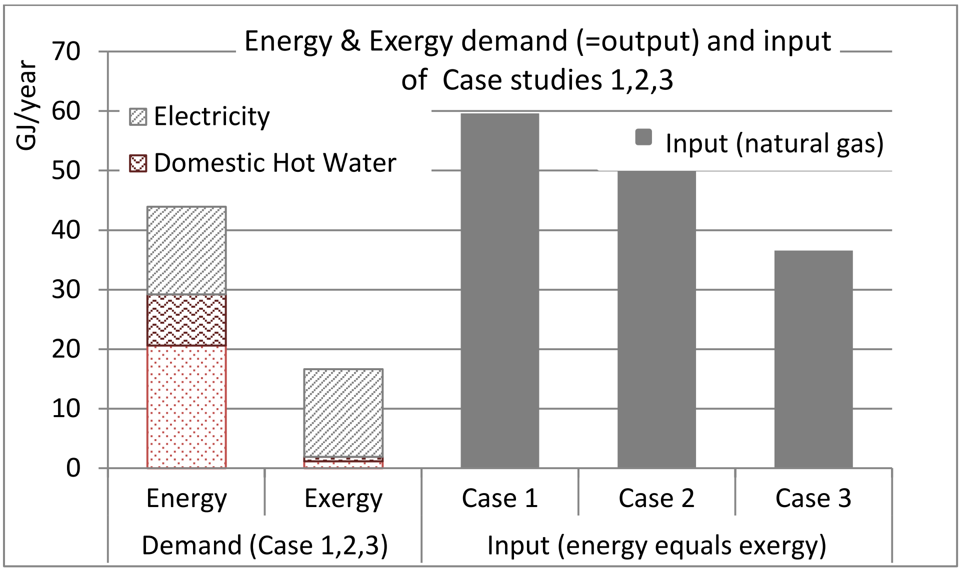

Figure 0-5: Energy and exergy demand of cases 1, 2 and 3.

In figure 0-6 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 (e.g. boilers, radiators, heat pumps etc.). The demand and losses together equal the total input as shown in figure 0-5.

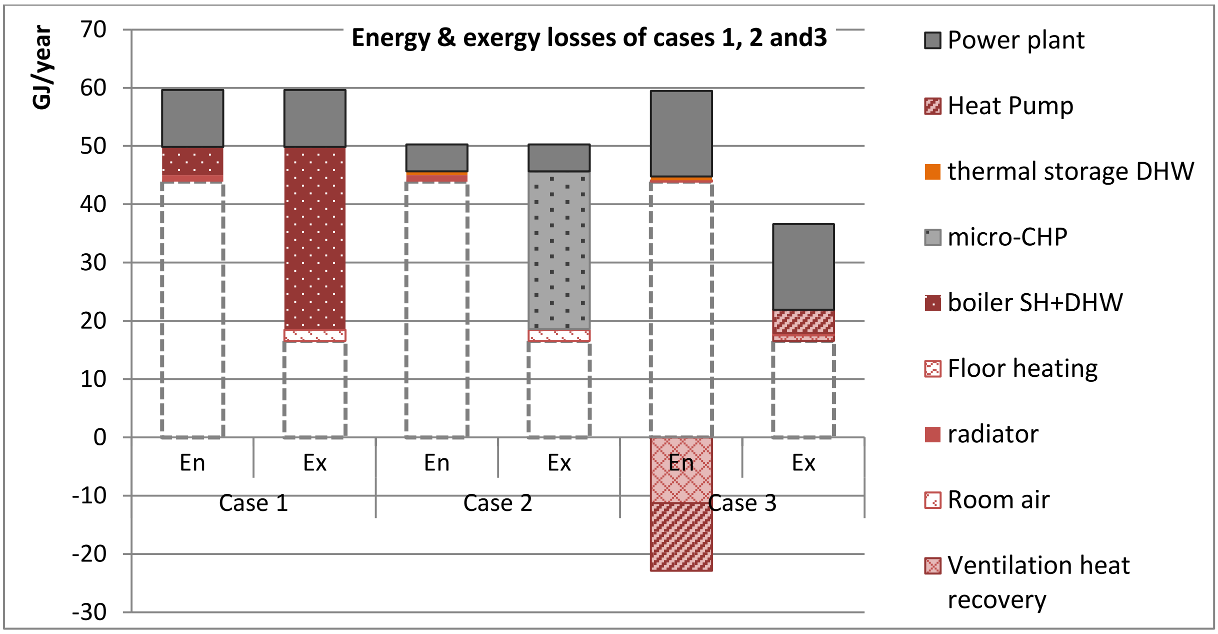

Figure 0-6: Energy and exergy demand of cases 1, 2 and 3.

The exergy losses offer a totally different insight than the energy losses: The first losses are introduced in the so-called ‘room air’ component, presenting the losses between the demand (at indoor temperature) and the emission system. These losses are non-existent 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 plus 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.

How to use exergy to develop improved systems

The examples shown in the previous section demonstrated the added value of exergy to provide additional insight into where systems could be improved. The next important question is obviously: How can this help us to actually develop better performing systems?

The first answer is unfortunately slightly disappointing: exergy analysis does not automatically lead to solutions. However, the concept can provide guidelines for the design of energy systems with minimum use of high-quality resources. The exergy concept can mainly be used in two ways:

1) By using exergy principles to be considered when developing energy concepts.
2) By using exergy analysis to quantify exergy losses at each step of an energy chain.

While exergy principles can be used to generate energy concepts with maximum potential to minimize exergy loss and thereby minimize the need for high-quality energy input, a quantitative analysis can help to further improve a (preliminary) energy concept.

The exergy principles aim at minimizing the exergy losses by choosing the right processes and combination of processes, and by making the best use of the potential synergy between all demands and resources within a project. All principles are described in chapter 4 and summarized below:

Principle 1: *Avoid large chains of components.*
Principle 2: *Match the quality of demand and supply.*
Principle 3: *Use exergy smart thermal storage strategies.*
Principle 4: *Use high-quality energy sources effectively.*
Principle 5: *Avoid processes known to cause exergy losses*
Overall: *Take an integrated and exergy-ware approach of the overall 'problem'.*

When applying such principles during the 'conceptual' design phase, when the first concepts are generated, the most promising concepts will be developed and fundamentally flawed systems (that have many unavoidable exergy losses) will be avoided. The next step, the exergy analysis, can further support improvement of a given concept.

Using exergy principles and exergy analysis is can support the development of better energy systems. These make better use of the potential of energy resources and thus reduce the required input of high-quality energy.

What to expect from the exergy approach?

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.
- The exergy approach, including the use of exergy principles and the use of quantitative analysis of exergy losses can support the development of energy systems with minimized exergy losses.

This seems all very promising. However, to develop energy systems with significantly higher efficiencies than current best practice energy systems is not easy, even though overall exergy efficiencies - even of best practice examples - are not very high. Two important reasons for this can be given: Firstly, various processes are needed to get the energy in the right form at the right time and place. As each process requires a driving force in order to take place the exergy losses in a total energy chain easily add up. Secondly, a designer of energy systems for the built environment is dependent of existing system components.

To significantly reduce exergy losses and hence improve energy systems for the built environment, further development of essential system components is necessary. The following components demonstrated to be essential for highly exergy-efficient systems: heat pumps (HP), combined heat and power systems (CHP), exergy smart thermal energy storage (TES), ventilation preheating systems and heat recovery , intelligent building control systems and finally very-low-temperature emission systems for heating & very-high-temperature systems for cooling.

Further research is required to investigate how much further we can improve the energy systems for the built environment and how much more we can reduce the need for high quality energy. As shown in this summary and explained in more detail in the following chapters of this publication, exergy is a better tool for this investigation than energy. This publication will hopefully broaden your vision on energy:

The more you know about exergy, the stranger it seems not to use it.

1 Introduction

About this publication

Exergy is a thermodynamic concept that can be used to evaluate the performance of energy systems. It provides additional insight by showing how far energy process are from the theoretically ideal process. Due to this added value, the application of the exergy concept to energy systems for the built has increased in the last decades. This is however primarily in scientific publications; the application in practice is still very rare.

This book aims to provide a clear handbook on the use of exergy in the built environment as well as on its added value in addition to an energy approach. It provides:

1. An introduction and explanation of the concept of exergy
2. Instructions on how to calculate exergy for processes relevant for the built environment
3. Exemplary case studies demonstrating the exergy performance of current systems as well as the difference between energy and exergy assessment
4. Guidelines on how to use the exergy concept to develop improved systems
5. Outlook: What to expect from the exergy approach

This publication is based on the authors doctoral thesis, entitled 'Exergy in the built environment – The added value of exergy for the assessment and development of energy systems for the built environment', which was published in November 2013. This means that apart from the general chapter on understanding the exergy concept, this book also presents the most important findings and conclusions from this research. Where possible additional simplifications are provided. The details regarding calculation approaches, case studies and conclusions can also be found in the aforementioned thesis.

Additional text frames

Sometimes additional text frames are used to present further discussions on a certain topic. These are not required for understanding the essential content of the book, but do give interesting additional knowledge or background.

Acknowledgement

This publication as well as the aforementioned thesis are realised with the financial support of RVO ('Rijksdienst voor Ondernemend Nederland', before named Senternovem), within the Long Term Energy Research Programme (EOS LT02003). This support is gratefully acknowledged.

The people who contributed to the doctoral thesis have also indirectly contributed to this publication, for which I would also like to express my gratitude (Sabine, October 2014).

Background: Energy use in the built environment

The built environment accounts for around 40% of the energy use in many European countries. This energy is used to provide heating, cooling, lighting and the electricity used within these buildings for appliances such as computers and dishwashers.
For getting the energy in the form we need it (heat, cold, lighting or electricity) at the right time and the right place, the available energy resources need to be converted (from one form into another), distributed and stored. Energy systems for the built environment can thus be described as consisting of a user demand on the one hand, the energy resources on the other and energy system components for conversion, distribution and storage in-between. A general scheme of energy systems in the built environment including environmental impact is shown in figure 1-1.

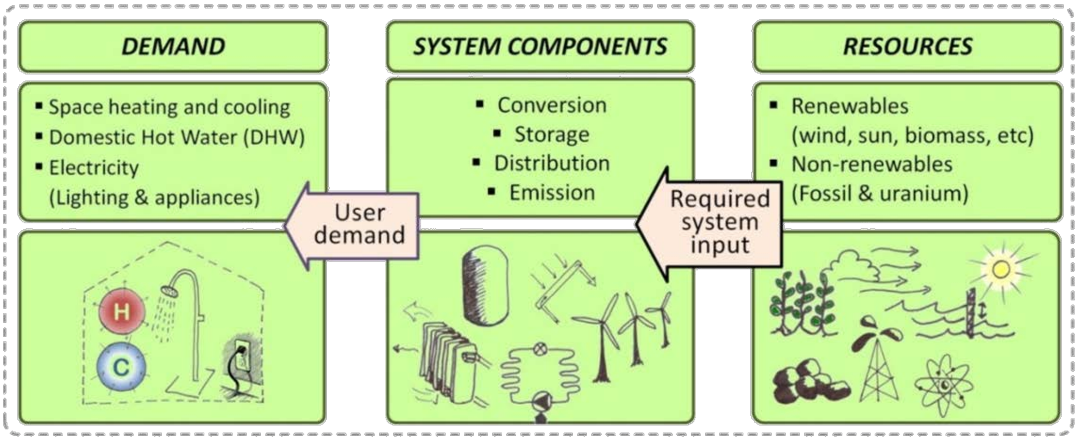

Figure 1-1: General scheme of energy systems for the built environment

As a first condition for sustainable energy systems for the built environment the required energy input must be supplied with renewable energy resources. To achieve this, a combination of reducing the required input and increasing the renewable supply is needed.

A reduction of the required input can be achieved by a smaller demand (smarter, more efficient or 'bioclimatically designed' buildings and smarter users) and more efficient system components (smarter and more efficient systems). Furthermore, the possibilities of using 'low-quality' renewable energy sources such as waste heat or environmental heat can be increased.

Traditionally these systems are regarded using an energy approach. However, as will be explained in this book, exergy can provide added value for improving these systems. The energy concept, which does not differentiate between different forms of energy, 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.

The exergy approach applied to energy systems in the built environment

Due to the expected added value of using exergy to analyse systems for the built environment, the interest in the application of the exergy concept to energy systems for the built environment has increased in the last decades, although this is still primarily in scientific publications. In the text frame below a very short literature review is provided. In the daily practice of engineers and energy consultants for the built environment, the exergy concept is still hardly used.

Short literature overview

The concept of exergy originates from the second law of thermodynamics, which was 'discovered' in the nineteenth century. In 1956 the word 'Exergy' was introduced by Zoran Rant (Rant, 1956), to refer to the amount of work 'ergon' that could be obtained from a form of energy (ex-ergon). Traditionally, exergy analysis is applied to chemical and mechanical processes. Application to the energy systems for the built environment is relatively new.

Some early works applying the exergy concept to energy systems for the built environment include for example Nieuwlaar and Dijk (1993) and a practical study by Haskoning (1994), but interest increased in the last years. Two international research activities on the topic have taken place in within the framework of the International Energy Agency (IEA) - Energy Conservation in Buildings and Community Systems (ECBCS) Programme: Annex 37 (1999-2003) 'Low- Exergy Systems for heating and cooling', and Annex 49 (2005-2010) 'Low Exergy Systems for High Performance Buildings and Communities'. CosteXergy is a third international activity within the European framework for Cooperation in Science and Technology (www.cost.eu) that took place between 2006 and 2011. In 2013 a new IEA activity has started (IEA EBC Annex 64 'LowEx Communities: Optimised Performance of Energy Supply Systems with Exergy Principles').

Also many scientific publications on the subject of exergy analysis of energy systems in the built environment have appeared in these recent years. A thorough review of exergy analysis related to renewable energy systems for the built environment is given by Torío et al. (2009). Several case studies on energy systems for the built environment can be found in literature. Most of these are steady state based calculations of heating systems (often based on an excel based Pre-design tool that was developed within the Annex 37 and Annex49). A small number of publications using a dynamic approach can be found. The exergy of cooling is hardly discussed.

Also studies applying the exergy concept to large-scale energy system design can be found, one of the first being the study by Haskoning (1994). This application can be considered an emerging field of science (e.g. the SREX project 'Synergy between regional planning and Exergy', www.exergieplanning.nl). The larger scale is also the focus of the new IEA Annex 64 on 'LowEx Communities'.

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2 Understanding 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, but it is not possible to use the energy from the hot water in the pan for the synthesis of butane gas. Furthermore, we can use the hot water to heat up cold water in a bathtub, while it is not possible to split the lukewarm water into the original cold water in the bathtub and hot water in the pan. 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 2-1 shows a sketch of this process, which is in fact very similar to the traditional way of heating our homes by using a condensing boiler. The energy efficiency of this process may be 100%, but the exergy efficiency certainly is not.

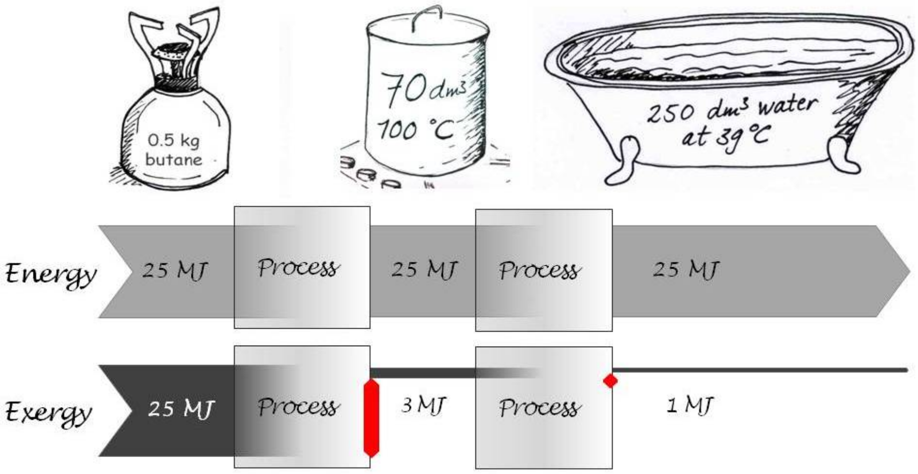


Figure 2-1: Energy and exergy values of the process of using gas to heat water

- ***Even though energy is always conserved, exergy is always destroyed in real processes.***
- ***Only in thermodynamically ideal processes no exergy is lost.***
- ***The exergy losses are therefore equal to the ideal improvement potential.***
  Exergy thus tells us whether a system can be improved and how much.
- ***Exergy gives a more meaningful indication of the performance of an energy system.***

A metaphor for an intuitive understanding of the quality of energy

A metaphor: material efficiencies and energy efficiencies

Imagine a furniture factory, where trees are converted into shelves. Due to the required size of the shelves only 60% of the wood can be converted into shelves. The material efficiency of this conversion is 60%. Now imagine a toothpick factory where trees are converted into toothpicks. If they are very efficient, almost 100% of the wood can be converted into toothpicks. We assume the toothpick factory to have a material efficiency of 98%. According to these material efficiencies the toothpick factory seems to perform better than the furniture factory.

However, one might intuitively consider it rather wasteful to convert this wood with large dimensions into tiny toothpicks: the toothpicks could have been produced from smaller pieces of wood; they could even be produced from the waste from the furniture factory. If the required size of the product is addressed, these options become clear and the total system can be improved, as is shown in figure 2-2. In this example the size represents the quality of the material needed.

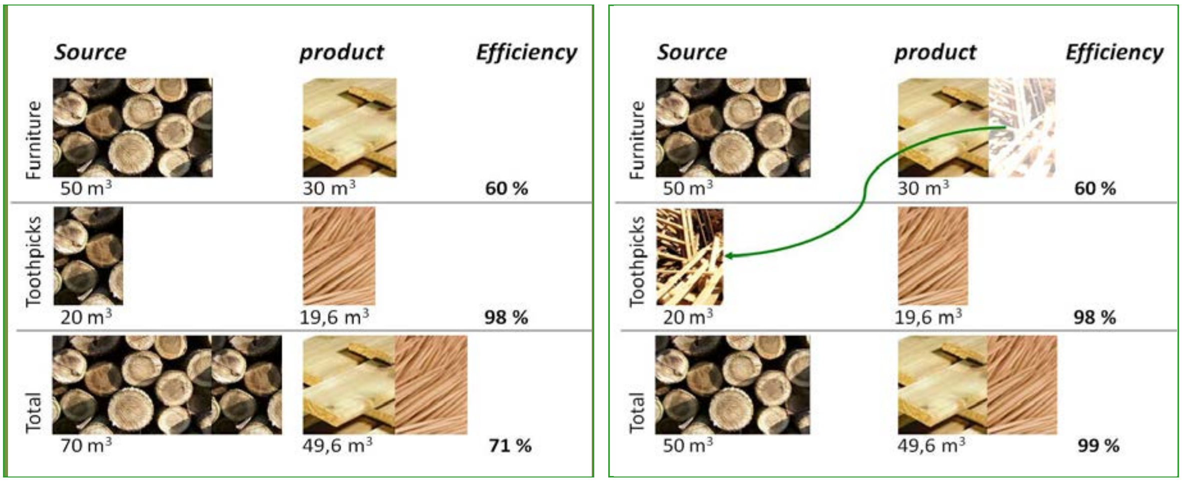


Figure 2-2: Scheme of material efficiencies for different processes. When not only addressing the material need but also the required size of the product, the resource use can be optimised, as is shown in the right figure.

This example shows that apart from the material need it is important to consider the size or quality of the material needed, in order to evaluate the performance of the process and to optimize the use of resources.

- ***A material efficiency that does not address the type of material involved does not give an adequate representation of the performance of a process and is also inadequate for optimizing the use of resources.***

Analogue to this material example the following energy example can be imagined:

Firstly, imagine a power plant or engine converting natural gas into electricity at an efficiency of 60%. The remaining 40% is waste heat (which is partly inevitable according to the second law of thermodynamics, as will be explained in section 2.3). Secondly, imagine a condensing boiler which converts natural gas into heat for domestic heating. The energy efficiency of this equipment is 98%, which means 98% of the energy content of the gas is converted into useable heat.

Also in this energy example the second system (the boiler) seems to perform better than the first. The energy efficiency however does not address the 'quality' of the energy output. As will be explained later in this chapter, heat at indoor temperature is energy at a very low quality level, and it could be provided by a low-quality source; in fact, it could be provided by the unavoidable waste heat from the power plant. In such a way the resource use could be optimized. This is shown in figure 2-3.

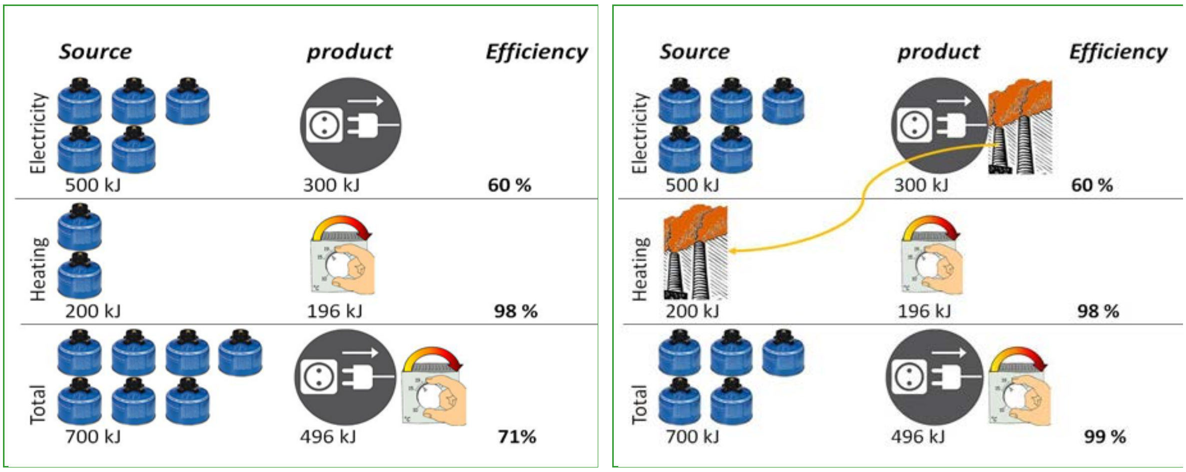


Figure 2-3: Scheme of energy efficiencies for different processes. When not only addressing the energy need but also the quality or exergy of this energy, the resource use can be optimised, as is shown in the right figure.

This example shows that the energy efficiency of almost 100% for converting gas into low-quality heat does not give a correct representation of the performance. The fact that the quality of the energy is degraded and that energy would have sufficed is not identified.

- ***An energy efficiency not addressing the type of energy involved does not adequately measure the performance of energy systems and is not suitable for optimizing the use of energy resources.***
- ***The exergy of a form of energy can be compared to the size or quality of a material. By taking into account the exergy of the energy forms involved, the quality losses can be identified. This can contribute to a better use of resources.***

2.1 Energy and the first law of thermodynamics

Energy

Energy is a concept that includes many different forms, such as electrical energy, kinetic energy, potential energy, chemical energy and thermal energy. Even though the concept of energy is commonly used, it is actually a complex concept and a short scientific definition cannot be given. The most important characteristic of the energy concept that energy is never lost. This is stated in the first law of thermodynamics, the 'law of energy conservation'.

- ***Energy cannot be destroyed nor created: When one form of energy is converted into one or more other forms of energy, the total amount of energy remains equal. The SI unit of all forms of energy is joule (J).***

Energy 'stored' and energy 'transferred'

There is a difference between energy contained by a system (or an amount of matter) and the energy transfer between two systems.

- ***The most common forms of energy that can be contained by a system are:***
  kinetic energy, thermal energy, elastic energy, gravitational energy, electrical energy, chemical energy, radiant energy.
- ***The two ways in which energy can be transferred from one system to another are:***
  Heat & Work

Heat

Heat is the transfer of energy between two systems as a result of a difference in temperature. Heat transfer always takes place from a warmer to a cooler system. This energy is not related to matter. When analysing one system, heat is the transfer of energy across the system boundary, which takes place at the temperature of the system boundary. Heat can also refer to the transfer of energy at temperatures below the environmental temperature T_0.

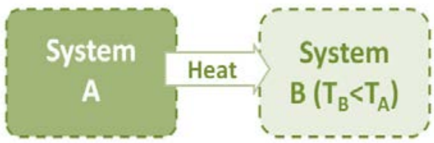


figure 2-4:
Heat is the transfer of energy as a result of a difference in temperature

- ***Heat is the transfer of energy between two systems as a result of a temperature difference.***
  The symbol for heat is Q, and - as heat is a form of energy - the SI unit is J.

Before the nineteenth century people thought that heat was something like a fluid, which they called 'caloric'. Later they found out that heat is actually motion. An interesting history of the understanding of energy is given in the book of Muller (2007).

Work

If a weight is lifted over a certain height it means **work** is done on the weight; the energy transferred by work is converted into gravitational energy of this weight. In general, work is defined as a force acted over a distance. In a simplified way 'work' can be described as 'ordered motion'.

Work is defined as a force acted over a distance.
The symbol for Work is W and - as work is also a form of energy - the SI unit is J.

Heat and work

It is easy to convert work into heat (try rubbing a surface), but it is very difficult to convert heat into work. This is because work is high-quality' energy and heat is 'low-quality energy', and it is not so much related to the first law as to the second law of thermodynamics. This is further explained in the next section.

Background information: Energy quantity versus energy power

Energy quantity

Energy can be measured as a quantity. For example: An average household uses approximately 50 GJ of energy for heating per year. However, for many systems it is not only important how much energy is used, but also how fast the energy is used (for example in order to heat up a building within a sufficiently short period of time).

Power

The rate at which energy is transferred (both by work and by heat) is called the 'power', which defines an amount of energy transferred per unit time.
Power is the rate at which energy is transferred; it is the energy per unit time.
The SI unit for power is Watt (W), which is the same as Joule per second (J/s)

Common units for a quantity of energy

Apart from the SI unit Joule (J) often the unit kWh is used, mostly related to electricity use: 1 kWh (kilowatt-hour) is the amount of energy used when running a system with a power of 1 kW (=1000 J/s = 1 kJ/s) during an hour (3600 seconds):
1 kWh is equivalent to 1000 W x 3600 seconds = 3600 kJ = 3,6 MJ.

Hence, kWh is NOT a measure of power! (a mistake that is often being made). Power is energy per unit time (measured in W or J/S), while kWh is a quantity of energy.

A very clear explanation on basic energy issues is given in the Dutch book by Hermans (2009), the "Energie Survival Gids".

2.2 Entropy, exergy and the second law of thermodynamics

The second law of thermodynamics

Even though energy is always conserved, this does not mean all processes where energy is conserved are possible. For example:

- ***Heat will not flow spontaneously from a cooler to a warmer body***
- ***Heat cannot be totally converted into work.***

These examples are not just accidental examples. In fact, they are the rules of the second law of thermodynamics. The natural law behind the fact that some processes will not take place take place, is that in all process the total amount of entropy must be increased. **Only in ideal processes, there is no creation of entropy.**

Entropy

Entropy is a measure of chaos or spreading. In all spontaneous processes chaos is increased. This means spontaneous processes tend to maximize equilibrium: they minimise differences in temperature, pressure, density, and chemical potential that may exist between systems. A system in total equilibrium is considered as maximum 'chaos' or 'entropy' (symbol S). All real processes are accompanied by the creation of entropy. The entropy change of a system is a calculated with the function $dS=dQ_{rev}/T$ ('rev' stands for 'reversible', see also page 27)

- ***While the energy of the universe will always remain equal, the second law states that the entropy of the universe is always increasing (Feynman et al., 1989)***
  The symbol for entropy is S (and the SI unit is J/K)

There are forms of energy that contain no entropy. These include electrical energy, kinetic energy and potential energy. Also work (see previous section) contains no entropy.

Exergy

Exergy is in a way the opposite of entropy. It is a measure of order or difference between two things. However, there is an important additional feature: exergy always measures the difference between a system (that is: an object containing energy) and its environment. Exergy is therefore a property of a form of energy or a system in relation to its environment.

It can be imagined that in an environment where everything is in total equilibrium nothing will happen. The fact that something is different from its environment (for example: a glass of hot water in a colder room) means there is a 'driving force' for something to happen. A qualitative explanation of exergy can therefore be that something contains exergy when it is different from its environment and thus has a driving force for a process to happen. It can also be imagined that the greater the difference between a system and its environment, the larger the driving force and thus the larger the exergy.

Hence, there is a certain hierarchy within all the forms of energy and exergy is consequently often referred to as 'the quality of energy'. Energy of a higher quality can always be fully converted into energy of a lower quality, and not the other way around.

- *__'High-quality' energy__ refers to a form of energy with high exergy content (and low entropy).*
  __'Low-quality' energy__ refers to energy with a low exergy content (and high entropy).
  __Zero quality energy__ is energy that is in total equilibrium with the environment.
- *High quality energy can be fully converted into low-quality energy;*
  low-quality energy can only be partly be converted into high-quality energy.

Thermodynamic definition of exergy

Referring to exergy as 'the quality of energy' is not the complete definition. Exergy is more accurately defined and exergy is also quantifiable: It is defined as *the theoretical maximum work obtainable from a system as it comes to thermodynamic equilibrium with the reference environment*. In short, the exergy of something can be defined as its 'ideal work potential'.

For the example of the glass of hot water in the colder room, the exergy of the hot water can be quantified as the maximum work that could be obtained while this warm water comes to thermal equilibrium with the room. **The maximum work is obtained using an 'ideal' process.**

- ***In short, exergy is the ideal work potential of a system or amount of energy,***
  while coming to equilibrium with the reference environment.
  The symbol for exergy is E or Ex (Ex is used in this book); the SI unit of exergy is joule (J).

The exergy entropy process

The exergy- entropy process is illustrated in figure 2-5: In a state high exergy (low entropy) the location of the energy is known; in the state of high entropy there is more 'chaos'; the energy can be everywhere.

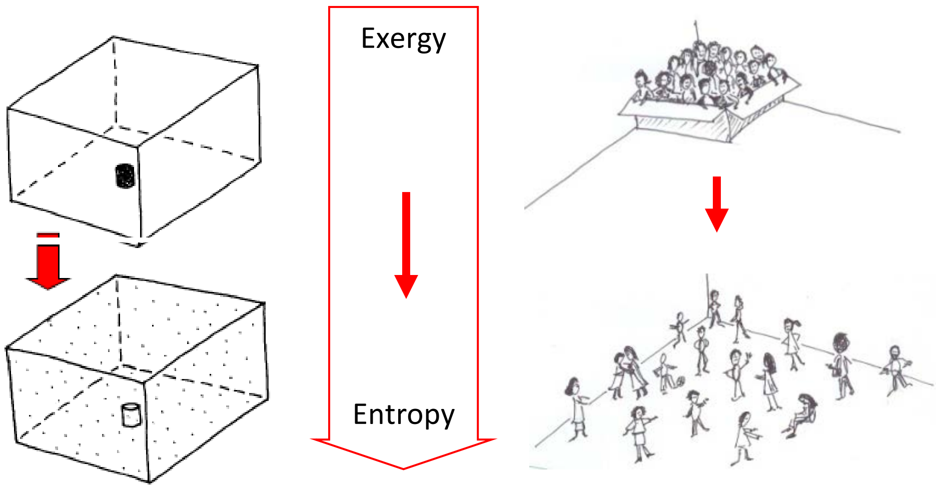


Figure 2-5: exergy-entropy process. Left: as illustrated by Shukuya (2013); right: applied to humans (Jansen, 2013)

What is an ideal process?

Exergy is defined as 'the theoretical maximum work obtainable from a system as it comes to thermodynamic equilibrium with the reference environment. Or in short: Exergy is the 'ideal work potential'. But how do we know what is the theoretical maximum?

The theoretical maximum work is determined by the fact that – as stated in the second law of thermodynamics - in an ideal process there is no creation of entropy. This also implies that the original situation can be re-obtained, which means an ideal process is 'reversible'. This is a very important fact. It means that the exergy of an amount of energy is based on the work obtained with an ideal process that creates no entropy and that is reversible.

- ***In ideal processes the exergy (work potential) of the output equals the exergy of the input.***
- ***An ideal process is reversible and there is no entropy created.***
- ***Ideal processes can never be achieved in reality.***

Reversibility and irreversibility

A reversible process, which was first formulated by Sadi Carnot (Carnot 1824) is a process "in which an infinitesimal change in the external conditions to which a body is subject will cause a reversal of the direction of the process" (Wheeler and Willard-Gibbs 1951), in such a way that the original situation can be re-obtained. A reversible process is for example the heat transfer between two systems at the same temperature. In reality no processes will take place between two systems that are in equilibrium with each other; for something to happen a small difference has to exist, such as a difference in temperature. This means all real processes are irreversible: the initial situation cannot be re-obtained without causing a change somewhere else.

- ***A reversible process is a theoretical ideal process in which no exergy is lost.***
- ***The more irreversible the process (for example: the bigger the temperature difference between two systems that exchange heat), the larger the exergy losses.***
- ***Exergy losses are sometimes called 'irreversibilities'.***
- ***Reversibility is a mathematical limit which can never be obtained in reality.***

The entropy change according to dS=dQrev/T

The entropy change of is system is calculated according to the heat transferred to this system divided by the temperature, given a reversible process. This means the heat is transferred at the temperature of the system. If heat is transferred between two systems at the same temperature (a reversible process), there is no net entropy production: the entropy decrease of the system supplying heat is equal to the entropy increase of the system receiving heat. If the temperatures of the systems differ, there will be a net creation of entropy.

Thermodynamic ideal improvement potential

As repeatedly stated: in ideal process no exergy is lost. The amount of exergy destroyed during a process therefore equals the ideal **thermodynamic improvement potential**. This improvement potential of a conversion process reveals how much more exergy output could theoretically be produced or how much less input would be ideally required. As has been shown in the beginning of this chapter, the improvement potential reveals a potential that cannot be identified by means of energy analyses. **The thermodynamic improvement potential therefore is a key added value of the exergy approach in addition to energy analysis using only the first law of thermodynamics.**

- ***In ideal process no exergy is lost.***
  The amount of exergy destroyed during a process therefore equals the ideal thermodynamic improvement potential.
- ***The ideal improvement potential (IP) cannot be identified using energy analysis: it is therefore the main added value of using exergy***

In real processes exergy is always destroyed, sometimes a little but more often a lot. The aim of using exergy is to minimize the exergy losses, resulting in a reduced need for high-quality energy resources (or an increased output of useful product).

In the figure shown on the first page of this chapter the process of using gas to heat up water in a bathtub was shown (see also below). This process involves large exergy losses. According to what was just called the thermodynamic improvement potential, this means the process can be much better, i.e. more output (heat added to the water) can be produced using the same input. But how does this combine with the first law of thermodynamics? Energy cannot be created so how can more output be produced? This will be explained in the next section.

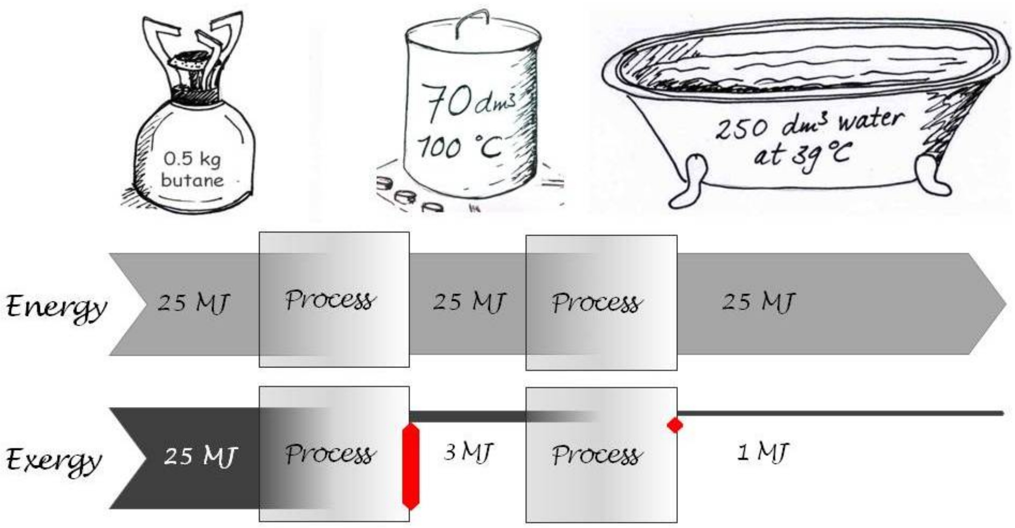


Figure 2-6: energy and exergy losses in the process of using butane gas to heat up water in a bathtub. The exergy losses equal the thermodynamic improvement potential.

2.3 Energy conversions: combining the first and the second law

All conversions have to obey the first and the second law of thermodynamics: energy must be conserved *and* degraded (i.e. exergy must be destroyed). Now, how can these two laws be combined in order to understand how 'high-quality' energy can be converted into low-quality energy and vice versa?

Converting 'high-quality' energy into 'low quality' energy and vice versa

Let us imagine that we convert high-quality energy into low-quality energy. According to the second law the higher quality energy can be converted into 100% of a lower quality. (For example: the pan of boiling water from the previously shown example can be used to heat up cold water in a bathtub).

However, if we want to convert the lower quality energy into higher-quality energy, the second law prevents us from creating the same amount of higher quality energy. Hence, a smaller amount of energy of a higher quality must be obtained. This means that another output of energy must be 'produced', in order to obey the first law of thermodynamics (otherwise energy would not be conserved). This output of 'unavoidable waste' energy must have a lower quality than the quality of the energy used as input (in the example the lukewarm water). The lowest quality possible (0-quality energy) is energy that is in balance with the environment. A scheme of this conversion is shown below:

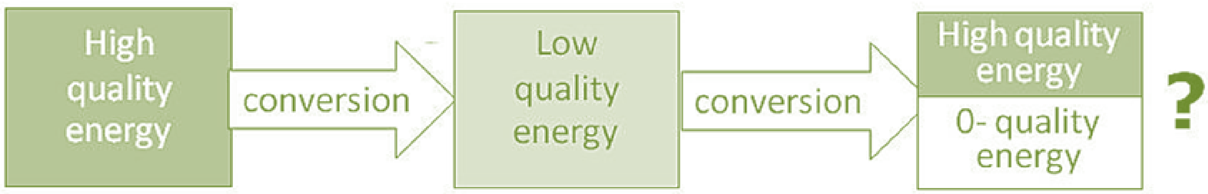


Figure 2-7: Not ideal conversion of high-quality energy into low-quality energy and vice versa.

As can be seen in the above figure the original situation is not re-obtained, which means exergy is destroyed. In an ideal process no exergy is destroyed. Looking at the second conversion of figure 2-7 (converting low-quality energy into partly higher quality energy and partly zero-quality energy), this means that in an ideal process the amount of high quality obtained must be sufficient to produce the original amount of low-quality energy. This also means that in order to be an 'ideal process', high quality cannot be converted into the same amount of low-quality energy, but *a larger amount of* low-quality energy must be produced. But how is this possible while still obeying the first law of thermodynamics?

This is only possible when an amount of high-quality energy *plus* an amount of zero-quality energy is converted into low-quality energy. A scheme of ideal processes is therefore as follows:

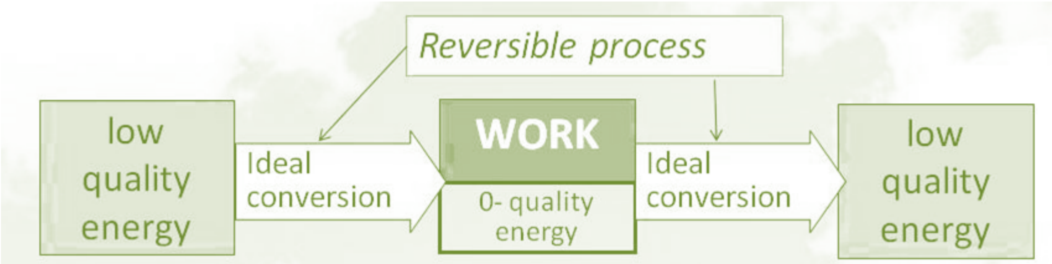


Figure 2-8: Ideal conversions of low-quality into high-quality energy and vice versa. In deal conversions the original situation can be re-obtained. Ideal conversions are therefore reversible conversions.

This may all seem a little bit abstract or theoretic. However, this is not so. Two very commonly used energy processes in energy systems for the built environment are actually in principle doing what is shown in figure 1-8, be it that they include some losses:

- All engines produce motion (or 'work'), together with an unavoidable amount of waste heat. The waste heat is usually low-quality heat, but it could even be almost zero quality heat, in which case the engine could produce more work. Also power plants are based on this principle.
- A heat pump produces heat by using partly 'high-quality' energy (e.g. electricity) and partly low-quality (or zero-quality) environmental heat. Also a refrigerator is based on this principle.

Thus:

- ***When converting low-quality energy into high-quality energy, the amount of high-quality energy is obtained plus and amount of very-low-quality or zero-quality energy.***
- ***Hence, for an ideal (or close to ideal) conversion of high-quality energy into low-quality energy, also an amount of zero-quality energy must be used, in order to produce a larger amount of low-quality energy than the available high-quality energy.***
  (This is in principle what happens in a heat pump process).
- ***This way both the first and second law of thermodynamics can be obeyed.***

<u>Anergy</u>

Sometimes the word 'Anergy' (introduced by Baehr and Bergmann in 1965) is used to refer to the part of an amount of energy that could not be converted to work, or in other words, to the '0-quality-energy' as shown in figure2-8. According to the equation Energy = Exergy + Anergy, an amount of energy is composed of an amount of exergy plus an amount of anergy. By definition energy at the level of the reference environment (0-quality energy) is 100% 'Anergy'.

For the understanding the exergy of systems at a temperature higher than the environmental temperature (i.e. 'heat'), anergy can have an added value; however, for understanding the exergy of systems at temperatures lower than the environmental temperature, the anergy concept becomes confusing by becoming negative in value. In this book the concept of anergy is therefore not further utilized. (For a more detailed discussion see also Szargut, 2005 and Jansen and Woudstra, 2010).

2.4 The exergy factor (f_{ex})

To indicate the thermodynamic potential or quality of a certain form of energy an exergy factor (or quality factor) is often used. It gives the ideal work potential per unit of energy, given the reference environment, and is therefore defined as the ratio of exergy to energy.

$$f_{ex} = \frac{exergy}{energy} \tag{2-1}$$

The process of converting low-quality energy into high quality energy and zero-quality energy is shown again in figure 2-9. The exergy of the amount of low quality energy of the left box equals the work obtained using an ideal process, which is thus the amount of work in the right box. The exergy factor of this low-quality energy is thus the work of the right box divided by the amount of energy in the left box.

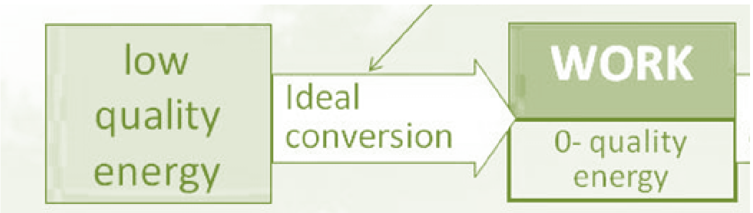


Figure 2-9: Ideal conversions of low-quality into high-quality energy. The work produced from an ideal process equals the exergy value of the low quality energy.

In table 2-1 the exergy factors of various forms of energy are displayed. The calculation of the exergy of heat will be explained in detail in the next section.

Table 2-1: Exergy factors of various forms of energy and fuels

Energy form	***Exergy factor (exergy to energy ratio), f_{ex}***
Kinetic energy	1
Gravitational potential energy	1
Electrical energy	1
Solar radiation	0.9336 (Szargut, 2005 p. 39)
Chemical exergy of some fuels:	
Coal	1.03 [a]
Wood	1.05 [a]
Natural gas	0.94 [a]
Exergy of heat(for T_0= 5 °C):	
Heat 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] ratio of chemical exergy of the fuel to the higher heating value (Szargut 2005)

Using the exergy factor as an exchange rate for energy conversions

To demonstrate the usefulness of the exergy factor we can go back to the story of the man going to an exchange office to convert 100 euro into Mexican pesos, as was described on the first page of this book. Imagine that the cashier plans on giving him 98 Mexican pesos for this transaction. Probably nobody will agree with this deal (at least not in December 2012), although they are both monetary units. Everybody will rapidly find another place for the transaction. Nobody will say this transaction has 98% efficiency, because everyone is aware that different monetary units have an exchange rate for conversion into one another.

However, the majority of all Dutch households is using equipment that converts 100 kJ of natural gas into 98 kJ of low-quality energy, i.e. heat at a temperature somewhat above indoor temperature (around 30°C). This boiler is generally appointed an efficiency of 98%. Hardly anyone is aware of the 'ideal convertibility' or in other words 'the exchange rate' of different forms of energy.

Nature however has ideal exchange rates for energy conversions, since in ideal conversions no exergy is lost. As shown in figure 2-1 the exergy of 0.5 kg of butane is 25 MJ, while the exergy of warm water at 39°C is only 1 MJ, while the energy value of both is the same. This means in this process, which is similar to the process occurring in a household boiler, 96% of the exergy is destroyed. Ideal processes do not destroy exergy; the process is thus very far from what is ideally possible, and if it were a money conversion nobody would agree with it.

A strange metaphor?
This metaphor may seem strange, as how can these two concepts be compared? Aren't euros obviously different from Mexican pesos, while chemical energy and thermal energy are both energy? The answer is: energy is not just energy! The value of one form of energy is not equal to the value of another form of energy, just as the value of one monetary unit is not equal to the value of another monetary unit! We are talking about converting chemical energy into heat, a conversion of one thing into another, and for this conversion there is an ideal exchange rate which determines the theoretically obtainable conversion.

- ***Exergy is a measure of the ideal conversion of one form of energy into another.***
- ***The exergy factor can be used as the ideal exchange rate for converting a given form of energy into high quality work.***

(Note: A similar metaphor was published in a Swedish newspaper in 1975 by Alfvén where he compared the energy accounting, regardless of different energy values, with a cashier counting his cash only by the number of coins or notes, and neglecting their value (Wall, 1986)).

2.5 Energy and exergy efficiencies

Exergy efficiencies are much more meaningful than energy efficiencies. In fact, energy efficiencies can even be misleading. This will be demonstrated using two examples, but first the energy and exergy efficiencies are defined.

Energy efficiency definition

Energy efficiency (η) is commonly defined as: the energy of the desired output or product / total energy input. Since energy is not destroyed the only energy 'losses' in a process are 'leaks' of heat or matter across the system boundary, or unused waste flows.

$$\eta = \frac{En_{product}}{En_{source}} \qquad (2\text{-}2)$$

For example:

The energy efficiency of a household boiler is the amount of heat supplied to the heating system (i.e. the 'product') divided by the chemical energy content of the natural gas input. The energy 'lost' is the amount of heat in the flue gas that is leaving the chimney. For a condensing boiler the energy efficiency is very high, since only a small portion of the energy input is leaving through the chimney. Figure 2-10 shows the energy efficiency scheme of a boiler.

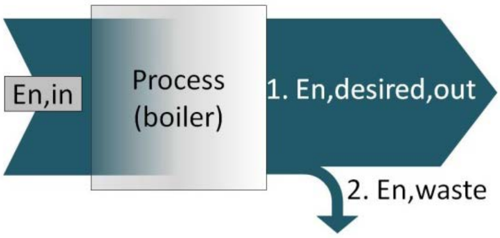


figure 2-10: Scheme of the energy efficiency [η] of a boiler

Exergy efficiency definition

In line with the common definition of energy efficiency, the most simple definition of exergy efficiency is: exergy output of the product / total exergy input of the source (equation 2-3). This is the efficiency used in this book and referred to as the 'exergy efficiency' ψ.[2]

$$\psi = \frac{Ex_{product}}{Ex_{source}} \qquad (2\text{-}3)$$

[2] This definition is in accordance with other authors including Tsatsaronis (1993) and Woudstra (2012).Various other definitions of exergy efficiencies can be formulated and found in literature (Cornelissen, 1997; Torío et al., 2009), but the one used here is the most commonly used one.

The exergy efficiency (ψ) can also be calculated by multiplying the energy efficiency (η) with the ratio of the exergy factor (f_{ex}) of the product to the exergy factor of the source, as shown in equation 2-4 (Moran and Shapiro 2005).

$$\psi = \frac{En_{product} \cdot f_{ex,product}}{En_{source} \cdot f_{ex,source}} = \eta \cdot \frac{f_{ex,product}}{f_{ex,source}} \qquad (2\text{-}4)$$

Example:

For the example of the boiler the exergy destruction is very high, due to the combustion and heat transfer processes. A scheme of the exergy efficiency is shown in figure 2-11. In exergy terms the needed output of heat (in this example 70°C is assumed) is very small. The amount of exergy destroyed in this process is therefore very large, which means the thermodynamic performance of the boiler is very far from the almost perfect performance suggested by the energy efficiency.

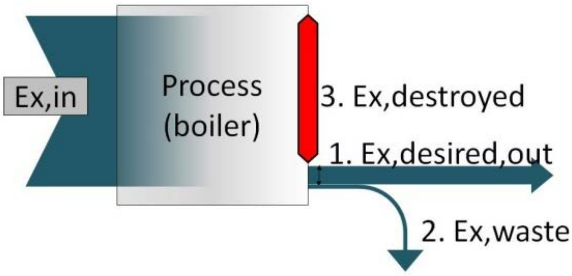


figure 2-11: Scheme of the exergy efficiency [ψ] of a boiler.

Energy losses and exergy losses and destruction

Since energy according to the first law of thermodynamics cannot be lost or created, the energy 'losses' of a system refer to the amount of energy that is not used for the product; in line with figure 2-10 it could also be called 'wasted energy'. In exergy terms however there are two quantities of exergy not used for the product: the exergy of the wasted energy (Ex,waste in figure 2-11) and the exergy destroyed during the process (Ex,destroyed in figure 2-11). Exergy destruction is also often referred to as 'irreversibilities'. The exergy of the waste can theoretically be used for something, while the exergy destroyed is really 'gone'.

For analysing potential improvements it is informative to differentiate between the two: exergy waste can in principle be used elsewhere, exergy destruction is really gone and actually means that a thermodynamically 'flawed' process is chosen. In this book the words 'exergy losses' are mostly used, referring to both the exergy 'wasted' and the exergy destroyed.

Examples showing the value of an exergy efficiency

The difference between energy and exergy efficiencies is demonstrated with two examples below, showing the usefulness of exergy analysis in addition to energy efficiencies only.

- Example 1: a condensing boiler: energy efficiency of 90%, producing water at 70°C.
- Example 2: a geothermal power plant that that converts geothermal heat (at 350°C) into electricity; with an energy efficiency of 22% (electricity output divided by thermal energy input; values taken from a report by MIT (2006)).

In figure 2-12 the energy and exergy schemes of these devices is shown, where the systems are depicted as black boxes and only the exergy of inputs and outputs is analysed. Also the energy and exergy efficiencies are given. The exergy of input and output is calculated by multiplying the energy quantity with the exergy factor f_{ex} (see next section for the exergy factor of heat, assuming an environmental temperature of 5°C).

	Condensing boiler	**Geothermal power plant**
	Gas → heat at 70°C $f_{ex,Gas}$= 1 → $f_{ex,70°C}$= 0,19	Heat at 350°C → electricity $f_{ex,350°C}$ = 0,55 → $f_{ex,elec}$= 1
η ψ	90% 17 % (90%·0,19)/1 = 17%	22% 40% (22%·1/0,55) = 40%

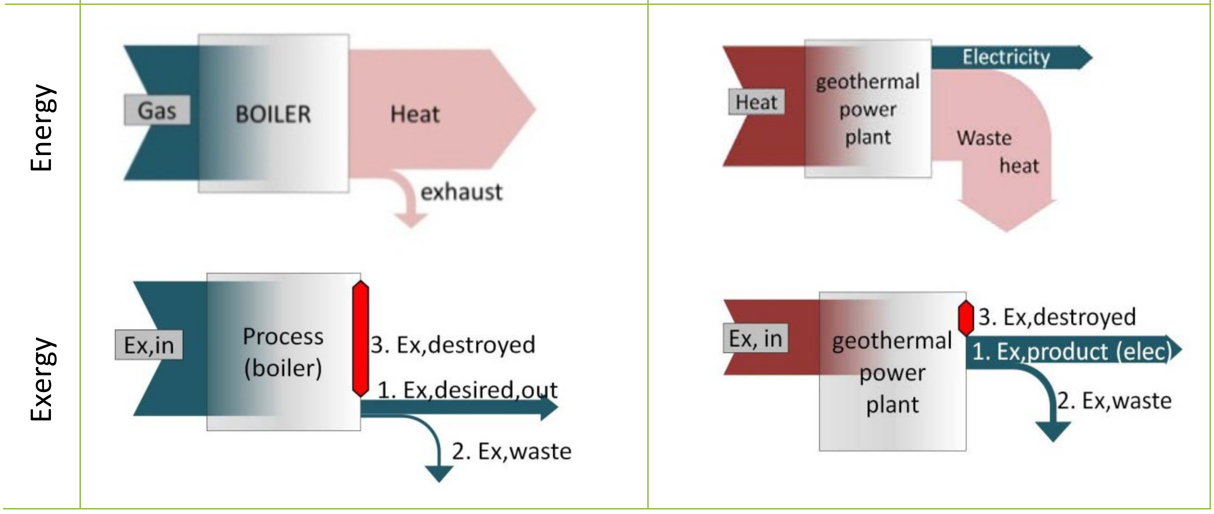


figure 2-12: energy and exergy schemes of two energy conversion processes.
(f_{ex} = exergy factor, η = energy efficiency, ψ= exergy efficiency)

This example clearly shows the added value of the exergy efficiency: while the energy efficiency of the boiler suggests that there is no room for improvement, the exergy efficiency shows a large improvement potential. On the other hand, while the energy efficiency of the geothermal power plant suggests large room for improvement, the exergy efficiency shows that the actual improvement potential is in fact lower. The examples show that energy efficiencies can be very misleading, as is also frequently mentioned in exergy literature (e.g. Wall, 1977; Gaggioli and Wepfer; 1981 or Dincer, 2002). The exergy efficiency is the proper indicator of the thermodynamic performance compared to the ideal (theoretically) obtainable.

Ideal energy efficiencies are not always 100%, ideal exergy efficiencies *are*!

The ideal energy efficiency is not 100%!

According to the first law of thermodynamics the total energy output always equals the total energy input. However, this does not mean that the output can consist for 100% of energy in the desired form. As explained in the beginning of this chapter the convertibility of one form into another depends on the form of energy; to be more precise: it depends on its exergy value.

When converting high-quality energy into low-quality energy in principle more output can be 'produced' than high-quality input is needed (be it with the addition of free environmental energy as is done in a heat pump or refrigerator process), i.e. the ideal 'efficiency' is greater than 100%.

When converting low-quality energy into high-quality energy, *less* output can be 'produced' than low-quality input is needed (the remaining energy is unavoidably discarded as low-quality heat). This means the ideal 'efficiency' is lower than 100%.

- ***The energy efficiency is therefore not a very meaningful indicator in the sense of how optimal the resource is being used.***

The ideal exergy efficiency is always 100%!

Different from energy efficiencies the ideal exergy efficiency for converting a given form of energy into a desired form of energy is always 100%, since in ideal processes no exergy is lost. For a desired conversion of one form of energy (with related exergy value) into another form (with related exergy value), the ideal exergy efficiency is therefore 100%. Hence, the exergy efficiency is a correct indicator of thermodynamic performance by comparing the process with the ideal process (see also Dincer, 2002). In this way the exergy efficiency gives information about the performance of a system without the need for a 'reference' system or dwelling to be compared with, since the reference is implicitly the thermodynamic ideal.

- ***Ideal energy efficiencies are not 100%, they can be either higher or lower.***
- ***Ideal exergy efficiencies are always 100%.***

- ***Hence, energy efficiencies do not indicate whether a system can be improved or not.***
- ***Exergy efficiencies are therefore a more meaningful indicator of the performance of an energy system or process.***

"In general, more meaningful efficiencies are evaluated with exergy analysis rather than energy analysis, since exergy efficiencies are always a measure of the approach to the ideal" (e.g. Dincer, 2002 and many other literature sources)

2.6 Calculating the exergy of heat and cold

In the built environment, heat is one of the most important forms of energy. According to the definition of exergy (section 2.1), the exergy of heat is "the theoretical maximum amount of work that can be obtained by bringing the heat in thermal equilibrium with the environment using a reversible process." Thus: how much work can be obtained from an amount of heat (in a given environment).

The general equation for the exergy of heat is given below. The maximum amount of work obtainable from an amount of heat depends only on the temperature of the environment (T_0) and the temperature of the source (T) (both in Kelvin). This equation is also valid for temperatures "T" that are lower than T_0! Its origin and meaning is explained in this section.

$$Ex_Q = Q \cdot \left(1 - \frac{T_0}{T}\right) \qquad (2\text{-}5)$$

Heat and work

The question of how much work could be obtained from a heat engine was a question of great interest during the industrial revolution. In fact, the discovery of the second law of thermodynamics and the concept of exergy actually started with this question. To convert heat into work a special machine is needed, called a heat engine. (more scientifically, the set of processes required can be called a 'thermal power cycle').

- ***Hence, the exergy of heat is equal to the amount of work that could be obtained using an ideal heat engine.***

The Carnot Cycle: The maximum amount of work obtainable with an ideal cycle:

Calculation of the exergy of heat is based on the Carnot cycle, which is an ideal (= reversible) thermal power cycle. A thermal power cycle produces work from heat transfer between a hot and a cold reservoir as schematically shown in figure 2-13.

Heat (Q_H) is transferred to the system from the hot reservoir. According to the second law of thermodynamics heat to the system can be converted into work, but a certain amount (Q_C) must be rejected to the cold reservoir. Work is a form of energy that contains no entropy. The cycle must thus dispose of the entropy transferred to the cycle by Q_H. Hence, it has to reject heat at a lower temperature T_C.

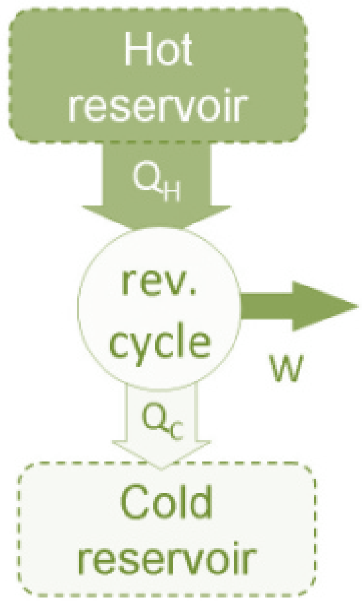


Figure 2-13: Scheme of a reversible thermal power cycle (e.g. Carnot cycle)

The equations of the Carnot cycle

Since a heat engine historically and commonly works by receiving heat from a heat source such as obtained by combustion of fuel and by releasing heat to the environment, the efficiency of a heat engine is defined as the work output divided by the heat input Q_H (i.e. not related to the cold that is disposed of). The energy efficiency is given in equation 2-6.

$$\eta = \frac{W}{Q_H} \tag{2-6}$$

The energy balance of the system can be determined using the first law of thermodynamics:

$$W = Q_H + Q_C \tag{2-7}$$

(*Since the heat transferred to the cold reservoir is transferred from the system, Q_C will have a negative value; see note below on 'sign convention'*)

The second law of thermodynamics determines the relation between Q_H and Q_C. This relation is only depending on the temperatures, as was discovered by Carnot. Since the Carnot cycle is a an ideal cycle, there is no net entropy production of this cycle. Work is a form of energy transfer with which no entropy is transferred. **This means that the amount of entropy transferred *to* the cycle by Q_H is equal to the amount of entropy transferred *from* the cycle by Q_C.** Since entropy change is calculated by Q/T, this results in the following relation:

$$\frac{Q_H}{T_H} = -\frac{Q_C}{T_C} \tag{2-8}$$

When combining the first and second law equations, the maximum work obtainable from a given Q_H at given temperatures can be calculated using equation 2-9. The factor $(1-T_C/T_H)$ is called the Carnot efficiency (η_{Carnot}):

$$W_{\text{rev}} = Q_H + Q_C = Q_H - Q_H \cdot \frac{T_C}{T_H} = Q_H \cdot \left(1 - \frac{T_C}{T_H}\right) \tag{2-9}$$

$$\eta_{Carnot} = \frac{W_{rev}}{Q_H} = \left(1 - \frac{T_C}{T_H}\right) \tag{2-10}$$

NOTE: Sign convention

The sign convention used in this book is according to most textbooks on thermodynamics:

- *Q > 0 = Heat transfer to a system; Q < 0 = heat transfer from a system.*
- *W > 0 = Work done by a system; W < 0 = work done on a system.*

figure 2-14: Sign convention for heat and work

Short historical background

The heat engine

Before 1712 the only source people had to produce 'work' or 'motion' were human power, animal power (e.g. horse power), wind and hydro power. But in 1712 Newcomen invented the first machine that could convert heat into work: The Newcomen machine. Later on James Watt made great improvements to this machine, resulting in the first 'modern' steam engine in 1775.

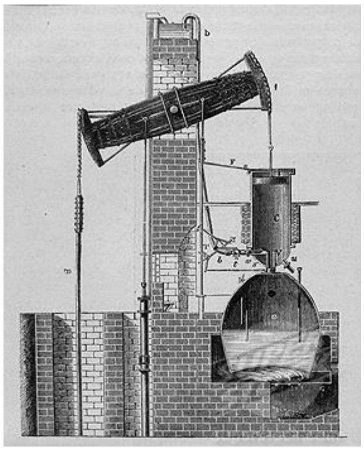


figure 2-15: Newcomen machine

Carnot and the Carnot engine

In 1824 the French engineer Sadi Carnot proved that the maximum obtainable efficiency was only depending on the temperatures of these reservoirs. The thermodynamic cycle that defines this efficiency was named after him: the Carnot Cycle. Although he could not determine this function, Carnot's reflections are the beginning of the discovery of the second law of thermodynamics and the function still referred to as the 'Carnot cycle' and 'Carnot efficiency'.

figure 2-16: Carnot

In his time the character of heat was not yet understood (they still thought it was a fluid, called 'caloric'), but nevertheless Carnot made very relevant statements (Carnot and Mendoza 1960, Muller 2007):

- *"The fall of caloric produces more motive power at inferior than at superior temperatures"*
- *" The temperature of the fluid should be made as high as possible, in order to obtain a great fall of caloric and consequently a large production of motive power"*
- *"For the same reason the cooling should be carried as far as possible".*

Twenty five years after Carnot, Clausius derived the calculation of the Carnot function or Carnot efficiency, resulting in the equation shown in equation 2-13. This was after Lord Kelvin suggested the absolute temperature scale. Clausius also made the first statement of the second law of thermodynamics as follows" "Heat cannot pass by itself from a colder to a warmer body", and he introduced the term entropy and defined it as S=Qrev/T (Muller 2007).

- ***A heat engine needs a source of the heat AND a sink to get rid of part of the heat.***
- ***The greater the difference between source and sink, the greater the work output.***

The Carnot cycle: An ideal (= reversible) cycle to convert heat into work

The Carnot cycle is based on four reversible processes: two isothermal processes (i.e. at constant temperature) and two adiabatic processes (i.e. without heat transfer). These processes are illustrated in figure 2-17 and described below.

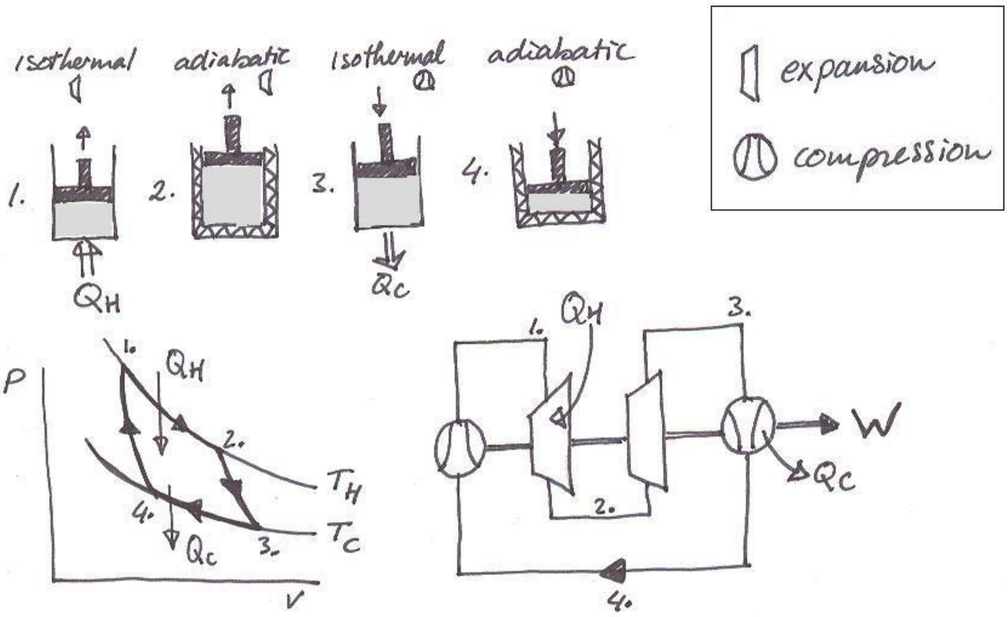


figure 2-17: schemes of the Carnot Cycle (using a piston-cylinder scheme, a pressure-volume diagram (p-v diagram) and a circular scheme adapted from Wisman (1990), p. 51)

1-2 (Isothermal): Heat is transferred from the hot reservoir to the gas at constant temperature (T_H), leading to expansion of the gas and thus mechanical work output. The heat (Q_H) equals the work output; there is no change in internal energy of the gas.

2-3 (Adiabatic): There is further expansion without heat supply. During this process the temperature of the gas drops. This loss of internal energy of the gas equals the work output. In order for this process to be reversible the pressure at the outside of the piston should equal the pressure in the cylinder.

3-4 (Isothermal): The gas is now at the temperature of the cold reservoir (T_C) and at lower pressure. It has to be compressed in order to return to the initial state. At this point it is crucial that heat is disposed of at T_C, since the compression would require more work input if this were not the case. (In fact, if no heat could be disposed of, the compression would bring the gas back along paths 3-2 and 2-1 and there would be no net work output!). The work input equals the heat disposal Q_C.

4-1 The gas in the piston is adiabatically compressed. No heat is released so the temperature increases and internal energy increases as well. This process stops when reaching T_H, the temperature of the hot reservoir. The work input equals the change in internal energy.

The net work output of the system is W1-2 + W2-3 - W3-4 - W4-1. Since the work input and output of the adiabatic processes (4-1 and 2-3) level out, the net work output equals the heat supplied (Q_H) minus the heat rejected (Q_C).

From a reversible thermal power cycle to exergy calculation

The Carnot cycle determines the work obtainable from an ideal cycle between two reservoirs at random temperatures $T_H > T_C$ (i.e. between a hot source and a cold sink). The exergy though is related to the environment, which means the environment has to act as the source or the sink.

The environment is freely and unlimitedly available, hence the work potential of the cycle is depending solely on the amount of heat (or cold) available. Whether T_0 acts as the hot or the cold reservoir depends on the temperature of the heat available, relative to the temperature of the environment ($T > T_0$ or $T < T_0$). This is illustrated by figure 2-18. For simplicity it is assumed that the source containing hot or cold thermal energy has a constant temperature while heat is being transferred.

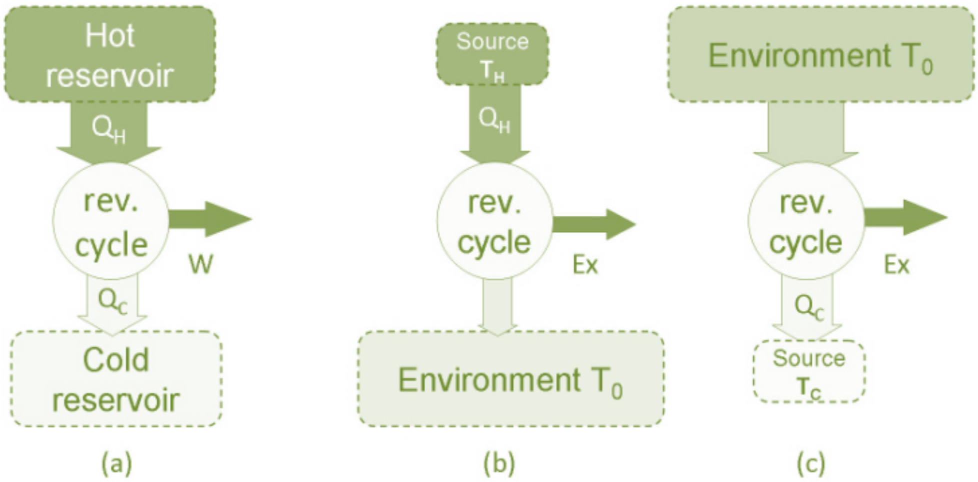


Figure 2-18: (a,b,c): Schemes showing the relation between a reversible thermal power cycle and the exergy of heat: (a) Reversible cycle, (b) heat available at $T>T_0$; T_0 acts as the heat sink, (c) heat ('cold') available at $T<T_0$; T_0 supplies heat.

The exergy of heat ($T>T_0$)

When heat is available at $T>T_0$, this heat is in fact Q_H at T_H, and the environment acts as T_C. The work obtainable from this cycle equals the exergy of the heat (Q_H) and can be calculated on the basis of equation 2-10 by replacing T_C by T_0. This results in equation 2-11:

$$Ex_{Q(H)} = W_{rev} = Q_H \cdot \left(1 - \frac{T_0}{T_H}\right) \qquad (2\text{-}11)$$

The exergy of 'cold' ($T<T_0$)

The exergy of cold can also be calculated using an ideal thermal power cycle. However, in this case the cold is available at $T_C<T_0$, which means the 'cold' is in fact a possible disposal of heat Q_C at T_C, meaning the available cold is actually a cold reservoir that can act as a sink. The environment then supplies the heat $Q_0=Q_H$. The equation for the exergy of cold can be derived from the fundamental equations 2-7 and 2-8, similar to the derivation as shown in equation 2-9. This results in equation 2-12:

$$Ex_{Q(C)} = W_{rev} = Q_{0(=H)} + Q_C = -Q_C \cdot \frac{T_0}{T_C} + Q_C = Q_C \cdot \left(1 - \frac{T_0}{T_C}\right) \qquad (2\text{-}12)$$

Equations 2-10 and 2-11 show that the exergy of heat at temperatures higher than the environment (the available system acts as a source) as well as at temperatures lower than the environment (the available system acts as a sink) can be calculated by multiplying the heat transfer Q with the same factor: $(1-T_0/T)$. The exergy of heat can therefore generally be calculated using equation 2-13, which was already shown in the beginning of this section.

$$Ex_Q = Q \cdot \left(1 - \frac{T_0}{T}\right) \qquad (2\text{-}13)$$

The exergy factor of heat and cold

The exergy factor of heat (the exergy divided by the energy) is given by equation 2-14 (valid for heat at constant temperature). Figure 2-19 shows the exergy factor of heat as a function of its temperature (on the x-axis), given an environmental temperature T_0 of 5°C.

$$f_{ex} = \frac{Ex_Q}{Q} = \left(1 - \frac{T_0}{T}\right) \qquad (2\text{-}14)$$

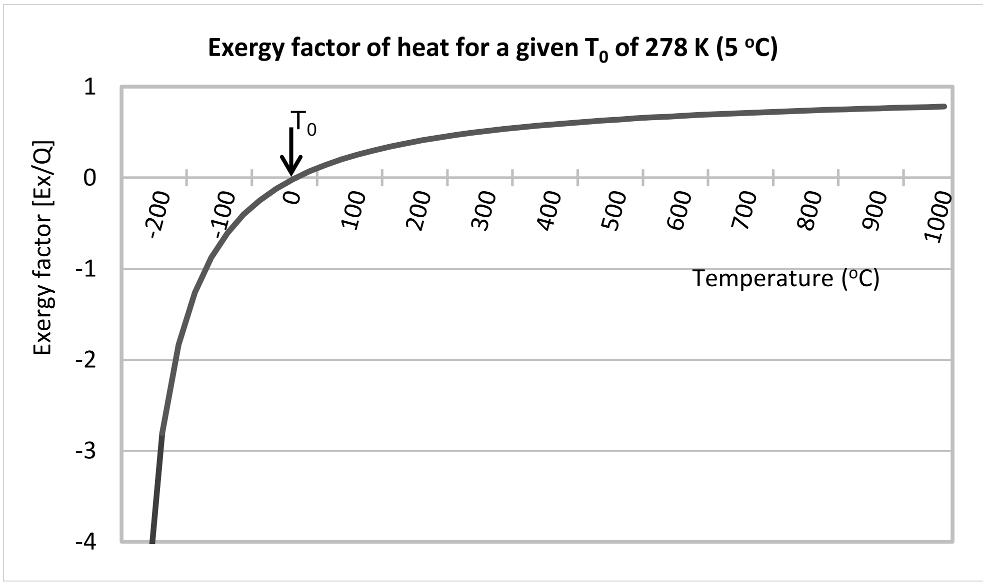


Figure 2-19: Exergy factor of heat at constant temperature T, for an environmental temperature of 5°C.

Figure 2-19 illustrates that when T approaches infinity, the exergy factor becomes one, meaning that heat at very high temperatures can theoretically be totally converted to work. When $T<T_0$ the quality factor is a negative value. A negative exergy factor means the exergy has the opposite value of the heat (see equation 2-14). Taking into account that Q_C has a negative value this means the exergy is positive, or in other words: when cold is available it has a potential to perform work. (See also figure 2-18).

Additional information

The exergy factor between absolute brackets

Since many (building) professionals are used to regarding cold as a positive value, sometimes the exergy factor is placed between absolute brackets, as was done by Wall and Gong (2001), resulting in equation 2-15 and figure 2-20.

$$\frac{Ex_Q}{Q} = \left|1 - \frac{T_0}{T}\right| \qquad (2\text{-}15)$$

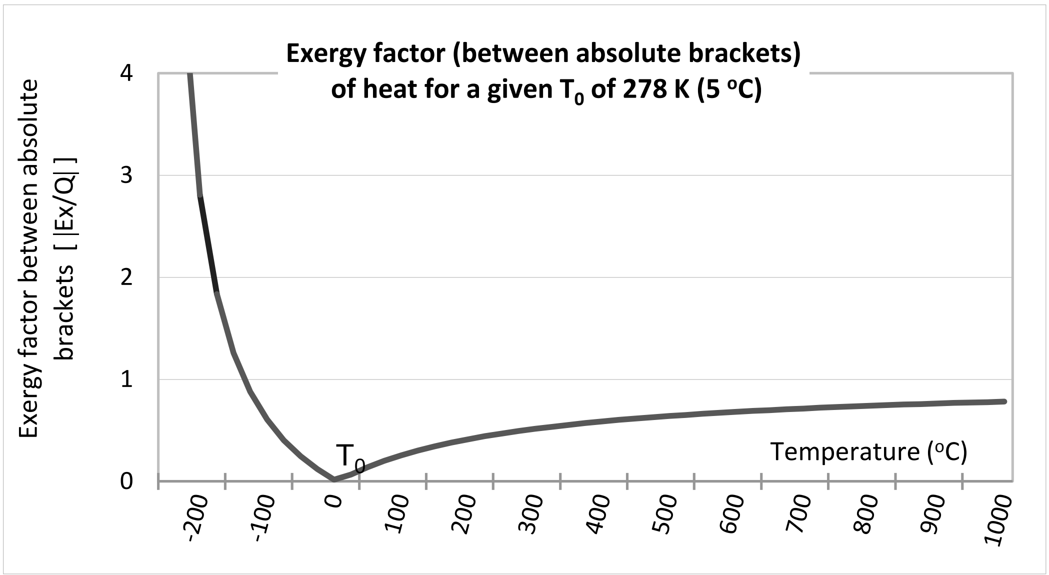


figure 2-20: Exergy factor of heat, placed between absolute brackets

Figure 2-20 offers an easier comparison of the exergy of heat and cold than figure 2-19. However, it is only valid when regarding both Q_H and Q_C as positive values. This also implies that the information regarding the direction of the flow is lost, since the exergy factor between absolute brackets can only result in positive values. This means the algebraic values for heat and exergy do not demonstrate whether they are inputs or outputs to a system under consideration, so that this must be additionally determined by logical reasoning.

More on the direction of heating and cooling processes can be found in section 2.8. This is very important for the evaluation of the exergy of a cooling demand in buildings, which will be treated in chapter 3.

Additional information

Why the exergy factor of cold can be can be larger than 1 (or lower than minus one)

As can be seen in figure 2-20, the exergy factor for heat at temperatures lower than T_0 becomes much higher than 1 (or referring to figure 2-19: the exergy factor can become lower than minus 1). This means the amount of (theoretically) obtainable work can be greater than the amount of available cold. Sometimes this can cause confusion since the Carnot efficiency can never be greater than 100%.

In fact the reason for this is very simple: The exergy of cold is the work obtainable from Q_C, which means, to the heat rejected to the sink. The environment acts as the supply of heat, and the environment is by definition always and unlimitedly available. Hence: the cold limits the heat to be rejected, while the heat supply by the environment is by definition unlimited and adjusts in such a way that $Q_H/-Q_C = T_H/T_C$. Therefore:

- *If $T_H > 2 \cdot T_C \rightarrow Q_H > 2 \cdot (-Q_C)$.*
- *Since $W=Q_H+Q_C$ this means $W>(-Q_C)$.*

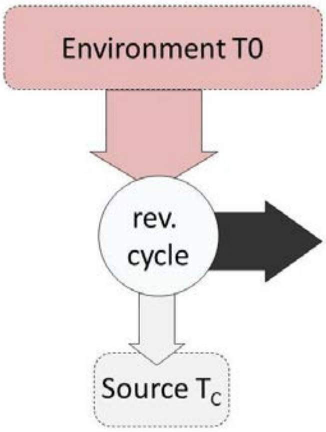


figure 2-21: Exergy of cold: The work obtainable from a limited sink can be larger than the heat rejected to the sink. (But it is always smaller than the heat supplied by the environment)

Comparison with the Carnot efficiency.

The exergy of cold is the work obtainable from Q_C (i.e. the heat rejected to the sink). The Carnot efficiency is always defined as the work obtainable from heat Q_H (i.e. the heat supplied to the cycle); the Carnot efficiency can therefore never be greater than 1, which means that the amount of work obtainable from heat (at $T<T_0$) is always smaller than the amount of heat available. But the amount of work available from cold can be greater than the cold available. (see also Jansen and Woudstra, 2010).

2.7 'Producing' heat or cold: ideal heat pumps

The Carnot cycle is a heat engine that produces work from heat. However, often we want the opposite: we want to produce heat or cold from work (or from electricity), especially in the built environment. A thermodynamic cycle that can produce heat or cold from work is called refrigeration or heat pump cycle, depending on the desired output (cold or heat respectively). This cycle operates in the opposite direction of the Carnot cycle.

As the ideal conversion of heat into work is reversible[3], the amount of work produced from this ideal cycle can in theory be used to get the original amount of heat (or cold) back, again using an ideal cycle. This is illustrated in figure 2-22. The reversed Carnot cycle thus represent the ideal 'efficiency' of a refrigerator or heat pump. From this figure it can also be seen that the maximum work obtainable from an amount of heat equals the minimum amount of work required to produce the same amount of heat. This is a direct consequence of the thermodynamic reversibility of ideal processes.

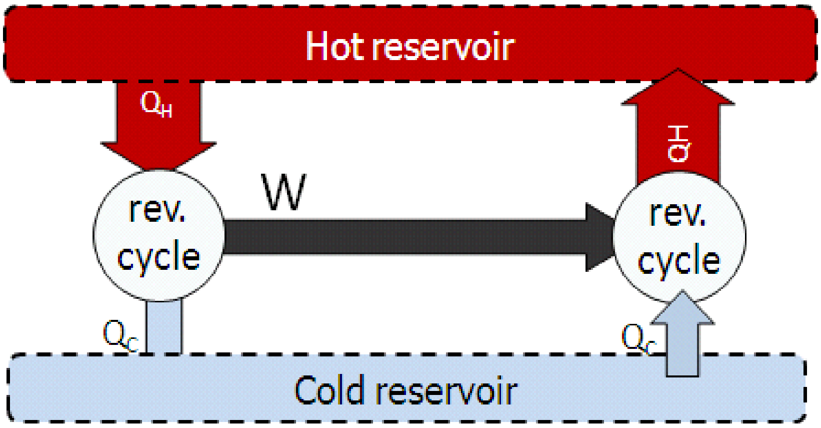


Figure 2-22: Scheme showing the reversible character of an ideal heat engine and an ideal heat pump cycle

The performance of a refrigeration or heat pump cycle is defined as the COP (coefficient of performance), which is the amount of heat produced, divided by the work input to the cycle. As can be seen from figure 2-22 more heat can be 'produced' from this cycle than work is supplied, since also 'cold' is added to the cycle. Real heat pump systems often use 'free' environmental heat which is not included in the COP calculation. The maximum obtainable COP for the production of heat is given by the COP_{Carnot}, which is the inversion of the Carnot efficiency for a heat engine (see equation 2-10 on page 37). This leads to the following equation:

$$COP_{Carnot} = \frac{T_H}{T_H - T_C} \qquad (2\text{-}16)$$

[3] The term 'reversible' refers to the thermodynamic reversibility of the process as explained on page 26. This is something different than the term 'reversible heat pump', which is used in the market for heat pumps that can be used for both cooling and heating a building.

Relating the COP to the environmental temperature (thus: assuming an ideal heat pump to operate between a temperature T and the environment), the equation becomes the opposite of equation 2-14 (Ex/Q= $1-T_0/T$, which is the same as $(T-T_0)/T$). Thus, the equation for the ideal COP of a heat pump operating between T and T_0 becomes:

$$COP_{Carnot(T,T_0)} = \frac{Q}{W} = \frac{T}{T-T_0} \quad (2\text{-}17)$$

Note: This equation is both valid for heat and cold: If T is above T_0, this means heat is produced and the environment supplies heat at T_0. If T is below T_0, this means heat can be extracted from a system (it can be cooled) and the environment receives heat at T_0. (Please refer to figure 2-22 for understanding). To be consistent with the sign convention the COP_{Carnot} for cold will result in a negative value (Work (+) x COP (-) = cold (-)). This is a scientific approach. In practice the COP is always displayed as a positive value (see next page).

In figure 2-23 the exergy factor of heat at a temperature T (x-axis) is shown in black. In the same graph the ideal COP (COP_{Carnot}) for a heat pump operating between a temperature T (x-axis) and the environmental temperature of 5°C is shown in green. It can be seen that the exergy factor is the inverse of the COP_{Carnot} (i.e. f_{ex} equals $1/COP_{Carnot}$).

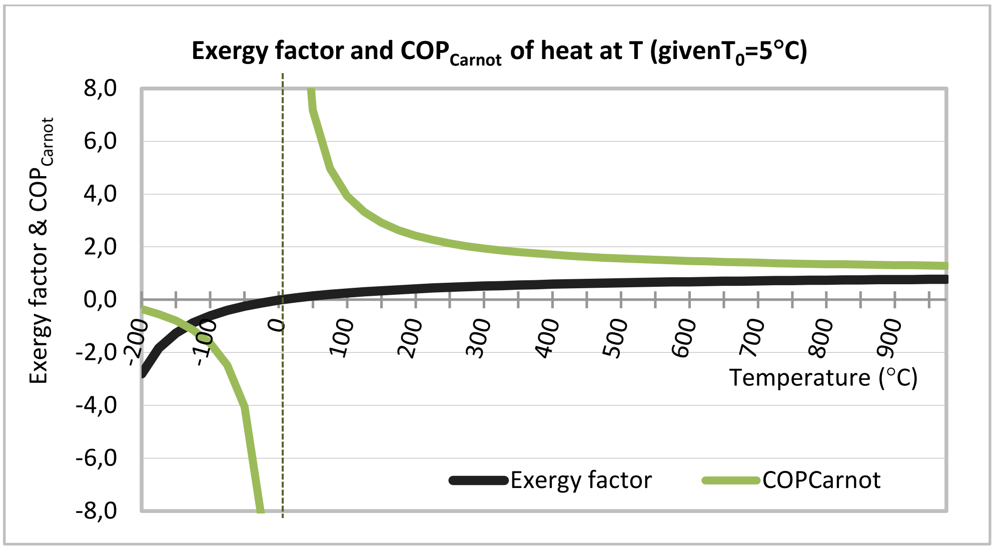


Figure 2-23: exergy factor of heat (Ex/Q) and ideal COP (Q/Ex) depending on the temperature of the heat (Q).

As can be seen from this figure, the ideal COP becomes very high for near environmental temperatures, which means one unit of work can produce large quantities of heat at near environmental temperature. For T_0 the COP reaches infinity, since it requires no work to produce heat at environmental temperature.

The COP for very high temperatures reaches 1, which means 1 unit of work is required to produce one unit of very high temperature heat. For very low temperatures the COP reaches 0. This means the production of very low temperature cold requires large quantities of work input, and the absolute 0 can never be reached. Cold is thus a very expensive product or a very valuable resource.

Additional information: COP as a positive value

In practice the COP is always displayed as a positive value. This means equation 2-17 becomes equation 2-18 and figure 2-23 becomes figure 2-14.

$$COP_{Carnot(T,T_0),positive} = \frac{|Q|}{W} = \frac{T}{|T-T_0|} = \frac{T}{\Delta T} \qquad (2\text{-}18)$$

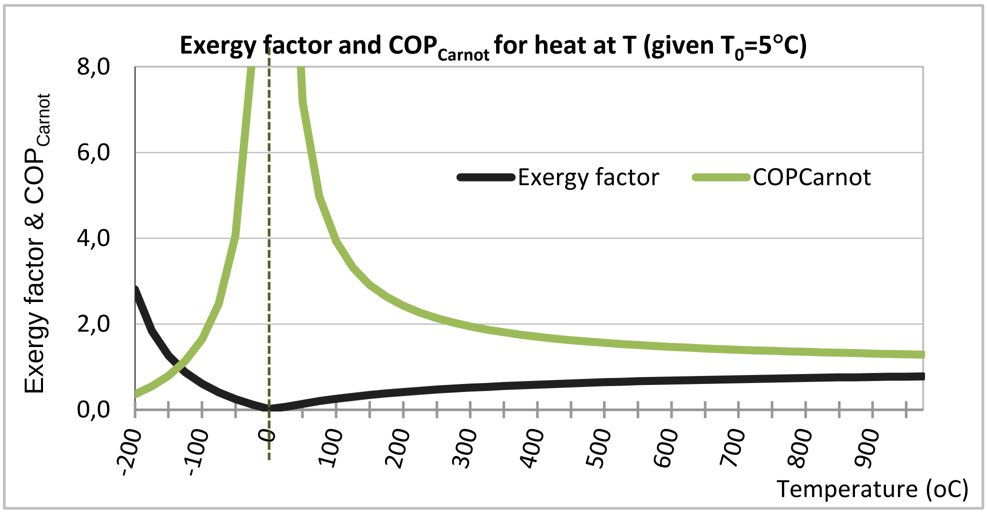


Figure 2-24: COP_{Carnot} for a given environmental temperature (T_0) of 5°C.

Using the heat pump for cooling and / or heating

In principle a heat pump can be used for cooling and heating at the same time. This is also the most effective use of the process. In practice often only one of these two processes takes place at a given moment. In this case a source is needed to supply or receive heat (heating or cooling situation respectively). This source or sink can be the environmental temperature, in which case the COP relates directly to the exergy calculation (COP_{Carnot} =1/exergy factor).

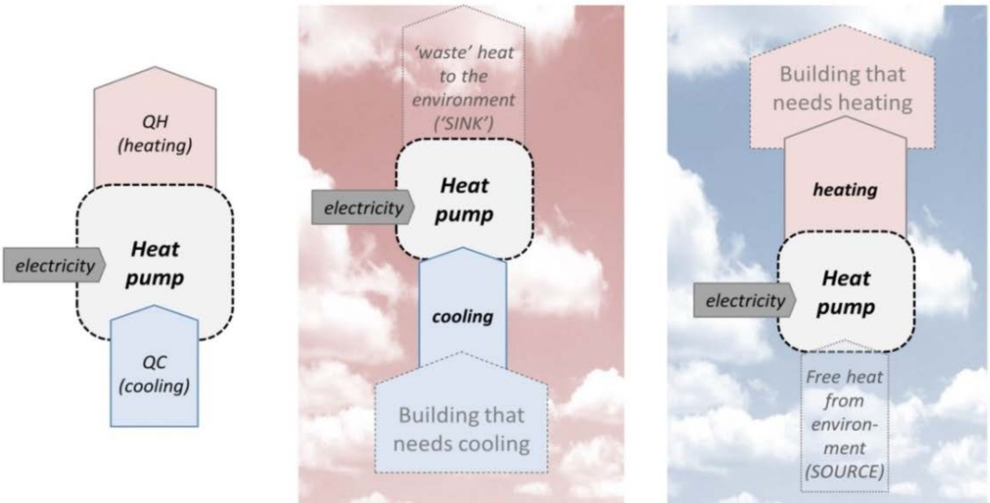


Figure 2-25: scheme of a heat pump, used for both cooling AND heating (ideal situation), or for either cooling (middle) or heating (right figure).

Additional technical information: A compressor (electricity) driven heat pump.

This text frame describes a compressor-driven heat pump, which is the most common type of heat pump used for the built environment. This heat pump is driven by electricity, which can be regarded as work. The general idea of a heat pump is that is uses electricity to 'pump' heat from a colder to a warmer body. A simplified scheme of this is shown in the figure on the left. The figure on the right represents the working of real heat pumps (which are not thermodynamically ideal).

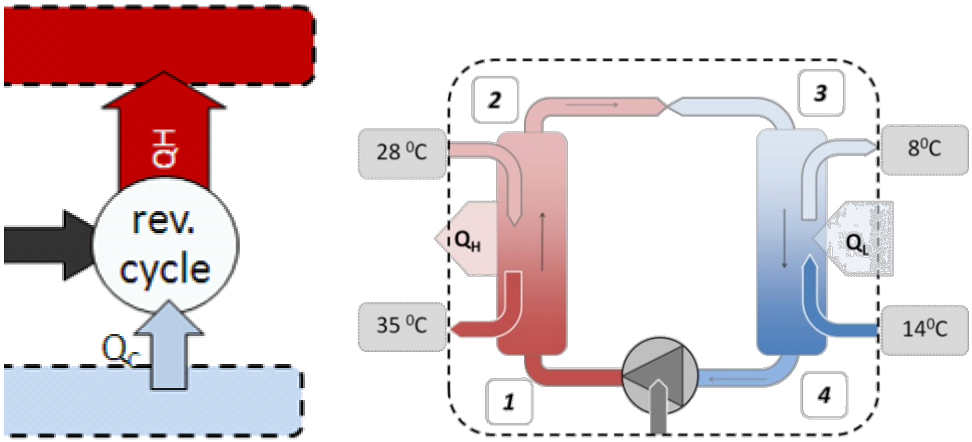


Figure 2-26: Scheme of a heat pump.

The steps in the heat pump cycle (figure on the right) are the following:

- *4-1 The medium in the cycle is compressed, requiring the input of work. The temperature increases. This is called the compressor.*
- *1-2 The medium enters a heat exchanger and transfers heat to an external source, causing the temperature of the medium to drop. Usually condensation takes place and this part of the heat pump is called the condenser.*
- *2-3 Between point 2 and 3 expansion takes place to lower the temperature and the pressure. In theory this process could deliver work if a turbine would be used; in practice however this does not happen.*
- *3-4 The low pressure liquid medium then enters another heat exchanger, the evaporator, in which the fluid absorbs heat and boils.*

N.B.:

- *The greater the temperature difference, the greater the pressure difference and consequently the more energy needed to compress the fluid.*
- *Depending on the goal either the heat supplied at the condenser side can be used (for example by a floor heating system) or heat can be extracted from something at the evaporator side (for example the inside of a refrigerator). In the ideal case both sides should be used.*
- *The main irreversibilities or exergy losses in real heat pumps are caused by the expansion without obtaining work and the temperature differences in the heat exchangers.*

Maximum COP's obtainable in practice

For several reasons real COP's can never be as high is the ideal COP. A technical limit to the maximum obtainable Carnot efficiency is imposed firstly by the required temperature difference for exchanging heat between the heat pump medium and the source and load temperatures of the heat pump. Hence, the internal temperature lift of the heat pump medium is always larger than that of external temperatures and therefore the COP is lower than COP_{Carnot} of the external temperatures.

This is illustrated in figure 2-27 with exemplary temperatures. A T with a line($\overline{T}$) refers to a mean temperature. The mean external temperatures are $\overline{T}_H$ = 309 K and $\overline{T}_C$= 278 K. For this temperature lift the COP_{Carnot} = 10. Assuming a minimum temperature difference for heat transfer of 3 Kelvin, the mean internal temperatures become $\overline{T}_H$ = 309+3=312 K and $\overline{T}_C$= 278-3=275 K. For this temperature lift the COP_{Carnot} = 8.4, introducing a reduction of 16%. In addition to the unavoidable losses related to the required temperature difference, the compressor always presents some losses and there are some losses in the throttling valve.

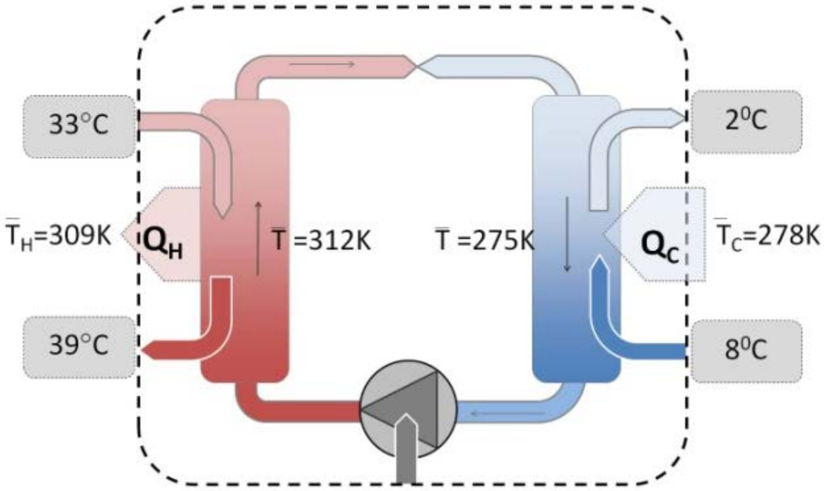


Figure 2-27: Scheme of a heat pump with external temperature lift =31 K and internal temperature lift=37 K.

Performance simplified as a fraction of Carnot

Taking into account the unavoidable losses, it can be stated in a simplified way that real heat pumps operate at a performance between approximately 40% and 60% of the Carnot COP (Meggers et. al, 2012). In addition, it can be imagined that the smaller the required temperature lift, the more significant the difference between external temperature lift (i.e. the lift from the available source, such as the outdoor air, and the actual goal, such as a floor heating systems) and the internal temperature lift (of the heat pump medium itself). With very low temperature lifts the values of 40 to 60% of Carnot are therefore not feasible.

In the figures below the ideal and maximum COP's for cooling and heating are displayed.

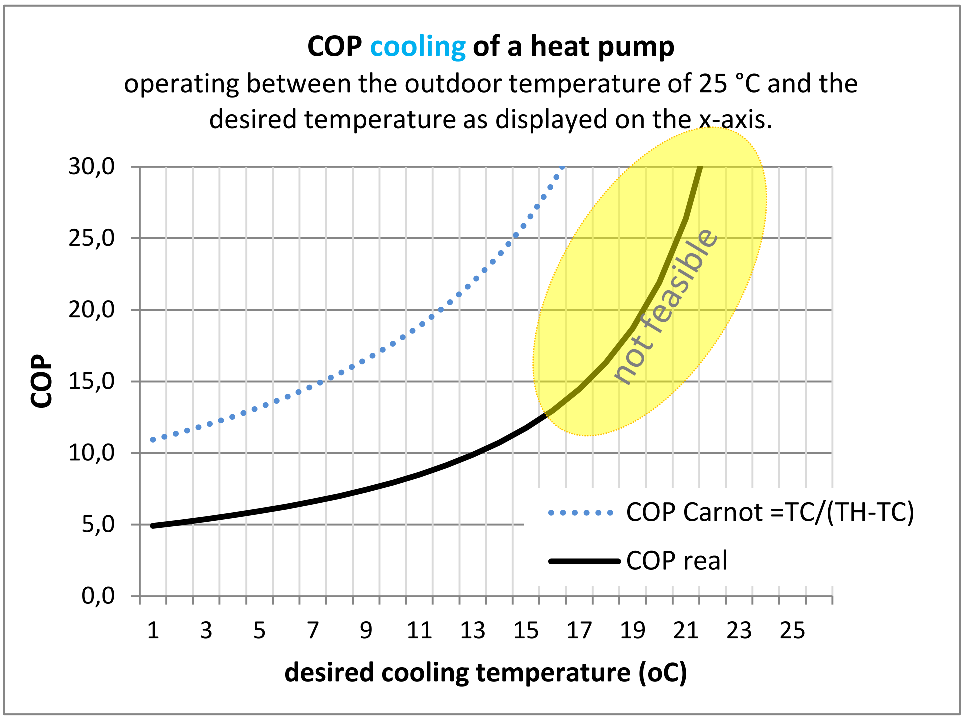


Figure 2-28: maximum ideal and achievable COP for cooling, given an available source of 25 °C

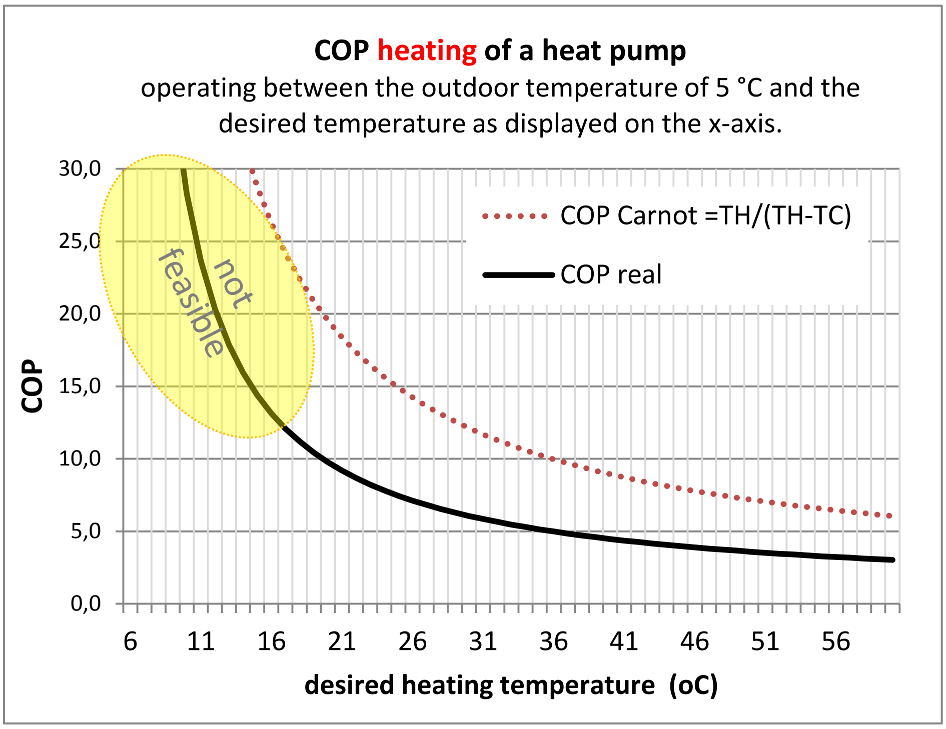


Figure 2-29: maximum ideal and achievable COP for heating, given an available source of 5 °C

2.8 Heating and cooling processes: exergy input or output?

Heating or cooling processes (i.e. adding or removing energy from a system) can have either the (theoretical) ability to produce work or requires the input of work. In the first case the exergy of the system is consequently *decreased*, in the second it will be *increased*.

It depends on the direction of the heat transfer *and* on the temperatures of the system and T_0, whether this heat has the ability to produce work or requires the input of work. In figure 2-30 two systems A ($T>T_0$) and B ($T<T_0$) are illustrated with for each system a heat input (heating) and heat output (cooling), with the accompanying exergy (these involve arbitrary systems, not necessarily thermal power cycles). The direction of the accompanying exergy can be determined using equation 2-5 at the beginning of section 2-6 (which equals equation 2-13).

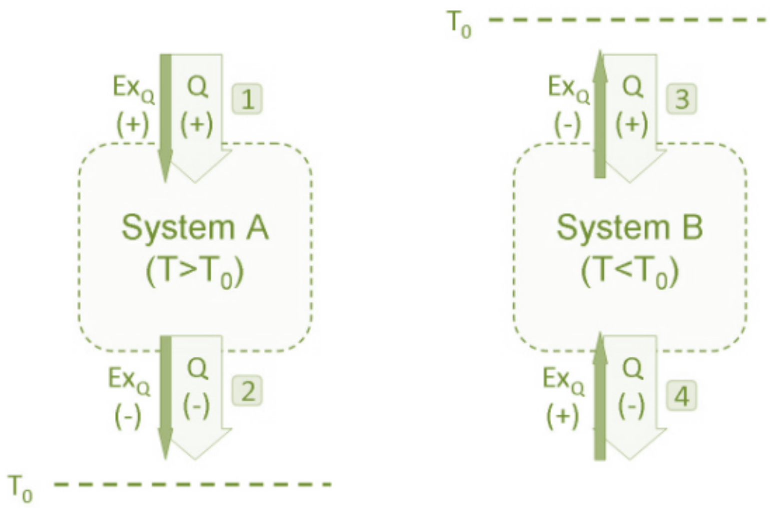


figure 2-30: Exergy accompanying heat transfer, depending on the temperatures T and T_0

From these figures it can be seen whether the heating or cooling process involve an exergy transfer *to* or *from* the system, implicating whether exergy is required or is available, as is outlined in table 2-2.

Table 2-2: Implication of heating and cooling processes on the exergy transfer to or from the system involved.

Process:	**Heat transferred**	**Exergy transferred**	**the process:**
Heating a system (A) at $T>T_0$	*to* the system A	*into* the system A	requires exergy
Cooling a system (A) at $T>T_0$	*from* the system A	*out of* the system A	has exergy available
Heating a system (B) at $T<T_0$	*to* the system B	*out of* the system B	has exergy available
Cooling a system (B) at $T<T_0$	*from* the system B	*into* the system B	requires exergy

In general these rules are valid (which are obviously a result of the second law of thermodynamics):

- ***Heat transfer bringing a system into equilibrium with the environment (and thus closer to T_0) can theoretically produce work. Or in other words: heat transfer that would also take place spontaneously can produce work.***
- ***Heat transfer bringing a system further from T_0 requires work (all non-spontaneous heat transfer requires work).***
- ***For heat transfer at $T>T_0$ the accompanying exergy is always in the same direction as the heat transfer.***
- ***For heat transfer at $T<T_0$ ('cold') the accompanying exergy is always in the opposite direction of the heat transfer.***

Additional information on the direction of heat transfer in relation to the use of the exergy factor equations with and without absolute brackets:

- *When using the sign conventions as explained in section 1.6 and the general equation for the exergy of heat without the absolute brackets (equation 2-13, page 41), the signs of the results reveal the direction of the heat transfer and the exergy in relation to the system studied.*
- *It is important to clearly define the system under consideration and its boundaries, since this is needed to determine the direction of the heat transferred and the accompanying exergy.*
- *It is noted that the negative value for the exergy should not be understood as "negative work", but as an indication of the direction of the exergy out of the system.*

The section described the exergy available from heat transfer or required to obtain heat transfer. Sensible heat of an amount of matter ($T>T_0$), or the lack of sensible heat relative to the environment in case the matter is at $T<T_0$, always contains exergy, since this is an available difference that can be used as a driving force to produce work. This means the air in a room, be it at $T>T_0$ or at $T<T_0$, contains hot or cool exergy, as also explained by (Shukuya 2009). However, to obtain air or any matter at $T \neq T_0$, exergy is required.

2.9 The exergy of an amount of matter

The exergy of an amount of matter is defined by the amount of work that will be obtained from a system that brings the matter into equilibrium with the environment by reversible processes (Woudstra 2008). The total exergy of an amount of matter consists of its thermal exergy (due to a difference in temperature), mechanical exergy (due to a difference in pressure) kinetic exergy, potential exergy and chemical exergy (neglecting nuclear and magnetic energy) .

For application in the built environment the thermal exergy is the most relevant. Almost all energy systems involve the use of an amount of matter, or in other words 'a certain medium' (for example water) to transport thermal energy. For example: the heating of a radiator is supplied by water that has a temperature of the supply (T_2) and a temperature of the return (T_1). With this temperature change a certain amount of heat is transferred (see figure 2-31).

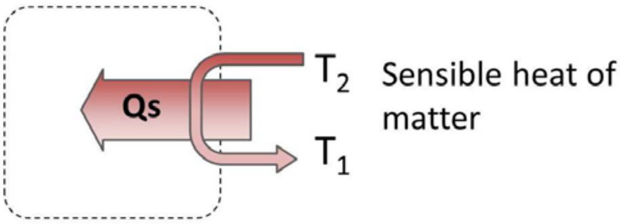


figure 2-31: energy transferred as a result of the temperature change of a flow of matter.

The sensible heat transferred in this process can be calculated using equation 2-19.

$$dQ_s = m \cdot c_p \cdot (T_2 - T_1) \qquad (2\text{-}19)$$

The exergy of the sensible heat is equal to the exergy of the heat transfer that can be obtained during this process. What is different from the exergy of heat as discussed in the previous section, is that the temperature of the heat transfer changes as the matter heats up or cools down. In fact the exergy must be calculated for each infinitesimally small amount of heat transferred, at the related temperature. A simplified approach for application in the built environment is presented here. The more accurate approach and the derivation can be read in the text frame at the end of this section.

Heat versus sensible heat

While heat refers to the transfer of energy between two systems as a result of different temperatures, the term 'sensible heat' is used for the part of internal energy of an amount of matter that is associated with its temperature. Sensible heat is thus energy 'contained' by an amount of matter. In literature also the word 'thermal energy' is often used, referring to the same thing. In many works related to the built environment it is also very common to use the term 'heat' to refer to what has just been described as 'sensible heat'. However, for correctly applying exergy calculations it is considered important to clearly differentiate between the two.

Simplified way of calculating the exergy of a temperature change of matter

The exergy transferred as a result of the change of temperature can be calculated by using the average temperature of the heat transferred, when assuming a constant value for the thermal heat capacity c_p (this is usually applicable for situations in the built environment). The calculation of the exergy of sensible heat of an amount of matter is as follows:

$$Ex_{(Qsensible)} = Q_s \cdot \left(1 - \frac{T_0}{T_{\text{average}}}\right) \qquad (2\text{-}20)$$

For an accurate calculation, the thermodynamic mean temperature has to be used as the average temperature, as is explained in the text frame on the next page. For application in the built environment however, the simple average can be calculated as follows:

$$T_{average,simple} = \frac{T_1 + T_2}{2} \qquad (2\text{-}21)$$

(Note: simplified for the built environment !)

The above equation (equation 2-21) can also be used to calculate the total thermal exergy of an amount of matter, i.e. the exergy transferred after the matter has taken the temperature of the environment. This means that the exergy of an amount of matter at temperature T is approximately half of the exergy of heat transferred at a constant temperature T (assuming the same T and the same reference temperature T_0).

Intuitive explanation:

When heat is transferred from an amount of matter, the temperature of matter decreases and the heat available has an ever lower temperature. A series of imaginary Carnot engine will each operate between the temperature of the matter and the environment. As T comes closer to the reference temperature T_0, the maximum work obtainable changes for each imaginary Carnot engine. This is illustrated in the figure below.

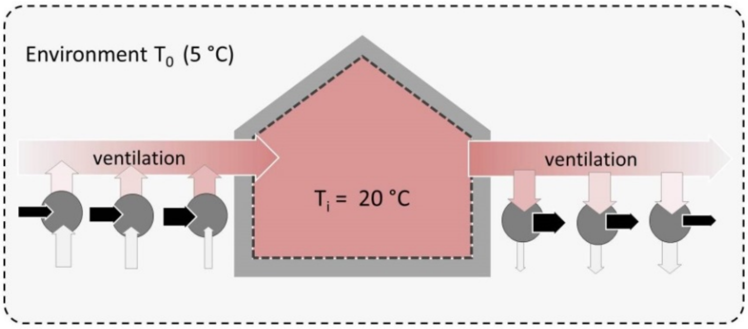


figure 2-32: imaginary Carnot engines to illustrate the exergy of sensible heat

The exergy of latent energy

Latent energy is the energy needed for or available from a phase change of an amount of matter, for example from liquid to gas. During this process the temperature is constant. The exergy of latent heat can thus be calculated using the constant temperature at which the phase change takes place, according to equation 2-13, page 41.

Derivation of the calculation of the exergy of sensible heat

The exergy of the sensible heat is equal to the exergy of the heat transfer that can be obtained during this process. The temperature of the heat transfer changes as the matter comes closer to equilibrium. This means the exergy calculation has to be integrated over the total temperature range of the process.

Assuming a constant value for c_p (heat capacity of the matter), the exergy of the sensible heat of matter can consequently be calculated using equation 2-22 (adapted from Bejan et al. (1996), Wall and Gong (2001), Szargut (2005)).

$$Ex_{Qs} = \int_{T_0}^{T} \left(1-\frac{T_0}{T}\right) dQ = \int_{T_0}^{T} m \cdot c_p \cdot \left(1-\frac{T_0}{T}\right) dT = m \cdot c_p \cdot \left(T - T_0 - T_0 \ln\frac{T}{T_0}\right)$$

(2-22)

The exergy factor of sensible heat

To derive the exergy factor of sensible heat, equation 2-22 is converted into the arrangement shown in equation 2-23.

$$Ex_{Qs} = m \cdot c_p \cdot (T - T_0)\left(1-\frac{T_0}{T-T_0} \cdot T_0 \ln\frac{T}{T_0}\right) = Q_s \cdot \left(1-\frac{T_0}{T-T_0} \cdot T_0 \ln\frac{T}{T_0}\right)$$

(2-23)

This results in equation 2-24.

$$\mathrm{f}_{ex,Qs} = \frac{Ex_{Qs}}{Q_s} = \left(1-\frac{T_0}{(T-T_0)}\ln\frac{T}{T_0}\right)$$

(2-24)

In figure 2-33 the exergy factor of sensible heat is shown for an environmental temperature of 5 ℃. In the same figure the exergy factor of heat is plotted in order to demonstrate the difference. This figure shows that the exergy factor of heat at constant temperature T is larger than the exergy factor of sensible heat. This can be explained by the fact that the temperature of the matter, which in the beginning is at temperature T, comes closer to T_0 while heat is being transferred. On the other hand, the heat transfer at constant T is, by definition, constantly available at T.

The difference between the exergy factor of heat and of sensible heat is relevant for the definition and calculation of the exergy demand in buildings, as will be explained in chapter 3.

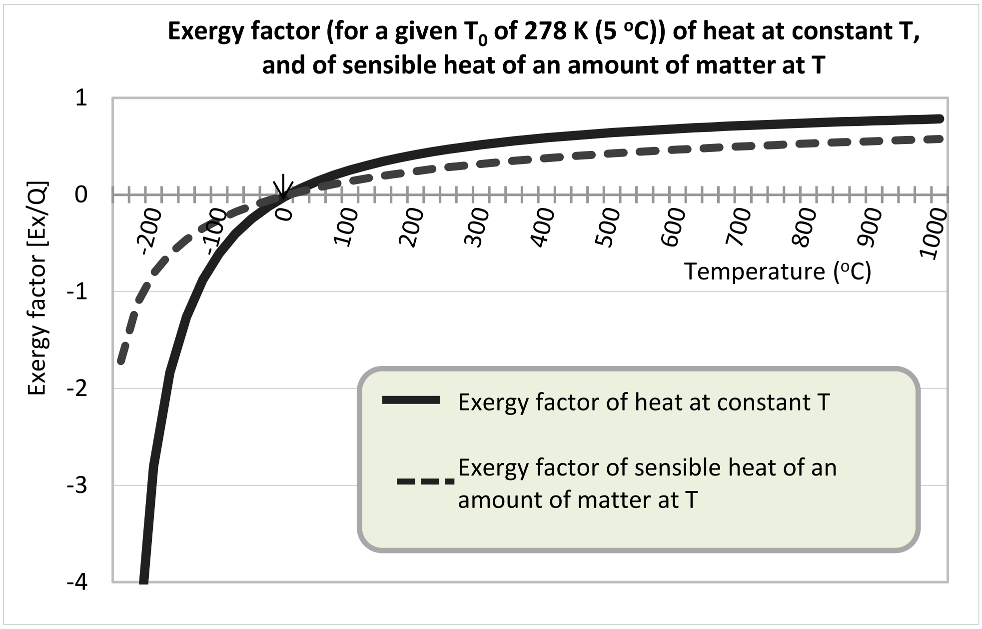


Figure 2-33: The exergy factor of heat at constant T (Ex_Q/Q) and the exergy factor of sensible heat ($Ex_{Qs}/(m \cdot c_p \cdot \Delta T)$)

The exergy change from T_1 to T_2 and the thermodynamic mean temperature

The exergy change due to change of sensible energy in matter from T_1 to T_2 can be calculated using equation 2-25 and 2-26. The smaller the temperature difference between T_1 and T_2, the closer the exergy factor (i.e. expression in parenthesis in equation 2-26) comes to the exergy factor of heat using either one of the temperatures.

$$Ex = c_p \cdot m \cdot \left(T_2 - T_1 - T_0 \ln \frac{T_2}{T_1} \right) \tag{2-25}$$

$$Ex = Q_s \cdot \left(1 - \frac{T_0}{T_2 - T_1} \cdot \ln \frac{T_2}{T_1} \right) \tag{2-26}$$

Equation 2-25 and 2-26 lead to the same results as using equation 2-20 while replacing T in equation 2-20 with the thermodynamic mean temperature $\bar{T}$, calculated according to equation 2-27, as is also used (e.g. Woudstra 2012).

$$\bar{T} = \frac{T_2 - T_1}{\ln \frac{T_2}{T_1}} \tag{2-27}$$

Note: The equations for the calculation of the exergy of sensible heat are in fact only valid for ideal gases; however, they can also be applied to flows of matter used in energy systems in the built environment, given a constant value for c_p.

2.10 Ways of exergy destruction (and exergy creation!)

Exergy destruction

Whenever a process is not thermodynamically reversible, exergy will be destroyed, which means all real processes destroy exergy since they need a 'driving force' or difference between two systems (e.g. in temperature, pressure or composition) in order to take place. When the difference is gone and the systems are in equilibrium, the driving force and thus the exergy is destroyed. Shukuya describes this as the exergy-entropy process: a process feeds on exergy, consumes it and creates entropy (Shukuya and Hammache 2002). The larger the difference, the faster the process but the larger the exergy that will be destroyed.

In many thermodynamic textbooks the main processes to be avoided in order to minimise exergy losses are listed (e.g. Bejan et al. 1996; Szargut, 2005). The most important and general guidelines to minimise exergy destruction are:

- Minimise temperature differences when exchanging heat
- Do not exchange heat between temperature above and below T_0
- Minimise mixing of streams with different temperature, chemical composition or pressure
- Minimise the use of throttling
- Avoid combustion
- Avoid unnecessary heat transfer
- Avoid resistance heating

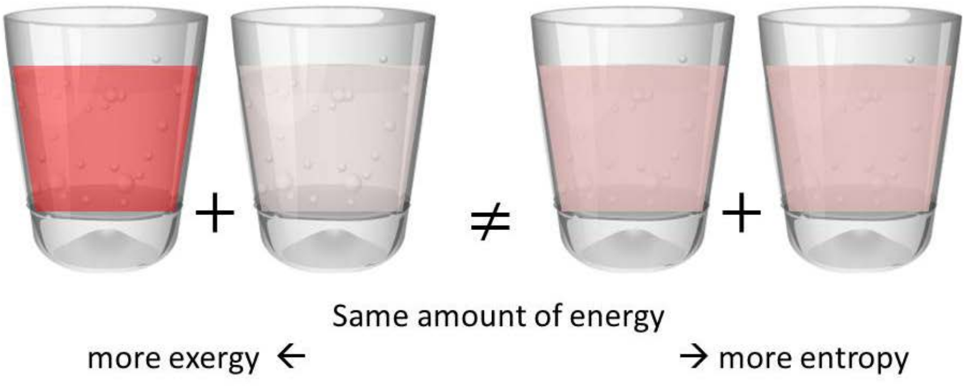


figure 2-34: mixing is an example of a process that destroyed exergy.

Exergy creation

In a given reference environment exergy cannot be created. However, given a dynamic reference environment, meaning the reference environment changes in time or space, it can. Assuming the local time-dependent environment as the reference environment, it is in practice possible to 'create' exergy: When moving a block of ice from the North Pole (where it is in equilibrium with the local environment) to a warmer country, exergy is created. Also by storing ice blocks in winter to be used in summer exergy can be created.

figure 2-35: Old ice-celler in the National Park of Elswout (Netherlands).

Storage is a way of 'creating exergy'.
In the old days, before people were able to produce cold using a refrigerator, the only way to have ice in summer was to store it in winter. Therefore many ice-cellars were built, which are not used anymore due to the use of (household) refrigerators. Since storage is a way of exergy creation, maybe their use should be reconsidered?

3 Exergy analysis method for the built environment

In the previous chapter the general concept of exergy was introduced and explained as far as relevant for application in the built environment. In this chapter a framework and calculation approach for performing an exergy analysis of an energy system for the built environment is presented. The method is based on existing methods (e.g. as developed by Schmidt (2004)), as well as on the research by Jansen (2013).

The method describes the following aspects:

- The framework for systematically presenting the entire supply chain of an energy system. This consist of the energy demand at building level, the energy system components for conversion, distribution, storage and emission of energy.
- Explanation on how to calculate the exergy of the demand (heating, cooling, domestic hot water and electricity), with a detailed discussion on how to calculate the exergy demand for heating and cooling.
- The approach for calculating the exergy of inputs and outputs of system components
- The exergy of resources.

The exergy analysis method presented is not a full calculation tool. Rather, it presents a general approach and calculation procedure that can be used as an addition to any energy analysis tool or calculation.

3.1 Framework

The aim of the exergy approach is to analyse the total energy chain of energy systems in the built environment. This is important, because the performance depends on the exergy losses in the entire system.

The total energy chain is composed of the energy (user) demand, the energy system components (conversion, distribution and storage) and the energy resources. The user demand is the amount of energy that is actually desired by the users in the form that is desired; it includes heating, cooling, domestic hot water (DHW) and electricity. On the other hand there are the energy resources available on earth, including both renewable and non-renewable resources. In-between there are energy system components for energy conversion, distribution and storage, since energy resources are usually not available in the right form and at the right time and place. The energy system input is the need of the energy system for resources, considering these transformation processes and the related energy wasted in the system components. The system is illustrated in figure 3-2.

The total energy chain of an energy system for the built environment consists of:

- ***The energy demand***
- ***Energy system components (for conversion, storage, distribution and emission)***
- ***The primary resources***

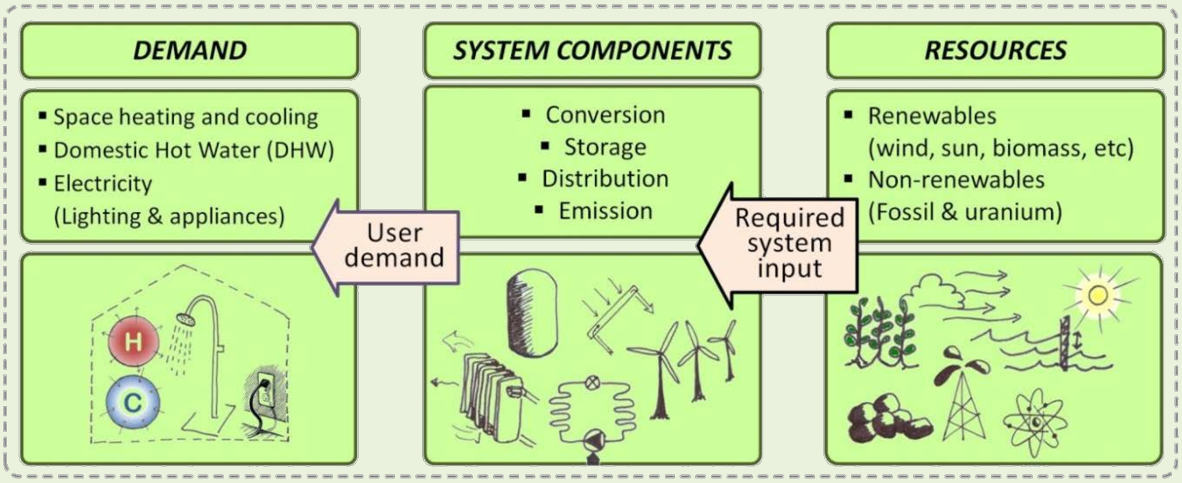
Definition of the reference environment

For performing an exergy analysis it is necessary to define the thermodynamic reference environment. The reference environment is considered as the environment that acts as the ultimate and unlimited source and sink of all energy interactions of the analysed system. This means the environment can supply or receive unlimited amounts of energy or matter present in this environment, meaning for example that at the environmental temperature an unlimited amount of heat can be supplied or received.

Although there is no general agreement in literature on the reference environment for the analysis of energy flows in buildings, it is mostly recommended to use the **variable outdoor environment**, since this is the environment that is freely and unlimitedly available to the energy systems for the built environment. (See Torío et al., 2009). In case of dynamic simulations the reference environment will therefore also vary in time.

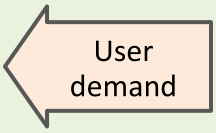
- ***For calculating the exergy of the energy systems for the built environment, the surroundings of the system can be used as the reference environment, (as long as these surroundings are freely and unlimitedly available).***
- ***Properties of the reference environment get the subscript 0 (e.g. T_0 for its temperature)***
- ***Thus, for application in the built environment, the reference temperature is the variable outdoor temperature.***

figure 3-1: General scheme of energy systems for the built environment



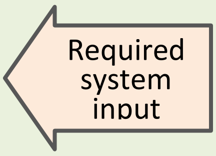
Description:
Energy systems for the built environment consist of the user demand, the energy resources and the energy system components in-between.

Demand*: The user demand is determined by the (comfort) desires of the user, the user behaviour, the building properties and the weather.*
NB: Note that the user demand is not the same as the 'final energy', with which the energy delivered to the door is meant (often in the form of natural gas and electricity)



The user demand is thus an energy need in the form of energy that is needed, such as heat, 'cold' (a removal of heat) or light. In fact electricity is not a user demand, but in this representation the demand for the functioning of devices (such as computers) is simplified into a demand for electricity.

System components*: System components are needed to get the energy in the right form at the right time and place. They include conversion, storage, distribution and emission.*

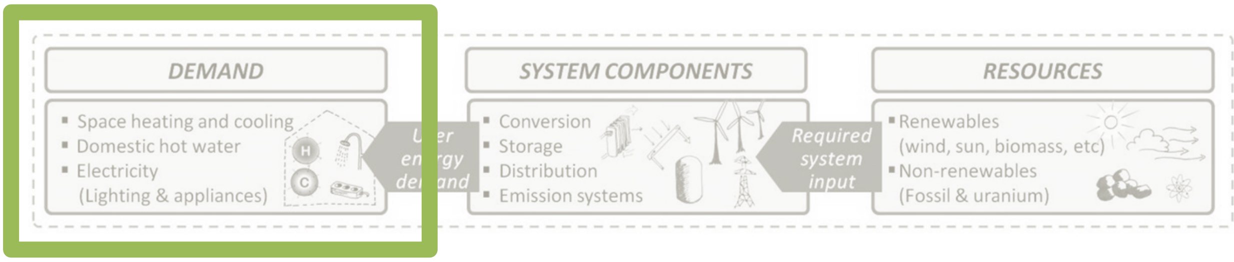


Due to the additional losses in in system component, the total required system input is larger than the user demand. The required system input needs to be supplied by the resources available on earth, such as solar and wind energy, biomass and fossil fuels.

Resources: *In the end the system needs to be supplied with energy resources as they can be found in nature. These include both renewable and non-renewable resources, but obviously in a sustainable situation we can only use the renewable ones.*

In order to supply the total required system input with 100% renewable resources, we can:
> Reduce the user demand (smarter users, more efficient buildings & bioclimatic design)
> Reduce the required system input (smarter & more exergy efficient system componentns)
> Increase the possibilities to use 'low-exergy' environmental resources or waste flows. This entails the use of system components that enable the input of low-exergy resources.

3.2 The exergy demand for space heating and cooling



Both an energy analysis and an exergy analysis start with determining the energy demand. For determining the exergy demand first the energy demand needs to be calculated. (see a recapitulation of the energy demand calculation on the right). Below the approach for calculating the exergy demand is explained.

Definition of the exergy demand for heating and cooling

The exergy demand can be defined as the exergy content of the energy demand, i.e. the ideal work potential of the energy demand. Since the maximum work that can be obtained from an amount of heat (or cold) is equal to the minimum amount of work required to produce this heat or cold (see chapter 2), the exergy demand for heating and cooling can be defined in a more clarifying way as follows:

- ***The exergy demand for heating and cooling is defined as the minimum amount of work needed to provide the energy demand for heating or cooling.***

Exergy demand calculation

The calculation of the exergy demand is usually performed by multiplying the energy demand with the exergy factor (f_{ex}) of the demand. This assumes that the heating or cooling is delivered at indoor temperature (T_i), according to equation 3-1. Ex_{dem} and Q_{dem} stand for the exergy demand and the energy demand for heating respectively, and ‘i’ stand for ‘indoor’.

$$Ex_{dem} = Q_{dem} \cdot f_{ex,dem} = Q_{dem} \cdot \left(1 - \frac{T_0}{T_i}\right) \quad \text{(T in Kelvin!)} \qquad (3\text{-}1)$$

Q_{dem} can be either a demand for heating (then it is a positive value since energy is supplied to the space) or a demand for cooling (then it is a negative value since energy is extracted). The approach is based on the fact that the minimum temperature at which heating can be supplied is at the indoor temperature, and the maximum temperature at which the cooling can be supplied is also at indoor temperature. This is of course a theoretical limit; in practice there needs to be a small difference in temperature for heat transfer to take place.

NOTE: The exergy factor for both a heating and cooling demand is very low:
Assume an indoor temperature of 20°C (293 K) and an outdoor temperature of 0°C (273 K); The exergy factor is then: 1-273/293= 0,068 (6,8%). This means only 0,068 units of work are needed to produce 1 unit of heat at 20°C.

Recapitulation of the energy demand calculation

The energy demand for heating and cooling is defined in ISO 13790 (2008) as 'the heat to be delivered to, or extracted from, a conditioned space to maintain the intended temperature conditions during a given period of time'.

This means the demand is based on the characteristics of the building, the climate in which the building is situated and the users (influencing ventilation and comfort requirements and internal gains). The additional energy need introduced by technical equipment is not included in the calculation of the demand.

The heating and cooling demand calculation is based on the energy balance of the building zone(s) (usually without regarding (de)humidification). The balance of the thermal zone(s) includes flows of energy (heat) and matter (ventilation and infiltration), which are illustrated in figure 3-2 and listed below :

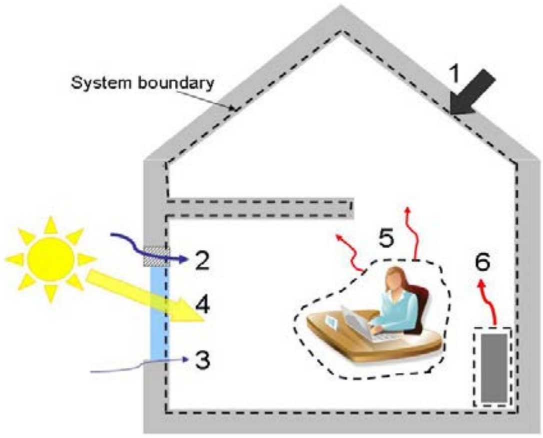


Figure 3-2: Scheme showing the flows of energy and matter across the system boundaries of the room.

Flow (energy or matter)	**Description of the (sensible) heat gain accompanying the flow of energy or matter**	**abbreviation**
1. Transmission	heat transfer from the building envelope into the conditioned indoor spaces	Qtrans
2. Ventilation	Sensible heat gains from the supply and exhaust of controlled ventilation air (the fresh air required by the use of the building)	Qvent
3. Infiltration	Sensible heat gains from uncontrolled inlet and exhaust of air through cracks of the building	Qinf
4. Solar gains	heat gains from the sun entering the zone(s) through transparent surfaces	Qsol
5. Internal gains	heat gains from people, lighting and equipment within the zone(s)	Qint
6. Demand	the heat to be delivered to, or extracted from, a conditioned space to maintain the intended temperature	Qdem

Energy balance equation

The energy demand, (Q_{dem}) can be calculated using an energy balance equation as shown in equation 3-2. A positive value represents a heat demand, a negative value a cooling demand.

$$Q_{trans} + Q_{vent} + Q_{\inf} + Q_{sol} + Q_{\text{int}} + Q_{dem} = 0 \quad (3\text{-}2)$$

The exergy of cooling in buildings

Few publications can be found on the exergy of cooling in buildings. However, it is sometimes noted that the exergy of a cooling demand cannot be calculated using a monthly average mean outdoor temperature. This is very true. The monthly mean outdoor temperature is usually below the indoor temperature, which means there is actually not a real exergy demand for cooling based on these averages.

In the beginning of this section, the exergy demand was defined as the minimum amount of work required to produce the required heat or cold. And, work is only required if a system needs to be brought to a state *further* from the state of the environment, e.g. to cool something to a temperature lower than the environmental temperature. Cooling something down to a temperature *closer* to the environmental temperature does not require work. Rather: it is actually a potential driving force to create work.

Two cooling situations

Hence, there are actually two cooling situations: The first type of situation occurs when the outdoor temperature (T_e) is higher than the indoor temperature (T_i): in this case there logically is a demand for cooling (heat output), since all flows of energy and matter represent heat gains. A second type of cooling demand exists even though the outdoor temperature (T_e) is lower than the indoor temperature (T_i), which often occurs due to high energy gains from solar radiation or internal heat sources (e.g. computers and lighting). For the exergy analysis of a cooling demand the difference between these situations is essential.

In table 3-1 the different situations are described[4]. These types of situations can occur in any kind of building and are not dependent on the exact building properties.

Table 3-1: characteristics of 3 essentially different types of energy demand situations

Situation	T_e vs T_i	gains vs losses	resulting energy demand
1	$T_e < T_i$	gains < losses	heating
2	$T_e < T_i$	gains > losses [a]	cooling
3	$T_e > T_i$	gains > losses	cooling

[a] In this situation there is a cooling demand since internal and solar gains exceed transmission and ventilation and infiltration losses

Exergy demand of the two cooling situations

In situation 2 from table 3-1 there is a cooling demand even though the environmental temperature is lower than the indoor temperature, which can occur due to high internal and solar gains. In this case the aim is to bring the temperature of the system *closer* to the environmental temperature. This theoretically means that work could be obtained, meaning there is no exergy demand but theoretically there is (warm) exergy available (i.e. the exergy of

[4] There is only one heating situation. A heating situation only occurs if the outdoor temperature (T_e) is lower than the indoor temperature (T_i) and the gains are lower than the losses, since there are no natural sources of cooling like there are natural sources of heating from internal and solar gains.

the heat at T_i). This is possible since buildings are not built with the aim to have the highest exergy content, but with the aim to provide comfortable thermal conditions.

In situation 3 from table 3-1 the environmental temperature is higher than the indoor temperature, which means the cooling demand represents a required exergy input, due to the fact that obtaining or maintaining any state different from the environmental state requires an exergy input, be it warmer or cooler. This cooling demand corresponds to the heat transfer (4) in figure 2-30.

The exergy consequences of the three types of situations that can occur in buildings are outlined in table 3-2. The two cooling situation are illustrated in figure 3-3, clarifying the results with an imaginary reversible (Carnot) cycle.

Table 3-2. Heating and cooling demand situations – consequences on the exergy demand

Situation:			**Energy**	**Exergy**
1	$T_e < T_i$	gains < losses	heating	*into* the building / exergy required
2	$T_e < T_i$	gains > losses	cooling	*out of* the building / exergy available
3	$T_e > T_i$	gains > losses	cooling	*into* the building / exergy required

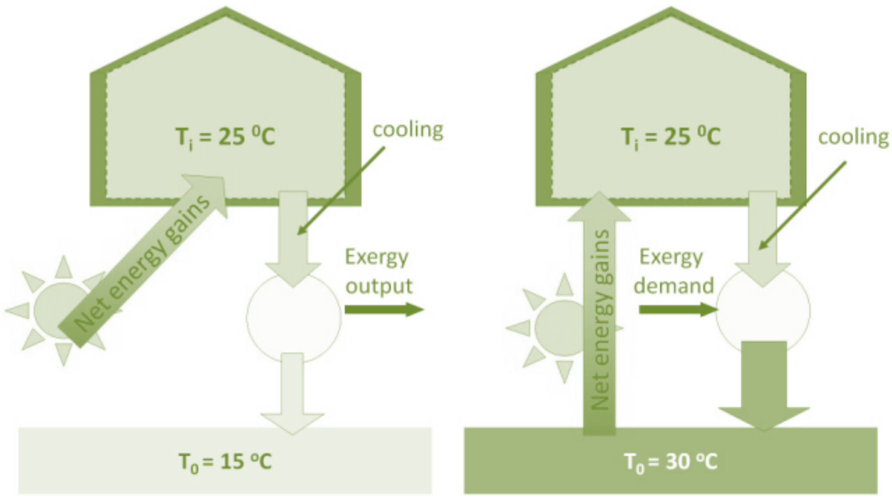


Figure 3-3: Scheme Exergy demand related to cooling at $T>T_0$ (left) and $T<T_0$ (right).

Since in the cooling season the cooling demand can occur both in situations with an environmental temperature above and below the indoor temperature, the exergy cannot be calculated using a monthly mean temperature. The exergy demand calculation needs to be based on a dynamic simulation.

<u>NOTE: The annual exergy demand for cooling</u>

The Dutch climate and many others are such that situation 2 ($T_i>T_0$) happens much more often than situation 3 ($T_i<T_0$). Additionally in situation 3 the temperature difference between T_i and T_0 is usually very small since temperatures above 30^{o}C rarely occur. This means the annual exergy demand for cooling is often extremely low and it confirms that passive systems should be optimized especially for cooling. Hence, in addition to energy analysis an exergy analysis gives insight into the difference between cooling demand at $T<T_0$ (required cool exergy input) and cooling demand at $T>T_0$ (theoretical warm exergy output).

Detailed exergy demand calculation

Also a more detailed approach for calculating the exergy demand can be taken. This approach, which was developed by Jansen (2013), results in a lower exergy demand for the same energy demand than the commonly applied equation (equation 3-1).

This detailed approach can best be explained by using simplified examples:

- *Imagine there is a simple room that has only transmission losses (heat transfer through the walls). There is no ventilation and there are no internal gains.*
  To keep this room at an indoor temperature of 20°C while the outdoor temperature is 5°C, a certain amount of heat needs to be supplied. This heat needs to be supplied at a minimum of 20°C (the indoor temperature). Hence, the exergy of the heat to be delivered can in this case be calculated according to the normal, 'simplified' way, using equation 3-1.
- *Now imagine a simple room that has only ventilation losses. All the walls are adiabatic (i.e. they have infinite insulation and thus no heat transfer); there are no internal gains. To keep this room at an indoor temperature of 20°C while the outdoor temperature is 5°C, it is also possible to preheat the ventilation air up to the required indoor temperature. In this case, the heat does not need to be supplied at the indoor temperature, but at a changing temperature, starting at outdoor temperature up to indoor temperature. As is explained in section 2-9, this requires less exergy. This can also be intuitively explained by imagining a set of ideal heat pumps to preheat this ventilation air, as is illustrated in the figure below. (note that also the ventilation exhaust air contains exergy).*

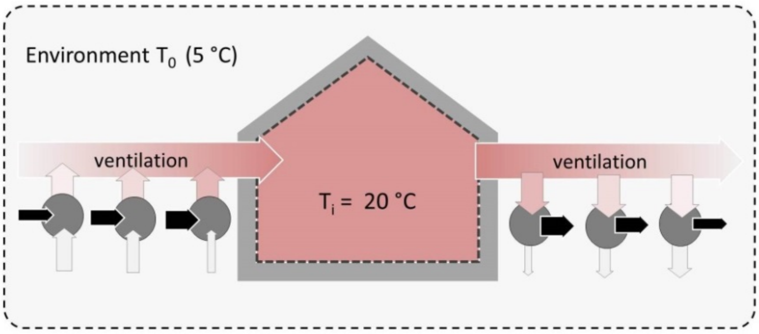


Figure 3-4: exergy of matter

- *For a case that has both transmission and ventilation losses, it can be considered that the exergy demand consist of a part that is used to preheat ventilation air, and a part that is used to compensate for the transmission losses. In case there are also heat gains, the minimum exergy need will be obtained when the ventilation air is preheated as much as possible or as much as needed, and heat supply at indoor temperature is minimised. The internal gains will be used to compensate for transmission losses.*

From the detailed demand approach it can be concluded that in principle it is more exergy efficient to preheat (or pre-cool) ventilation air than to heat ventilation air after it has entered the room. In practice of course preheating of ventilation requires a specific ventilation system (e.g. a heat recovery system) that may need another input of energy, such as fan energy. For a correct choice between preheating or not, the entire system must be analysed.

Steady state versus dynamic exergy demand calculation

Two basic types of energy demand calculation methods are distinguished (ISO 13790, 2008): (1) quasi-steady-state methods, calculating the heat balance over a sufficiently long time (typically one month or a whole season), which enables one to take dynamic effects into account by an empirically determined gain and/or loss utilization factor; (2) dynamic methods, calculating the heat balance with short times steps (typically one hour) taking into account the heat stored in, and released from, the mass of the building.

Many (national) building codes are based on the first type of method. For a more technical and scientific application dynamic simulation programmes according to the second type of method are mostly used.

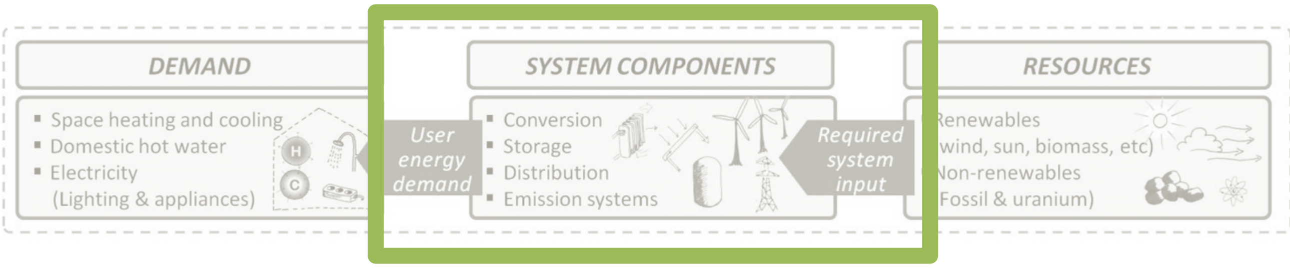
A detailed study on the difference between the results from a monthly mean exergy demand calculation ('quasi steady-state') and the results from a dynamic exergy demand analysis was performance by Jansen (2013). Using the monthly mean exergy demand calculation, the exergy demand is simply calculated by multiplying the energy demand with the exergy factor (equation 3-1), using the average indoor temperature and the average outdoor temperature. In a dynamic exergy calculation the exergy demand at each timestep (of 0,5 hour) is calculated, using the varying indoor and outdoor temperatures. For the study the dynamic energy demand values were used, so that the only difference was the result of the exergy calculations. Only the heating demand was analysed, as the cooling demand cannot be calculated using monthly mean values (see earlier in this section).

The general conclusion from this study was, that the exergy demand according to the dynamic calculation resulted in a higher value than the exergy demand according to the monthly mean calculation. This is quite logical: the largest heat demand occurs at the lowest outdoor temperatures, and thus as the highest exergy factors. The weighted average outdoor temperature is thus obviously lower than the straight average outdoor temperature.
(This is in fact very much comparable to the seasonal COP calculation of a heat pump: The largest heat demand occurs when the outdoor temperature is the lowest, and thus when the heat pump (if it uses the outdoor temperature as a source) has the lowest performance.

A brief summary of the conclusions is :

- *The dynamically calculated exergy demand results in a higher value than the monthly mean exergy demand calculation. This is because the largest heat demands occur at low outdoor temperature (and thus high exergy factors);*
- *The dynamic profile of the heat demand must be known to calculate the 'true' exergy demand. This is similar to the calculation of the seasonal COP of a heat pump, where the heat demand profile is also very important.*
- *The results show that in principle a combination of optimized heat pump use (i.e. use when outdoor temperatures are high) and thermal storage, can reduce exergy demand. This is further explained in chapter 5.*

3.3 Exergy input and output of system components



The energy system components for transformation of the energy include all technical devices for conversion, distribution or storage, such as boilers, radiators, heat pumps or distribution pipes. They are evaluated according to their in- and output, both in energy and exergy terms.

Input-output approach

The input-output approach means that the output of one component equals the input of the next component. This means there can be no losses between components and all losses are assigned to a certain component. For example: the output of a condensing boiler is hot water, which is the input of the radiator. In this way all the components are directly linked to another component. The chain is starting (or ending) at the demand and ending at a natural resource input. This is shown in figure 3-5 below. The input-output approach for the exergy analysis of energy systems for the built environment was first described by Schmidt (2004).

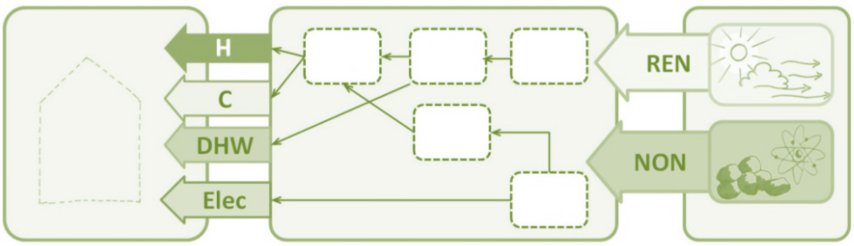


Figure 3-5: scheme of energy system components. All system components are connected to each other so that all losses can be assigned to a component .

'Room air' component

A special component is the so-called 'room air' component, first introduced by Schmidt (2004). This component is needed in the exergy analysis to assign the losses between the demand and the emission component (such as a radiator): Between the demand for heating (required at T_i) and the emission system (e.g. a radiator, at 60°C) no energy is lost. But there are (large) exergy losses as a direct result of the mismatch between demand temperature (T_i) and the temperature of the emission system. These exergy losses are not part of the demand or the emission system itself, but only a result of this mismatch.

Hence, the fictive component called "room air" is used to account for the exergy losses between emission system (e.g. a radiator) and space heating or cooling demand.

Calculating the exergy of inputs and output

An input or output can consist of heat at constant temperature, as sensible heat added or removed by an amount of matter, which is a result of a mass flow with defined inlet and return temperatures (as is for example the case with a radiator or floor heating system) or electricity. Fuel such as natural gas can also be used as an input. Components that produce fuels are not analysed in this book. A general scheme of a system component is shown in figure 3-6.

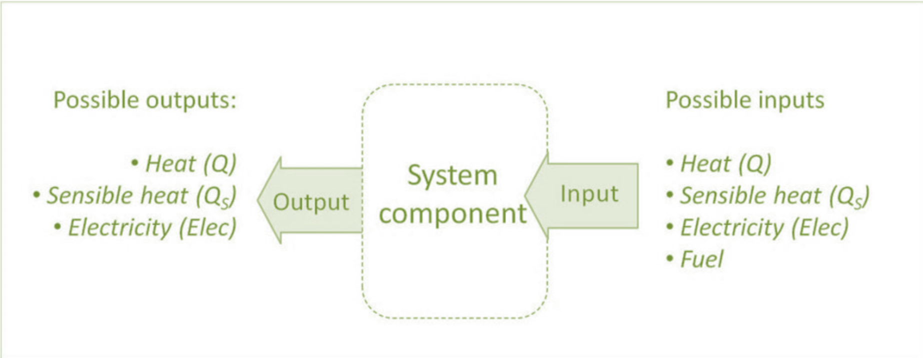


Figure 3-6: of energy systems components

The exergy of inputs and outputs is calculated based on the amount of energy and the applicable exergy factor.

The applicable exergy factors of input and outputs

The exergy factors of heat at constant temperature and of sensible heat contained by an amount of matter were discussed in Chapter 2. The exergy factor of electricity is by definition 1. The exergy factor of fuels involves a rather complex calculation, but for common fuels the values can be taken from literature (e.g. Szargut, 2005). Some of them are also shown in the next section on the exergy of resources. However, for simplification the exergy factor of gas can be considered to be 1 as well. The exergy factors commonly used for analyses of energy systems in the built environment are shown in figure 3-7 below:

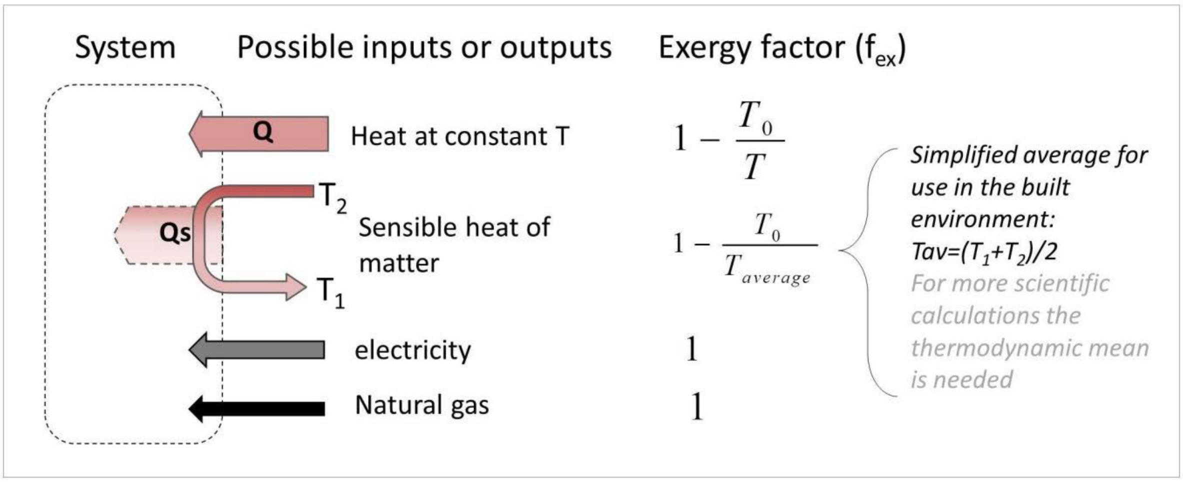
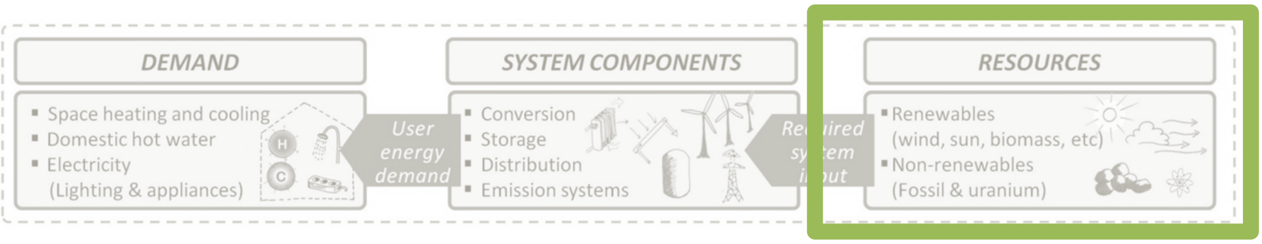


figure 3-7: scheme showing the possible component inputs or outputs and related exergy factors.

3.4 Exergy of resources



The system boundaries of the analysis framework are taken up to the input of primary energy resources. These are defined as "energy that has not been subjected to any conversion or transformation process carried out by humans". Primary energy can thus be considered as energy resources as they can be found in nature, including both renewable and non-renewable resources.

As is done for the exergy input into system components in the previous section, the exergy of resource can be calculated by multiplying the energy with the relevant exergy factor. In table 3-3 the exergy factors of various fuels and of heat are given. However, for simplification the exergy factor of gas can also be considered to be 1.

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)

Table 3-3: table of the exergy factors of various forms of energy and fuels.

The exergy of renewable resources

As can be seen both renewable and non-renewable resources can have a high exergy factor, i.e. can be 'high-quality' energy resources. For example, solar energy and wood (a renewable resources provided it is not used faster than it grows), are both high-quality energy.

The exergy content of a resource is thus not an indication of its renewability or sustainability. It is only a measure of thermodynamic potential: how much work it could ideally produce. This means the exergy approach is also suitable to promote an optimal use of high-quality renewable resources.

Energy, exergy and primary energy analysis

The final assessment of energy systems is currently usually performed according to the primary energy input. In principle, primary energy is in this publication defined as 'energy that has not been subjected to any conversion or transformation process carried out by humans' (adapted from NEN-EN 15603, 2008) and it includes both non-renewable energy and renewable energy. Hence, in principle the exergy factor of an amount of primary energy can be calculated by considering the specific exergy factor for each primary resource used.

However, the calculation method for calculating the national primary energy factors (PEF) is not always clear. It is even not always clear whether renewable resources are included in a national primary energy factor or not (Molenbroek et al.,2011 and Gommans, 2012). Therefore, it is not possible to correctly calculate the exergy of primary energy input according to the national primary energy factors. For a correct exergy calculation national primary energy factors should be avoided and the real resources should be identified as much as possible.

Sometimes an exergy factor of 1 is assumed for primary energy input (Torío et al (2011a) and Jansen et al. (2012)). This implies that a high quality primary energy source is assumed, such as natural gas (exergy factor between 0.94 and 1.03 according to Szargut, 2005). When using this approach the primary energy input obviously equals the primary exergy inputs assumed. Therefore people sometimes think a primary energy analysis is similar to an exergy analysis. This is not true!

Even though the final result may be equal due to this simplification, a primary energy analysis is something totally different from an exergy analysis:

- Primary energy analyses are a final assessment of a system according to the country or region where it is situated, using the national or regional Primary Energy Factor.
  The primary energy can only be calculated once all the energy transformation steps, the final energy carrier and the region where this carrier is produced and transported are known. The primary energy analysis can therefore only be used as a final assessment. It does not indicate whether a system can be improved.
- An exergy analysis evaluates thermodynamic losses at each transformation process of the energy system. This enables the identification and quantification of losses at each process or system component. It thus indicates whether a system can be improved and how much. It even quantifies the improvement potential for each process in the total chain. It can thus be used as a tool to improve systems.

4 Exergy analysis of state of the art energy systems

Currently energy systems are mostly analysed using an energy approach. This means only the exergy quantity is concerned and the quality as explained in the previous chapters is neglected. In this chapter three energy systems are analyses according to the exergy method explained in the previous chapter.

All cases are based on a single family terraced house, which is a typical type of dwelling in the Netherlands representing approximately 37% of the Dutch building stock. The following three energy systems are analysed:

1. Traditional energy system based on a condensing boiler for heating provide space heating and domestic hot water (a traditional Dutch system).
2. System with a micro CHP (combined heat and power) unit (in Dutch also sometimes called 'HRe ketel')
3. System with a heat pump for providing both space heating and domestic hot water.

Façade of the single family 'row-house' (terraced house).

As can be expected, the results from these analyses provide a different view on the performance of these systems and on the possibilities for improvement than the commonly applied energy approach.

Note: The case studies were originally published in the doctoral thesis at the basis of this book. All the details regarding the analysis, models and simulation method can be found in this thesis. The present chapter present a short explanation of the cases and the results.

4.1 Building model of the case studies: Dutch single family dwelling

In this book three case studies are presented. They are all based on the same single family dwelling. This is a single family row house, described by SenterNovem (2006) (in Dutch: SenterNovem referentie tussenwoning), which represents approximately 37% of the Dutch building stock (Agentschap NL 2012).

Dwelling description

The single family dwelling consists of two storeys and an attic, with a total gross floor area of 124 m^2 and a volume of 305 m^3. Two elevations and the floor plans are shown in figure 4-1.

figure 4-1: Façade and floor plans of the reference dwelling (Single family terraced house)

The most important building data are given in the tables below.

Table 4-1: Building characteristics of Dutch single family terraced house

Width	5.10	m
Dwelling depth	8.90	m
Gross floor area	124.30	m^2
Heat loss area	156.90	m^2
Volume	305	m^3
U-value ground floor	0.33	W/m^2K
U-value external facades	0.33	W/m^2K
U-value roof	0.28	W/m^2K
U-value windows	1.40	W/m^2K
g-value window	0.60	[-]

Building operation

The relevant operational data for determining the demand for space heating of the dwelling are displayed below:

Table 4-2: Schedules for building operation

	Ventilation rate (/h)	Infiltration rate (/h)	Internal gains W/m²	Set-point cooling °C (T_{op})	Setpoint heating °C (T_{op}) *Operation A*	Setpoint heating °C (T_{op}) *Operation B*
00.00-07.00 h	0.69	0.19	4.00	25	15	19
07.00-17.00 h	0.69	0.19	4.30	25	19	19
17.00-23.00 h	0.69	0.19	11.5	25	19	19
23:00-00:00 h	0.69	0.19	4.00	25	15	19

Electricity demand (ELEC)

The electricity demand schedule for the Dutch reference dwelling is based on the following assumptions:

- The annual demand is 4,086 kWh/year (de Jong et. al (2008).
- The electricity demand is considered equal for all days (no weekday-weekend distinction and no seasonal differences); the demand is thus 40,300 kJ/day.
- A 24-hour profile is created in line with the profile for internal gains (see table 4-2)

Demand for domestic hot water (DHW)

The domestic hot water demands are based on the following assumptions:

- The assumed annual demand for heating DHW is 8.6 GJ_{th}/year (de Jong et al. 2008).
- The daily use is 112 litres of hot water, with annual average 13°C supply and 60°C as required end temperature. (This results in the heat demand of 8,6 GJth/year).

The electricity demand and DHW demand schedules are presented in table 4-3.

Table 4-3: Schedules for electricity and domestic hot water (DHW) demand.

	Electricity demand W	DHW demand l/h
00.00-07.00 h	134	0
07.00-08.00 h	224	56
08.00-09.00 h	224	0
09.00-17.00 h	437	0
17.00-19.00 h	1030	0
19.00-23.00 h	1030	14
23:00-00:00 h	134	0

Building model and simulation model

The dwelling is modelled in the TRNSYS simulation software using type 56 as a single zone model. The description and development of the model and the influence of various simulation parameters including the number of zones can be found in the doctoral thesis at the basis of this publication (Jansen, 2013).

4.2 Energy and exergy demands of the reference dwelling

This section discusses the energy and exergy demands for heating and cooling of the Dutch Single family dwelling described in the previous section. The analysis is based on dynamic calculations using the dynamic simulation software TRNSYS, using a time-step of 0,5 hour. For each time-step the exergy demand is calculated using the method described in section 3.2.

Resulting monthly heat demand

In figure 4-2 the monthly energy and exergy demand are presented as well as the weighted average monthly exergy factor (i.e. the monthly exergy demand divided by the monthly energy demand.

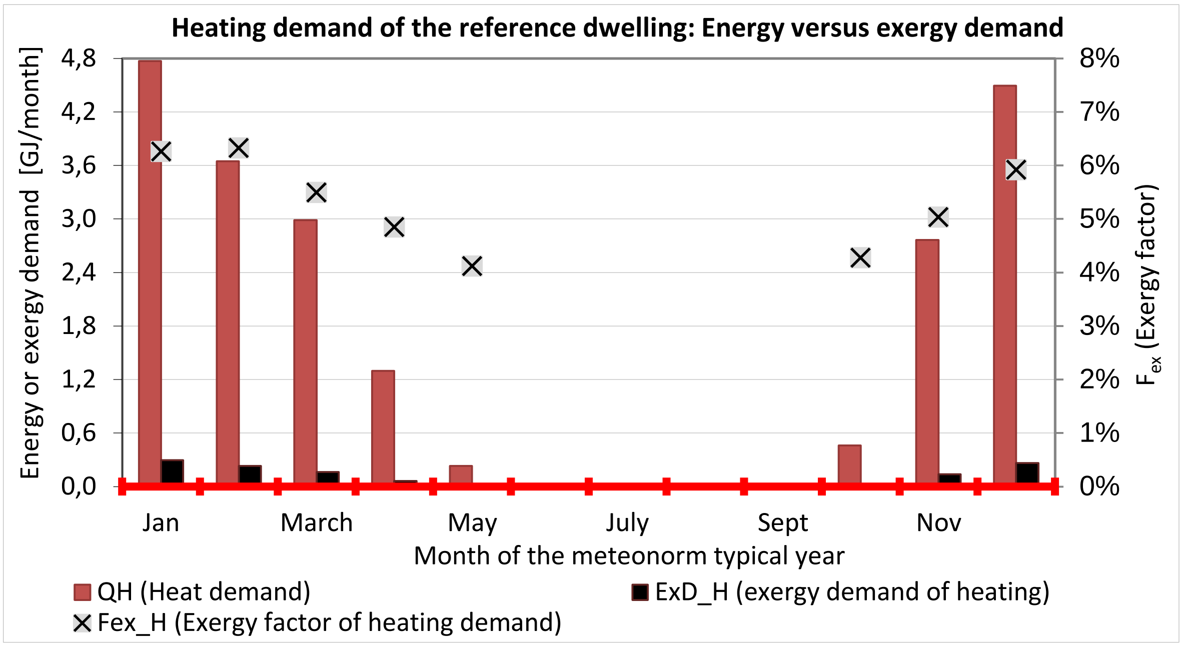


figure 4-2: Monthly energy and exergy demand and monthly weighted average exergy factor of the Dutch reference dwelling (Case 1A, operation schedule A).

The graph shows the seasonal profile of the heat demand. It also shows that the exergy demand only represents a fraction of the energy demand, which means that in theory the demand can be met with a an input of low-quality energy or with little high-quality input. The annual heat demand is 20,6 GJ and the simplified exergy demand is 1,2 GJ/year. The average weighted exergy factor for a year is therefore 5,8 %.

As can be seen from figure 4-2 the monthly exergy factor of the heat demand varies between 4,1% (for May) and 6,3% (for January and February), due to the fact that the exergy factor is related to the reference temperature, which equals the outdoor temperature. (Simply said: the closer the environmental temperature to the desired temperature of the system, 20°C in this case, the easier it is to produce this heat). Of course it has to be noted however that most heat is required at low outdoor temperatures, thus at high exergy factors; therefore the annual weighted average of 5,8% is much closer to the highest value of 6,3% than to 4,1%.

Annual results of all demands

In figure 4-3 the total annual demands are shown: It can be seen that the demand for space heating represents the largest energy demand, followed by the electricity demand and then the heat demand for hot water.

In exergy terms however the electricity demand is by far the largest demand and all other demands are fairly small in comparison. This is of course due to the low exergy factor for heating.

The cooling demand is negligible, but cooling will be discussed on the next page.

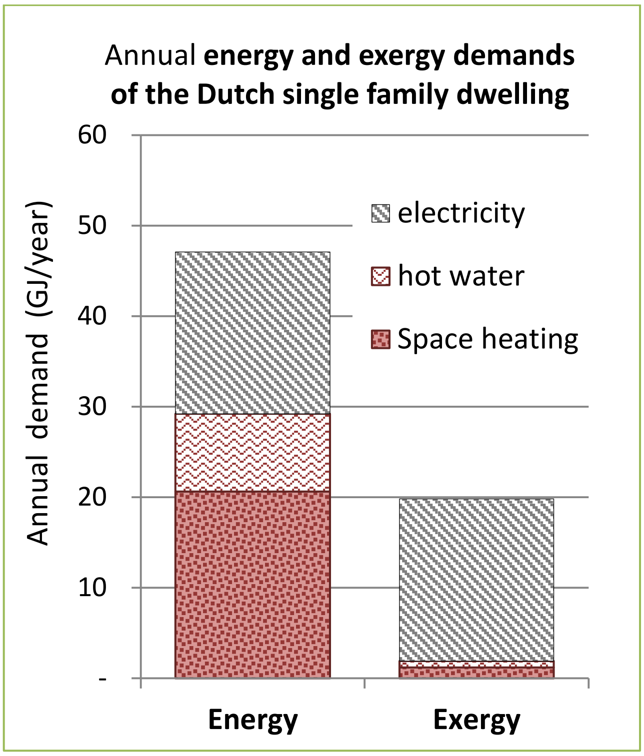


figure 4-3: Total annual demands of the reference dwelling).

Detailed dynamic results of the heat demand

In figure 4-4 the hourly energy and exergy demand for 10 days (February 12th until February 22nd) are plotted. This figure shows that the exergy factor not only varies significantly between months, but even between hours within one day. This means that a certain amount of heat at one moment ideally requires significantly less work than the same amount of heat at another moment. It shows the potential of 'smart' use of a heat pump in combination with thermal storage.

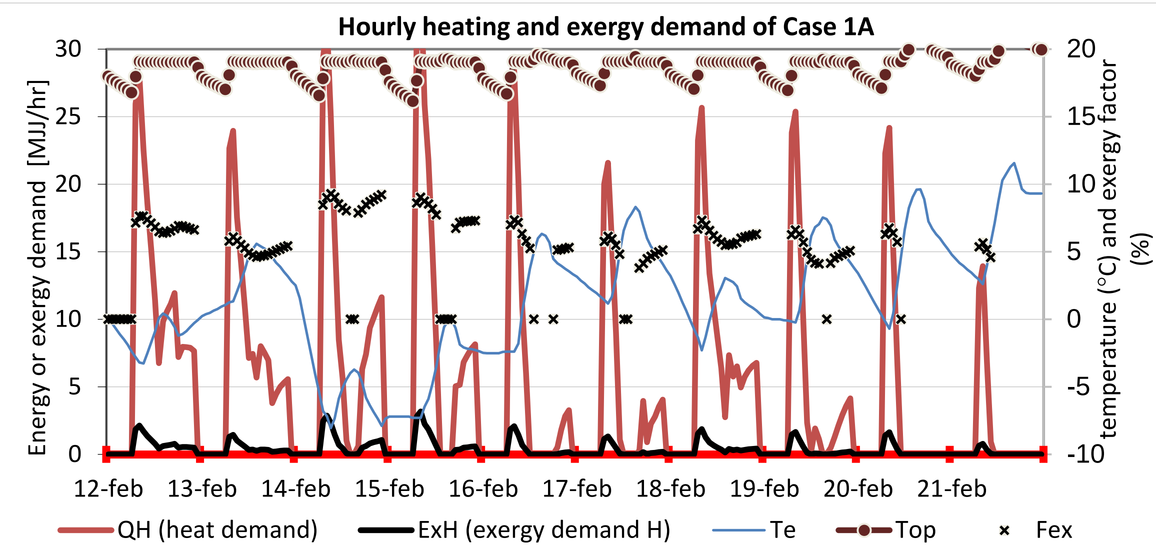


Figure 4-4: Hourly energy and exergy demand and hourly average exergy factor (from Feb 12-22).

Resulting cooling demand of the reference dwelling

Chapter 3 discussed two different cooling situations: Firstly a situation where there is a cooling demand even though the outdoor temperature is lower than the indoor temperature, as a result of (high) solar and internal gains, and secondly a situation where there is a cooling demand while the outdoor temperature is higher than the indoor temperature. In the first situation the cooling demand does not present an exergy demand since in fact the temperature in the building must be brought closer to (i.e. more in equilibrium with) the environmental temperature. Only the second situation presents a real cooling demand in terms of exergy required.

In figure 4-5 the hourly cooling demand of the reference dwelling as well as the exergy of this cooling demand (according to section 3.2) is presented for the period between August 15th and August 31st. The cooling setpoint is 25°C. The y-axis of this graph presents the amount of energy or exergy. Since the exergy values present only a fraction of the energy values, two graphs on top of each other are used, displaying the same period but having different y-axis scales. The figure shows that the exergy demand is only positive when the outdoor temperature is above 25°C, i.e. above indoor temperature, which rarely occurs. The largest part of the cooling demand (i.e. required heat output to maintain a comfortable temperature) actually represents a potential availability of 'warm' exergy.

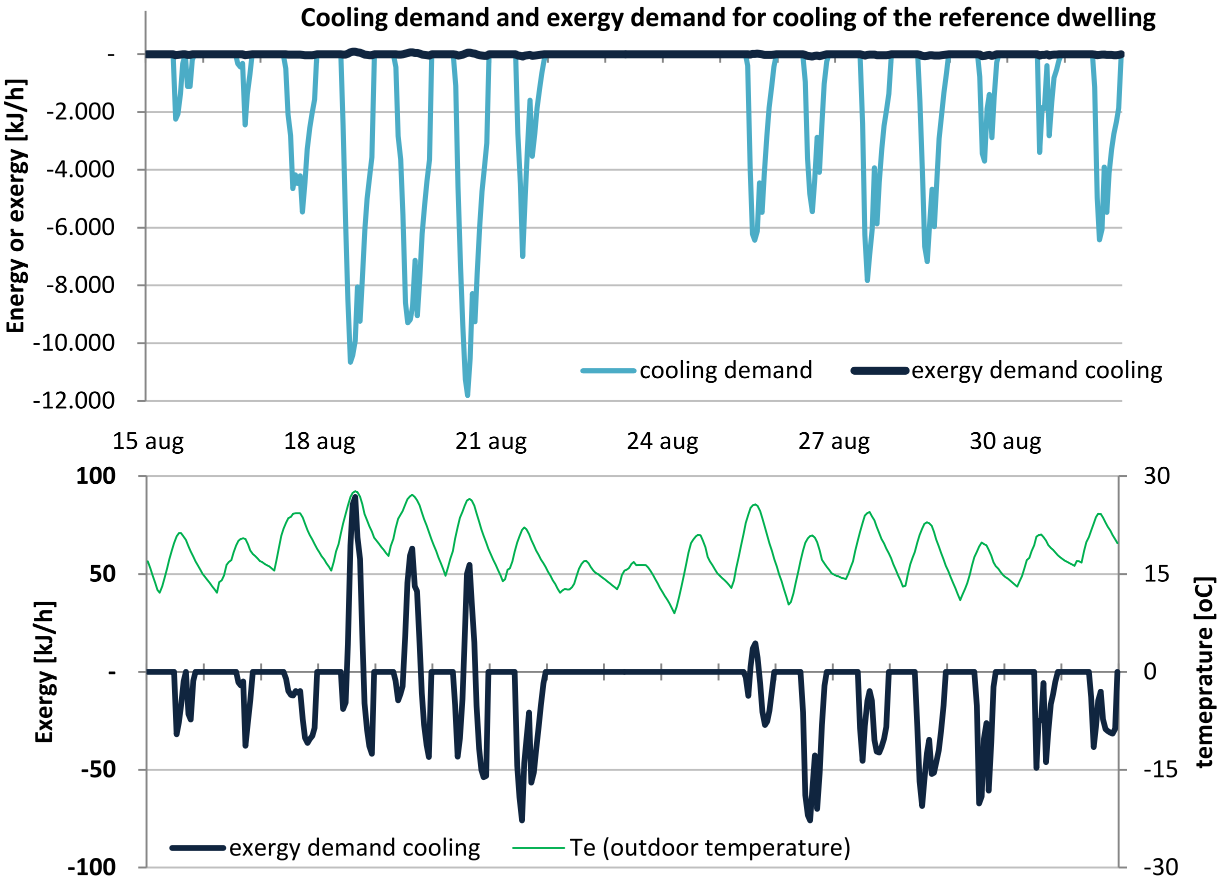


Figure 4-5: Hourly energy and exergy demand for cooling of from August 15th to August 31st. The exergy demand is plotted in both graphs, but the lower graph has a different scale than the upper graph for better visibility.

In table 4-4 the monthly energy and exergy demands for cooling of the reference dwelling are presented, distinguishing the two cooling situations. As can be seen the 'real' cooling demand is extremely low which means the work theoretically required to provide cooling is negligible. Unfortunately, also the exergy surplus, i.e. the theoretical work available is negligible. The reason for both is that the indoor temperature is in both cooling situation quite close to the outdoor temperature. Note that figure 4-5 and the results in table 4-4 demonstrate that it is not possible to calculate the exergy of cooling using monthly mean temperatures, as this approach is unable to distinguish the two different types of cooling demand. Moreover, since the monthly average outdoor temperature in moderate climates does not exceed 25°C, no exergy of cooling will result.

Table 4-4: monthly energy and exergy demand for cooling

	Average T_e	**Cooling demand**	**Exergy demand at T_i<T_e ('real' exergy demand)**	**Exergy demand at T_i>T_e (in fact exergy 'surplus')**
	[°C]	**Q_C[MJ]**	**ExD,Q_C [MJ]**	**ExSURPLUS,Q_C [MJ]**
June	14.7	- 147.2	0	- 1.5
July	16.4	- 343.4	0.6	- 2.8
August	16.8	- 654.3	0.9	- 4.1
September	14.1	- 19.6	0	- 0.2
TOTAL		**- 1,164**	**1.5**	**-8.7**

This case study is a dwelling and in office buildings the cooling demand is usually much more significant. However, in climates like the Dutch climate the cooling demand representing a demand for exergy input will always be very small, which means in theory hardly any work is required for providing cooling.

The exergy of cooling:

In moderate climates like the Dutch, the outdoor temperature rarely becomes higher than the maximum allowed indoor temperature. This means that:

- ***A 'real' exergy demand for cooling - in the sense that it really needs an input of high-quality energy – is always negligible.***
- ***Most of the cooling situations occur even though the outdoor temperature is below indoor temperature, as a result of high heat gains (solar and internal gains). This cooling demand does not require exergy. In practice this means it could be obtained by more ventilation or increasing spontaneous heat loss to the environment in other ways, such as decreased insulation.***
- ***The exergy of a cooling demand cannot be calculated using monthly mean temperatures, since the outdoor temperatures are both above and below the maximum allowed indoor temperature within a month.***

4.3 Case studies energy systems

Three energy systems are analyses in this section, all based on the reference dwelling described in the previous section[5]:

1. Traditional energy system based on a condensing boiler for heating provide space heating and domestic hot water (A traditional Dutch system).
2. System with a micro CHP (combined heat and power) unit
   (in Dutch also sometimes called 'HRe ketel')
3. System with a heat pump for providing both space heating and domestic hot water.

For all cases the electricity is assumed to be supplied by a state of the art combined cycle power plant (CC-plant) with an energy efficiency of 60%.[6]

Case 1

This case represents the reference dwelling with a traditional energy system based on a medium temperature radiator (T_{sup} =60°C, T_{ret}=40°C) and a condensing boiler for supplying space heating and domestic hot water (DHW). No heat recovery is assumed. The efficiency of the condensing boiler for providing space heating is assumed at 95% and for providing DHW at 70%. Electricity is supplied by a state of the art combined cycle power plant (CC-plant) with an energy efficiency of 60%. Primary energy factors are not used in this case study. A simplified scheme of the reference energy systems is shown in figure 4-6. As can be seen also a 'room air' component (see previous chapter) is included.

Case 2

Case 2 also is based on the Dutch reference dwelling without heat recovery, and with a radiator as heat emission system. The heat required to meet the demand for space heating is provided by a micro cogeneration unit (micro CHP). Also the demand for domestic hot water is provided by the micro CHP, supported by a thermal storage tank. The micro CHP is heat demand driven, which means electricity is produced when heat is required. The scheme of Case 2 is shown in figure 4-7.

Case 3

Case 3 is based on the Dutch reference dwelling with a constant setpoint temperature and ventilation heat recovery. The heat demand for space heating and domestic hot water is provided by a dual purpose heat pump ('combi-warmtepomp' in Dutch) with a thermal storage tank for domestic hot water. The electricity demand from the users as well as the required electricity related to the heat pump is supplied by a combined cycle plant. The scheme of Case 3 is shown in figure 4-8

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[5] N.B. These case studies are taken from the doctoral thesis (Jansen, 2013), and there they are numbered differently as case 3 (here: 1), case 4A (here: 2) and case 4B (here: 3). All the details regarding these cases can also be found in the same doctoral thesis.

[6] A combined cycle plant uses the combination of a gas turbine with a steam turbine cycle. They currently provide the highest efficiencies for producing electricity (Woudstra 2012).

Case 1

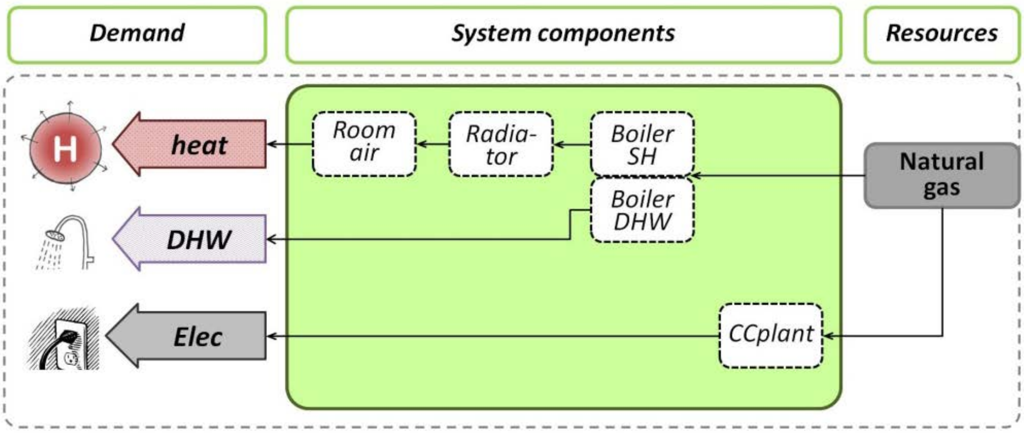

figure 4-6: Scheme of Case 1 representing the energy system of the Dutch traditional reference case. (SH= space heating, DHW= domestic hot water, CC-plant = combined cycle power plant)

Case 2

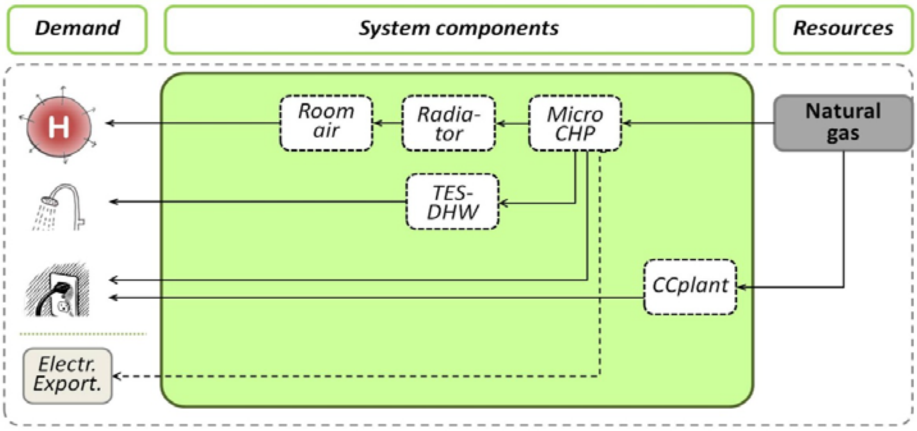

figure 4-7: Energy system scheme of Case 2: Dutch reference dwelling with micro CHP based energy supply ((SH= space heating, DHW= domestic hot water, TES = thermal energy storage , CC-plant = combined cycle power plant)

Case 3

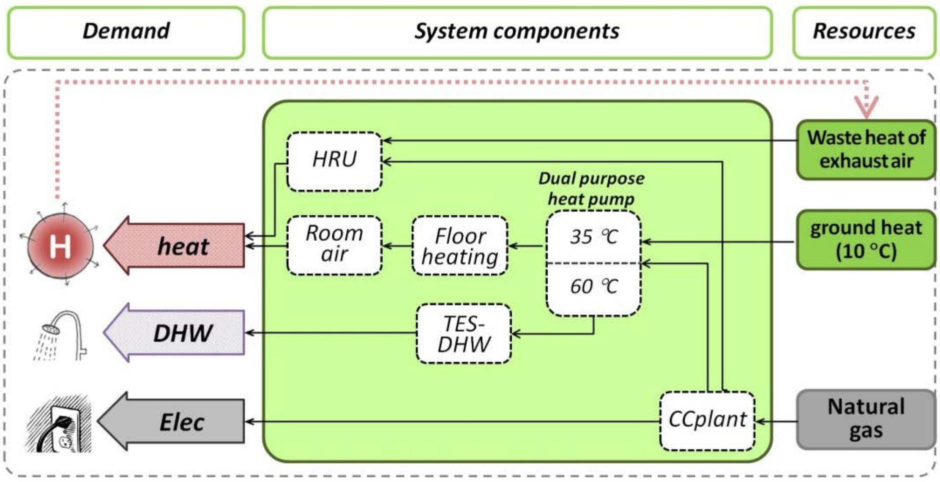

figure 4-8: Energy system scheme of Case 3: Dutch reference dwelling with heat recovery, floor heating and a dual purpose heat pump for proving space heating and domestic hot water.
(This system is similar to energy concept Ri.1 as described in the 'Toolkit Duurzame Woningbouw' (Hameetman et al. 2006), a Dutch handbook on efficient energy concepts for dwellings.)

__Description of the component models used__

Heat recovery unit (HRU)

For the heat recovery unit (HRU) an air-to-air counterflow heat exchanger is assumed. Latent heat exchange (i.e. condensation) is neglected. In figure 4-9 a scheme of the HRU is shown and the relevant characteristics are listed in table 4-5.

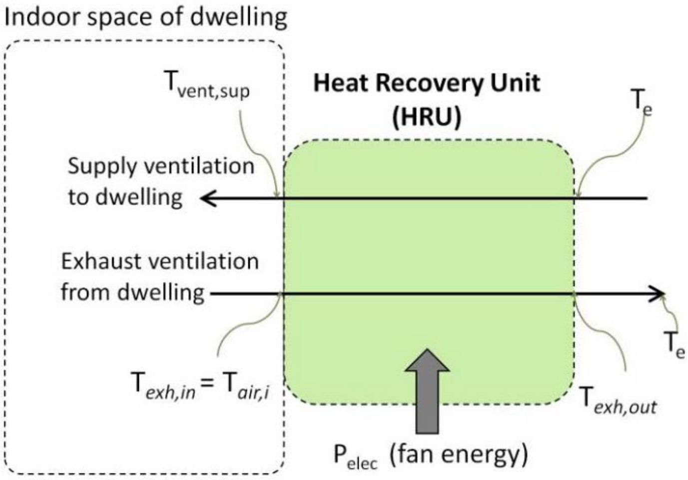

figure 4-9: scheme of the heat recovery unit (HRU) as used in Case 2

($T_{vent,sup}$ =temperature of supply air; $T_{exh,in}$ = temperature of exhaust air coming out of the dwelling, $T_{exh,out}$ = temperature of exhaust air after heat recovery)

Table 4-5: characteristics of the heat recovery unit

thermal efficiency	η*HRU*	*0.9*	
Fan electricity input	P_{elec}	*88*	*W*
Fan electricity in case of bypass	P_{elec}	*88*	*W*

The values are based on the following assumptions:

- *The fan power is based on the values given for the HRU ECO 4 unit as given by ITHO (2013a), for a capacity of 225m³/h and a pressure difference of 150 Pa.*
- *The ventilation airflow rate is based on the ventilation air change rate of the dwelling of 0.69 times the dwelling volume (305 m³) per hour, resulting in a capacity of 210 m³/h (0.058 m³/s).*

Floor heating

Very low temperature floor heating is assumed using a floor heating inlet temperature of 35℃ and a return temperature of 30℃. For the floor surface temperature a constant temperature of 29℃ is assumed. The floor heating system is not modelled dynamically in TRNSYS, but calculated as a steady state equation for each 0,5 h time-step.

Model of the thermal storage tank for DHW

The thermal storage tank used for providing DHW is modelled in a simplified way by assuming that the daily demand (112 litres/day) is spread evenly over the period between 7:00h and 23:00h and that the required inlet temperature of the storage tank is 5 ℃ higher than the required temperature for domestic hot water, thus resulting in a temperature of 65 ℃. The return temperature of the load-side of the thermal storage is considered equal to the water supply temperature (from the national distribution). By assuming a higher input temperature of the TES than of the DHW supplied some heat losses are introduced, which are calculated by the model. A scheme of the simplified TES model is shown in figure 4-10.

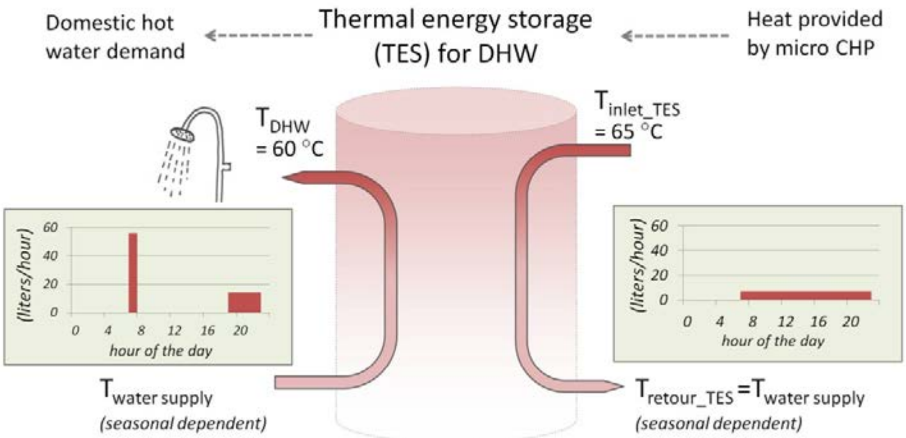

figure 4-10: Scheme of the simplified model for the thermal energy storage (TES) for DHW.

Heat pump model

It is assumed that all heat required can be provided by the heat pump in order to fully evaluate the exergy performance of the heat pump. A 'ground source' heat pump is meaning a heat exchanger is used to extract heat from the underground at a constant temperature of 10 ℃. The heat pump is modelled in a simplified way by using the annual constant COP values as listed below (Based on Techneco Toros combiwarmtepomp specifications (Techneco 2012)):

- *COP for space heating (source/load temperatures: 10 ℃/35 ℃) = 4.1*
- *COP for DHW (source/load temperatures: 10 ℃/60 ℃) = 2.5*

Simplified model of the micro CHP

It is assumed that all heat required can be supplied by the micro CHP. The input parameters of the micro CHP model are:

- $\eta_{CHP,Q}$ *(energy efficiency for heat production) = 80% (in accordance with Jong et al. (2006, update 2008)*
- $\eta_{CHP,el}$ *(energy efficiency for electricity production) =* $1-\eta_{CHP,Q}$ *= 20%*
- $Q_{CHP,out}$ *= the total heat demand to be supplied by the micro CHP. This value is calculated as the sum of the heat demand for space heating and the heat input required by the thermal storage.*

4.4 Annual results of the system case studies

Annual results of Case 1

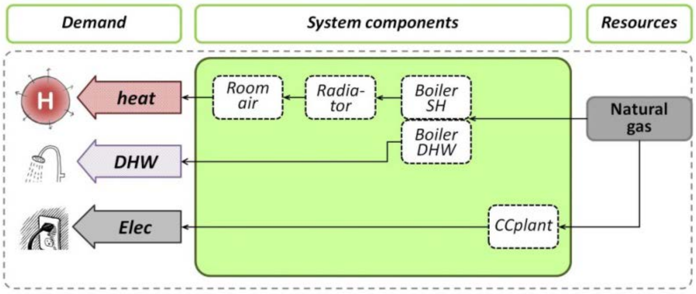

Figure 4-11 shows the annual demands (space heating, domestic hot water and electricity) *and* the losses of all system components in one bar (one for energy and one for exergy). The demands and all component losses (energy and exergy values respectively), sum up to be the value of the total primary resource input. The total energy input equals the total exergy input in this case, as the only input comes from natural gas and the exergy factor assumed for this resource is 1.

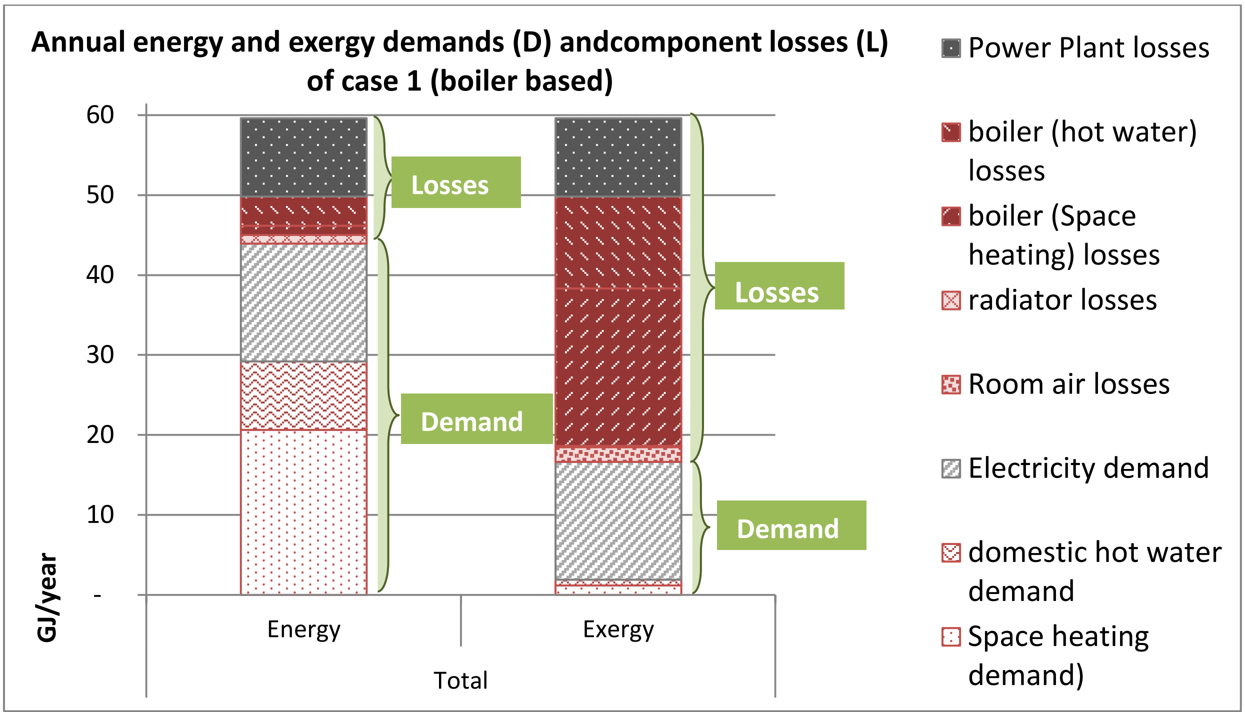

figure 4-11: Annual energy and exergy results of Case 1

As can be seen in energy terms the total product (= output or demand) represents a large portion of the energy 'used'. In exergy terms however the total output is significantly lower due to the low quality of the demands for space heating and domestic hot water (DHW). The exergy demand for electricity is equal to the energy demand and therefore large in comparison to the exergy of the heat demand.

In energy terms the only significant losses take place in the production of electricity by the combined cycle power plant. The exergy analysis reveals additional and different losses than those resulting from the energy analysis. The largest losses are created in the production of heat by the boiler (both for production of space heating and DHW). These losses are non-existent in the energy analysis. Also, the losses occurring in the production of electricity by the combined cycle plant are still significant. Furthermore new losses are introduced which are not present in the energy analysis. These are the losses of the component 'room air', quantifying the exergy losses caused by the temperature difference between demand (at T_i) and emission system (the radiator).

The difference between energy and exergy losses per component is also illustrated in figures 4-12 and 4-13, presenting the input and output per component in energy and exergy values respectively. These figures also clearly show the difference between energy and exergy analysis and the added value of the insight from the exergy approach.

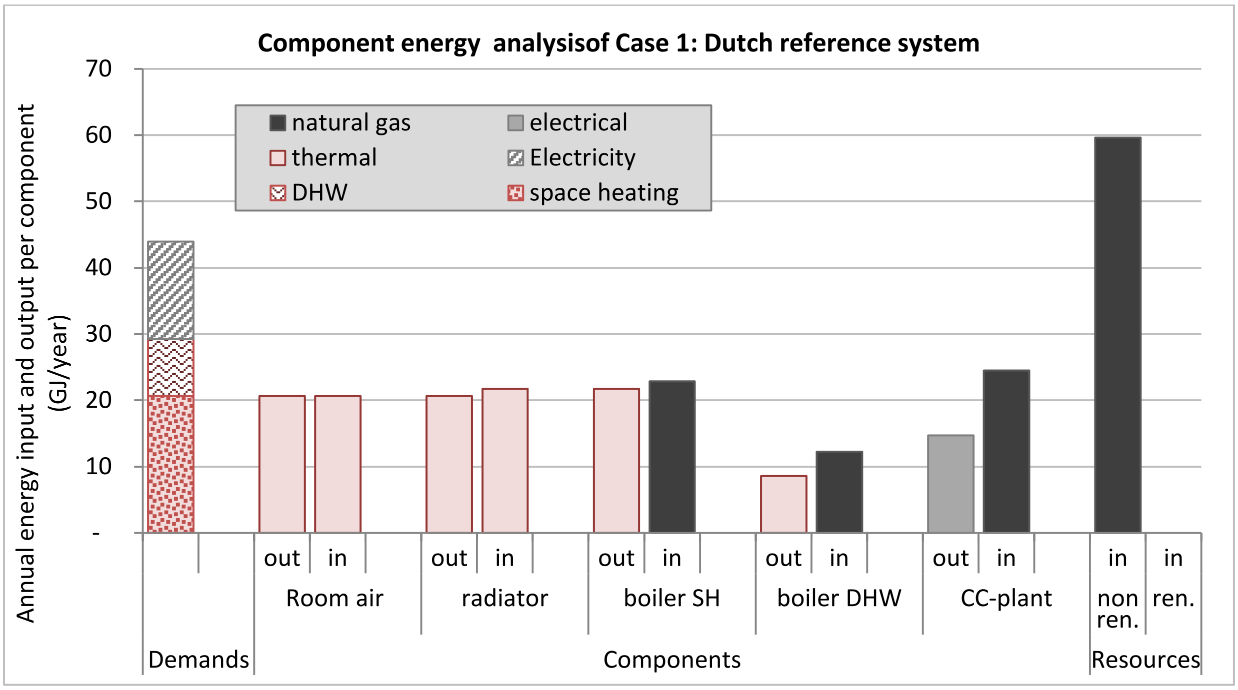

figure 4-12: Annual energy analysis of component in- and outputs of Case 1

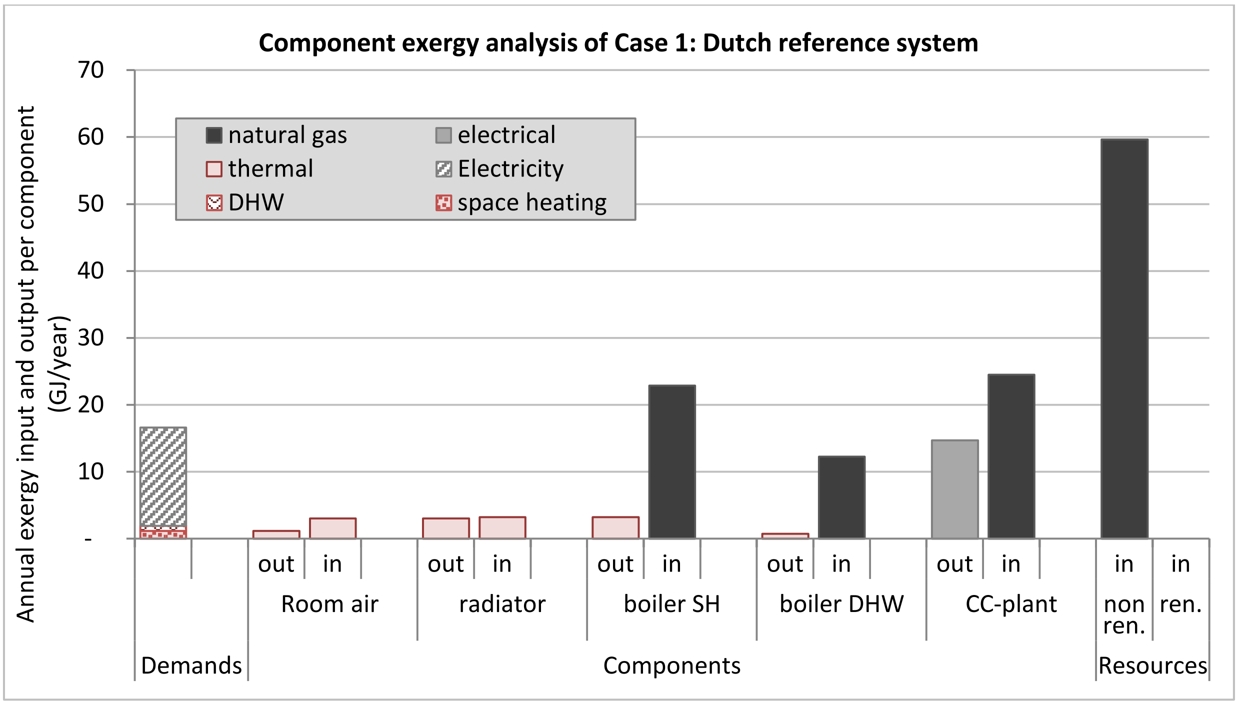

figure 4-13: Annual exergy analysis of component in- and outputs of Case 1

Annual results of Case 2

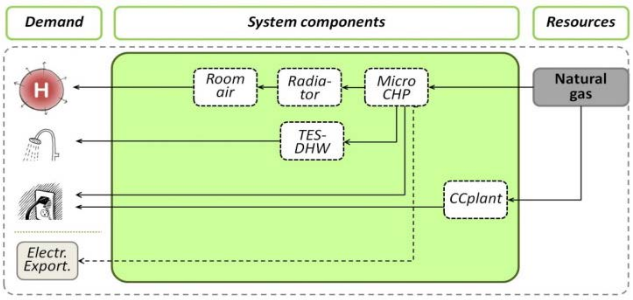

Figure 4-14 shows the annual demands (space heating, domestic hot water and electricity) *and* the losses of all system components in one bar (one for energy and one for exergy) of case 2. The demands and all component losses (energy and exergy values respectively), sum up to be the value of the total primary resource input. The total energy input equals the total exergy input, as the only input comes from natural gas with an exergy factor of 1.

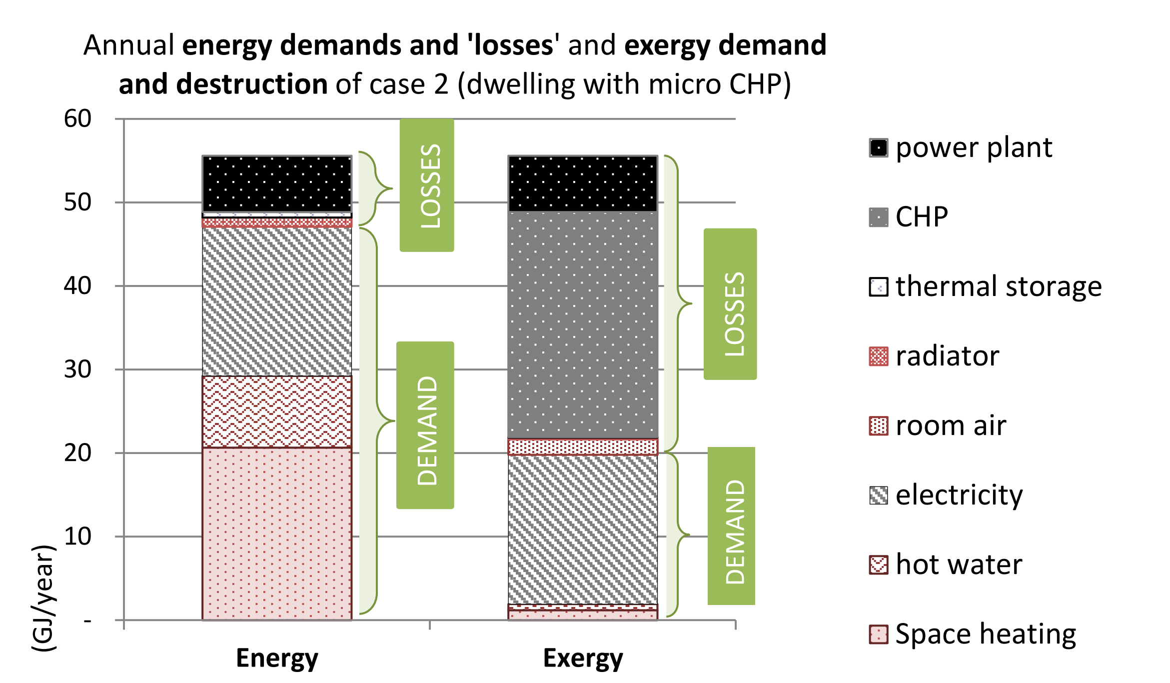

figure 4-14: Annual demands and losses (stacked) for Case 2

As can be seen from the results the micro CHP-based case performs very well in energy terms: the only significant losses take place in the production of electricity by the combined cycle power plant. This good energy performance is logically caused by the significant contribution of the CHP with an energy efficiency of 100% (20% electrical + 80% thermal efficiency). The only other losses are presented by the radiator and the thermal energy storage, but these amounts are almost negligible. Similar to the energy results of Case 1 also the energy analysis of case 2 suggests that the only way to reduce the required input is to reduce the energy demand.

In exergy terms however the system seems to perform less good. Very large losses are revealed in the CHP, which are not identified using energy analysis. The performance of the CHP in exergy terms is thus much lower than in energy terms, due to the large percentage of thermal output and the related low quality (used for the radiator and the domestic hot water). This means that thermodynamically there is much room for improvement.

Note: The CHP is 'heat driven'. This means it produces electricity when there is a heat demand. Therefore, at each time-step there can be either a remaining demand for electricity (electricity demand > electricity produced by CHP) or a surplus of electricity produced (electricity demand < electricity produced by CHP). In reality the surplus will be exported to the grid and the need will come from the grid. In figure 4-14 only the net input of electricity from the grid (CC-plant) is shown, i.e. all exported electricity is subtracted from the supplied electricity.

Similar to the results of case 1, the inputs and outputs in energy and exergy terms are also shown at component level in the two figures below.

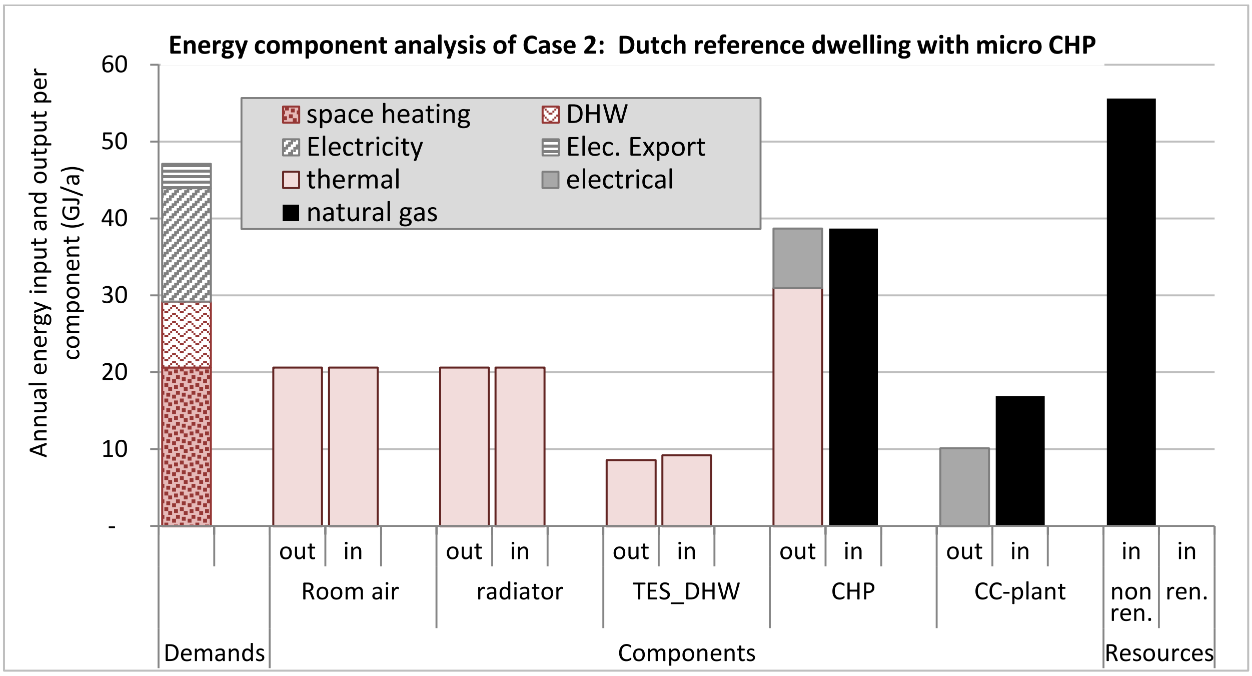

figure 4-15: Annual energy analysis of component in- and outputs of Case 2

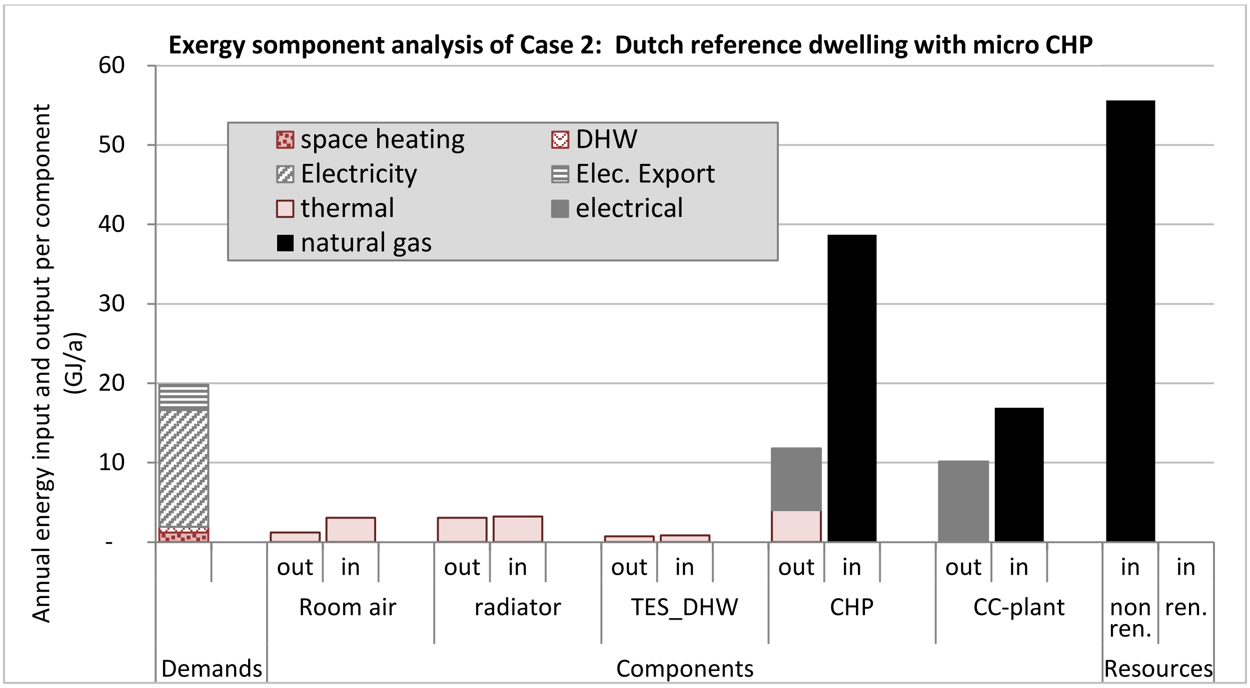

figure 4-16: Annual exergy analysis of component in- and outputs of Case 2

Annual results of Case 3

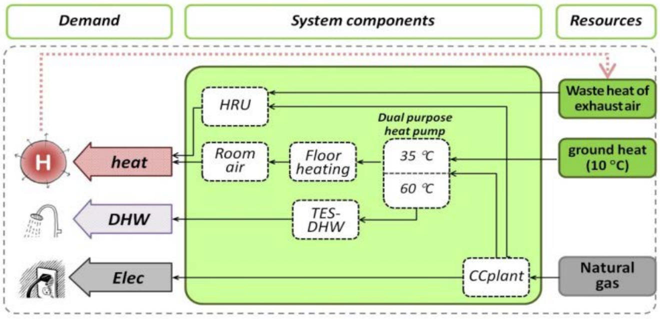

Figure 4-17 shows the annual demands (space heating, domestic hot water and electricity) *and* the losses of all system components in one bar (one for energy and one for exergy) of case 3.

In principle the demands and losses of this case also sum up to the total input for the whole system. However, in this graph only the losses related to non-renewable input into the components are presented. This results in negative energy losses for the heat recovery unit as well as the heat pump. Negative losses mean that the input of a component is smaller than the output. The energy input is therefore not directly visible from this graph but can be deducted from subtracting the (negative) losses from the positive values.

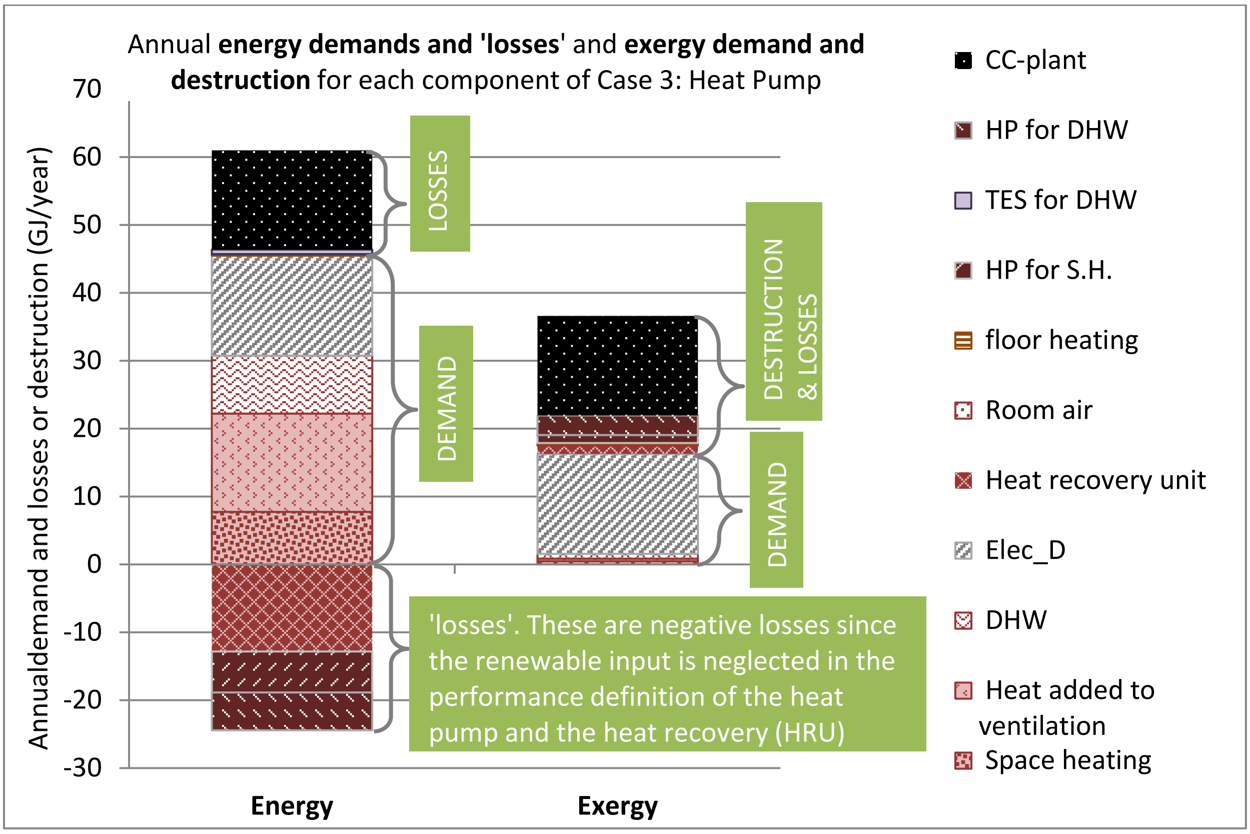

figure 4-17: Annual energy and exergy analysis of Case 3. In this graph only the losses related to non-renewable input into the components are presented. This results in negative energy losses for the heat recovery unit as well as the heat pump.

Since Case 3 also includes the use of heat recovery of ventilation air, the heat demand is split into two parts: a part that consists of the heat added to the ventilation air and a part that is the remaining heat demand (in this case to be supplied by the floor heating system). These parts are treated separately in order to be able to evaluate the performance of the heat recovery unit (HRU). As will be seen in the analyses in the figures on the right page, the energy performance of the HRU is quite different from its exergy performance. This is due to the fact that high quality electricity is used to recover low quality heat. Still, the performance is much better than when using a process like combustion to provide this heating.

In figures 4-18 and 4-19 the energy and exergy analysis per component is displayed. Also renewable inputs are included, making the performance of each component clearer.

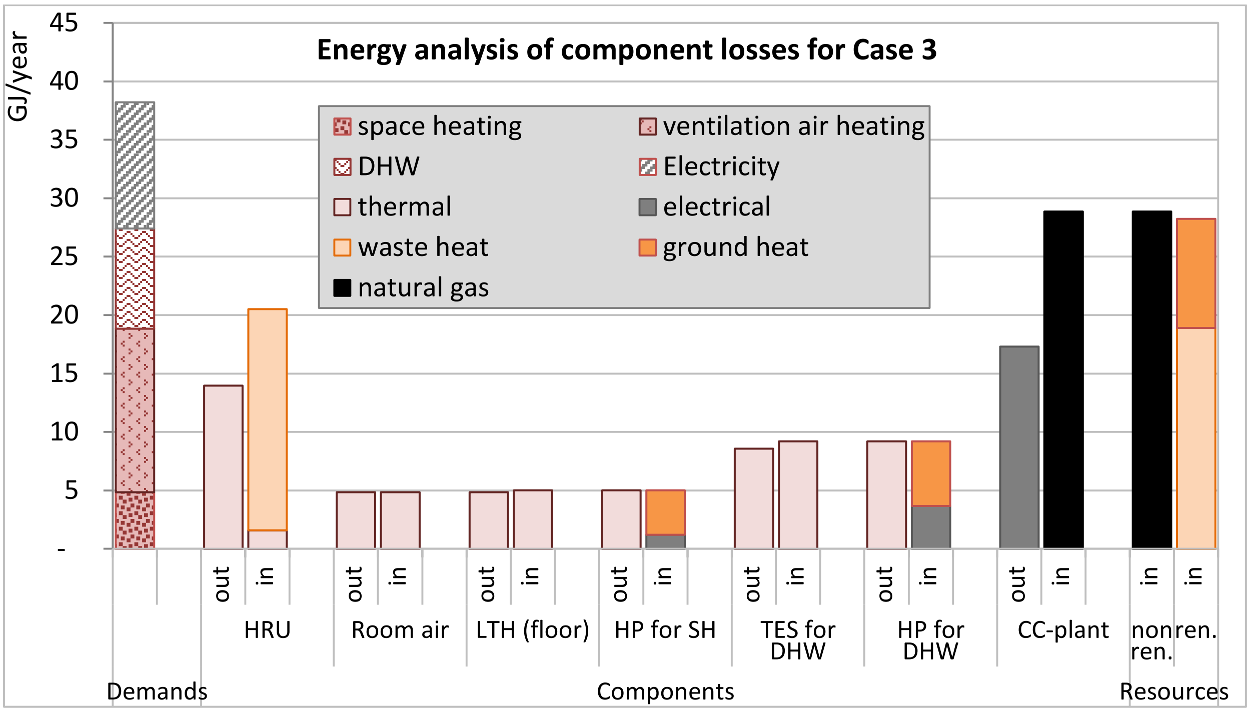

figure 4-18: Annual energy component analysis of Case 3, presenting both renewable and non-renewable input.

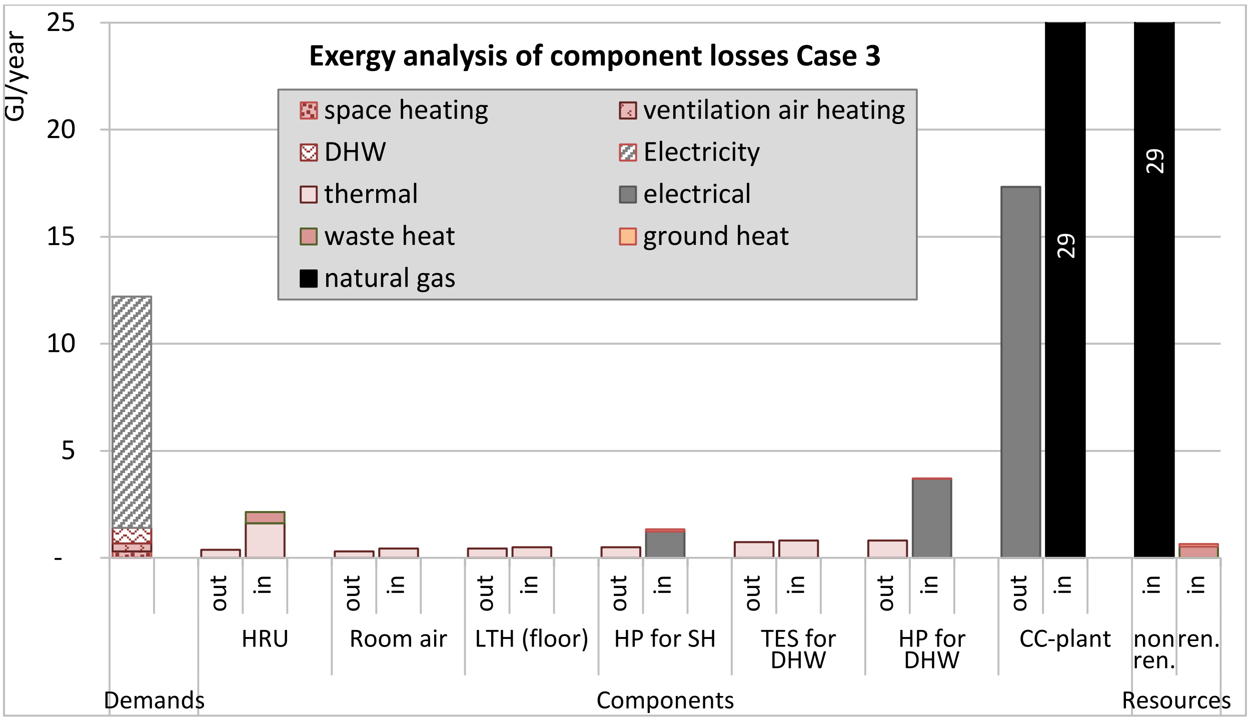

figure 4-19: Annual exergy component analysis of Case 3, presenting both renewable and non-renewable input.

4.5 Summary and conclusions of the case studies

Summary and conclusion regarding the exergy demand

The demand analysis of the Dutch reference case offers new insights into the thermodynamic character of the demand. The insights point into the direction of new potential solutions to consider. The results and ideas are summarized below.

Results

- The demand for space heating and cooling represent very small exergy demands, which means it is an energy demand of low thermodynamic quality which theoretically requires little input of work or high-quality energy. For the Dutch case studies the weighted average exergy factor (exergy to energy ratio) for space heating is 5,8%.
- Domestic hot water: Even though the required temperature of the DHW is much higher than the required indoor temperature, the exergy demand for DHW is still relatively low (the weighted average exergy factor is 8,5% for the Dutch case studies). This is due to the fact that the not all the heating energy is needed at 60°C, but the water needs warming up from the supply temperature up to 60°C (see also figure 3-7, page 69).
- Of all demands of the Dutch reference dwelling (space heating, space cooling, domestic hot water, electricity) the space heating demand represents the largest demand in energy terms, followed by the demand for electricity. In exergy terms however the electricity demand is by far the largest demand and all other demands are very small in comparison.
- The dynamic analyses provide insight in the variation of the exergy factor within the demand for space heating as a result of the varying outdoor temperature.

Conclusions and Ideas

- The low-exergy demand for space heating and domestic hot water in principle presents the potential of meeting this demand with little exergy, that is: with energy of low quality or with little high-quality energy.
- The variation between exergy factors within the seasonal heating demand indicate that in principle there is potential to further optimize storage systems in line with the exergy demand. In combinations with heat pumps an optimal use of the highest possible COP's can be achieved resulting in a reduced input of high-quality energy.
- The fact that the exergy demand for domestic hot water is rather low despite the relatively high temperature of 60°C is based on the fact that the water is heated from the temperature it is supplied to the dwelling (annual average 13°C) to 60°C. Preheating of DHW should therefore be considered by using 'lowex' means such as using waste heat or heat pumps.
- The use of waste heat from domestic hot water is not considered in this case study, but it could be used for space heating, heat recovery or a source for a heat pump.

Summary and conclusion regarding the energy system case studies

Three energy systems were presented, based on a condensing boiler (Case 1), a micro CHP (Case 2) and a heat pump (Case 3). The results in terms energy and exergy demand as well as energy and exergy losses are shown in figure 4-20.

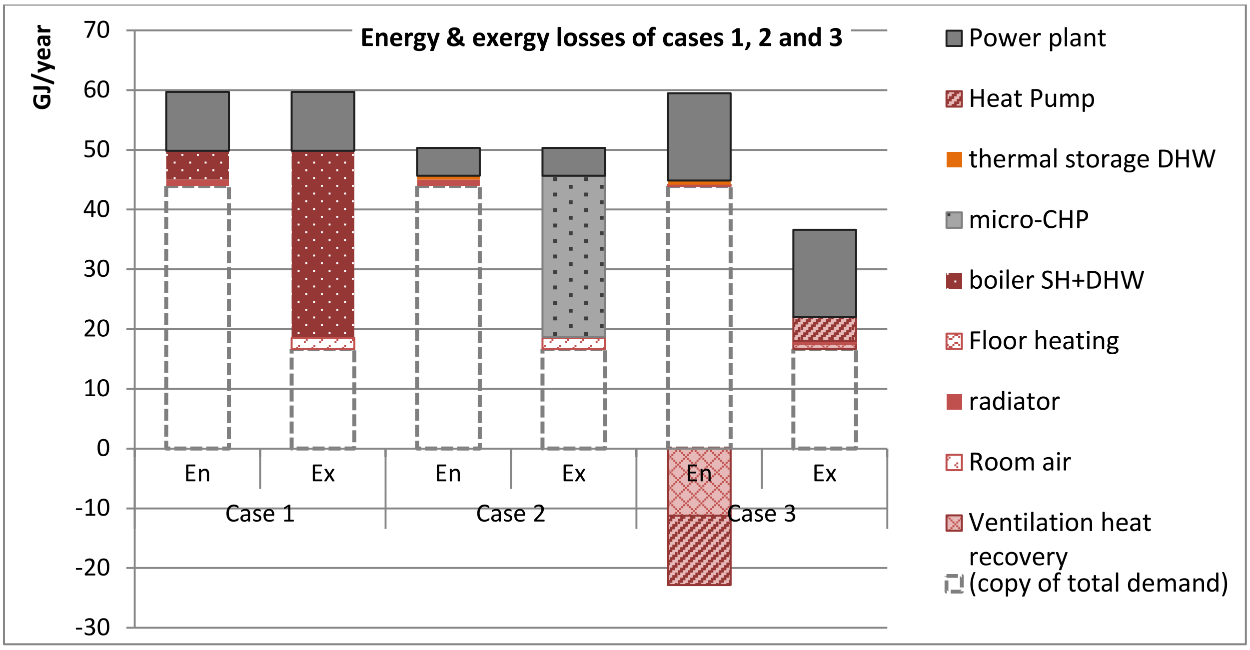

figure 4-20: Annual energy and exergy losses of cases 1,2 and 3.

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 non-existent in the energy approach. Furthermore major exergy destruction takes place in the boiler, as is almost commonly known (and also non-existent in an energy approach). Also significant exergy destruction takes place at the Micro CHP, while the energy efficiency is considered to be 100% (80% heat and 20% electricity). Also the heat pump and the heat recovery system present some exergy losses, while the energy losses are considered negative as a result of disregarding the input of free environmental or waste heat.

These results show that exergy analysis points in a totally different direction for improving energy 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 suggests it could be equally beneficial to develop a smarter and exergetically more efficient system.***

5 Using exergy to develop smarter energy systems

As demonstrated in the previous chapters, exergy provides a more meaningful evaluation of energy systems for the built environment than energy analyses, by comparing the performance of a system or process with the ideal performance. With exergy analysis the exergy losses and thus the improvement potential of systems and individual system components can be known. All chapters concluded that exergy analysis gives important additional insight into the thermodynamic performance of an energy system.

However, the question remains whether exergy can also be used to develop well performing energy systems or to improve them. Even though exergy does not directly lead to solutions, the insights from exergy can support this. This chapter discusses the possible approaches of using the exergy concept and related insights to contribute to the *development of improved energy systems* for the built environment.

Two main approaches that can contribute to the development of exergy-efficient energy systems are distinguished:

1) Using exergy principles to generate energy concepts:
   The use of principles increases the chance of generating promising system configurations that have potential to minimize exergy losses.
2) Using exergy analysis to improve energy concepts:
   When one or more possible system configurations are available, that need to be further developed, a detailed exergy analyses can be used to uncover and quantify exergy losses at each energy system step or component.

These two approaches can be integrated in the design process of energy systems for the built environment and can be roughly attributed to the phases of concept generation and detailed design. The two approaches are described in this chapter. Also, an example of an innovative idea based on the exergy approach is presented at the end of this chapter.

NOTE: Optimization versus improvement

A distinction can be made between improvement and optimization. Bejan et al. (1996) mention that while improvement may lead to new concepts or configurations, ".. . it should be recognized that applying a mathematical optimization procedure to a particular design configuration can only consider trade-offs for that configuration[..] such procedures are generally unable to identify the existence of alternative design configurations". In this sense optimization can be seen as a mathematical method to find the best solutions out of previously defined alternatives, and improvement can be seen as a creative design process that does not automatically lead to solutions. The approaches mentioned in this chapter aim at supporting the latter, i.e. the design of improved options that cannot be found 'automatically' or mathematically.

5.1 Using exergy principles

Awareness of the thermodynamic concept of exergy and knowledge of the main 'exergy destructors' of existing energy systems provide the background for developing exergy principles to be considered when generating energy concepts for the built environment.

Based on literature as well as on the work presented in the previous chapters several principles were developed in the doctoral research at the basis of this book (Jansen, 2013). The aim was to provide a more complete set of principles than was found in literature and to include clarifying discussions.

The principles are divided into two categories:

A. Thermodynamically based principles aiming at the minimization of exergy losses
B. Integral principles for an exergetic optimal use of the situation (both current and future)

With these two categories of principles the aim is to assist the generation and development of exergy conscious energy systems that make exergetic optimal use of a given situation. First the thermodynamic principles are described since an understanding of these is beneficial for understanding and applying the overall principles.

Thermodynamic principles applied to the built environment

Principle A-1: Avoid large chains of components

Every process involves exergy losses in order to take place, therefore large chains of components are best avoided. Obviously the best option depends on the available components and in some cases two good components perform better than one, but in general the fewer components and processes, the better.

Principle A-2: Match the quality levels of demand and supply (or in other words: use the lowest quality energy input possible).

This principle is the easiest way of minimizing exergy losses: By choosing a source that closely matches the desired output. This is the most often mentioned exergy principle in literature. It can be further elaborated into the following guidelines:

a) Use low-temperature heating (LTH) and high-temperature cooling (HTC).
This way the exergy of the heating and cooling demand, being a very low exergy demand, is still low at the emission system (e.g. floor heating) and a minimum exergy destruction between emission system and the thermal zones of the building takes place.

b) Minimize temperature differences when exchanging heat.
This is very important for all heat exchange processes and also explains why counterflow heat exchangers are thermodynamically better than parallel-flow heat exchangers: the temperatures of the 'source' flow and the 'load' flow are closer to each other.

c) Use low-temperature energy flows existing in or around the building.
These energy flows include for example the heat from exhaust air or domestic hot water return, possible nearby surface water or waste water from industry.

d) Use the cascading principle.
Often the principle of cascading is proposed as a means to meet demands at multiple temperature levels in an exergy efficient way (Tillie et al. 2009, Torío et al 2011b). In principle cascading refers to the use of high-temperature heat flows for high-temperature demands, and returning flow of this first demand to meet demands at lower temperatures. At the building level cascading can theoretically be applied between the demand for domestic hot water (DHW) at 60°C and space heating at ca. 30°C. For districts often the cascading within district heating networks is suggested.

It is very important to know that in order to be exergetically more efficient it is essential that the heat supply really benefits from this cascade: if the heat demand of the total cascade is still supplied by a boiler, there is no benefit. If the heat originates from combined heat and power production (CHP), there can be a benefit of around 5%. This is due to the fact that the waste heat actually represents the 'sink' of the power cycle, and the power cycle performs better if the sink temperature is lower, according to the ideal work output of the power plant W=1-TLow/Thigh (see also chapter 2).

<u>Cascading example</u>

In the figure below an example of cascading between different functions is illustrated.

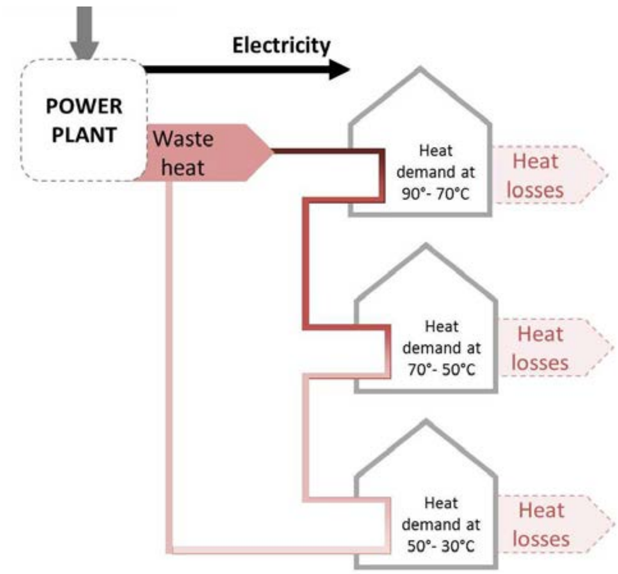

Figure 5-1: Cascading example:
In this scheme the waste heat of a power plant is used to provide the different functions with heat in a heat cascade, resulting in a lower return temperature to the power plant than if the total demand would be supplied with the higher temperature. This can result in an improvement of around 5%. Obviously, the total performance also depends very much on the heating network and related pumping energy etc.

Exergetic analysis of the advantages of using waste heat from cogeneration:
An ideal power plant produces only heat at 'zero-quality', i.e. at environmental temperature. In this case it has the highest output of electricity, but the heat is not useful for any process. If an elevated temperature of the heat is needed this means the electricity production is reduced according to the relation $W=1-T_{high}/T_{low}$ (where T_{high} is the temperature of the heat input - e.g. by combustion at ~ 1600 °C -and T_{low} is the waste heat temperature). In principle, the combination of an ideal heat pump supplied with electricity from an ideal CHP is exactly as efficient as the direct use of heat from an ideal cogeneration process (CHP). In practice, all the real equipment properties, heat losses of district heating networks, pumping energy etc. need to be taken into account to determine the optimal system configuration.

Principle A-3: Optimize (thermal) storage strategies

Especially renewables and free energy sources are not always available at the time they are required, hence, when using renewable energy or waste flows storage becomes more important in the design of a system. The most important exergy considerations when optimizing storage are:

a) When thermal energy is available at different temperature levels (i.e. exergy factors) the storage should be organised at these separate levels. Also stratified storage tanks make better use of the exergetic potential than mixed ones (see for example Torío, 2012).
b) As stated in chapter 2 exergy can be 'created' in time when considering the reference environment to vary with time. For harvesting and preserving this 'free' exergy, storage systems are required. In practice this is what already happens in seasonal storage systems. This principle can be broadened by making use of the variation within the exergy factors in shorter periods of time by means of a heat pump, (e.g. 1 to 7 days, as discussed in chapters 3 and 4). The potential of this variation for 'creating exergy' by using storage is investigated and described in the next chapter.
c) For exergy-optimised storage systems phase change material (PCM) becomes more important. A general advantage of using PCM is that it requires less space for large storage capacities, but the main advantage in exergy terms is that large amounts of thermal energy are stored as latent heat, which means the energy can be stored at small temperature intervals and thus it can be stored at the ideal temperature, i.e. the temperature at the lowest quality necessary, if the right PCM is chosen.
d) Storage can be done passively (using thermal mass), semi-passively (e.g. making active use of thermal mass with for example a trombe wall or concrete core activation) or actively (storage tanks that can be charged and discharged when needed). For exergy-optimized storage an active storage system has the most potential since in this case the moment of charge and discharge can actively be controlled.

Principle A-4: Use high-quality energy sources effectively

Apart from using low-quality heat sources for providing heating (i.e. matching the quality levels of demand and supply), also some components that make use of high-quality energy input can be exergy efficient for heating purposes. In general the *exergy efficiency* of the system components should be looked at, rather than the *energy efficiency*. For the built environment the following conversion devices can in principle make smart use of the high quality input:

- **A heat pump** (which generates more heat or cold than the electricity input). Available heat pumps have exergetic efficiencies between 40% and 60% and possibly future research could develop heat pumps with even better performance.
    a. Use heat pumps in the most effective way, by using small temperature lifts. Recent research has shown that for small temperature lifts heat pumps can achieve COP values of 10 to 15 (Meggers et al., 2012).

   b. Find energy flows with higher temperature than the outside temperature, in order to reduce the temperature shift and increase the COP (can also be surface water, geothermal water, waste water)

- **A cogeneration process (CHP)** (combining the production of heat and power)
  This option will only be profitable if both heat and electricity outputs can be used (and preferably also if CO_2 emissions are used). The electricity production should be large in order to have high exergy efficiency.
- Also the sun is a high-quality energy resource (Szargut 2005). Therefore the use of solar photo-voltaic panels is in principle exergetically more favourable than solar thermal collectors, which produce low-quality heat. The optimal choice within a given project however depends on many choices such as the type of demands to be met and, which is very important, the alternative options for meeting this demand (Dobbelsteen et al. 2007c).

Principle A-5: Avoid processes known to cause exergy losses

Many processes currently used are fundamentally 'flawed', since they inevitably destroy exergy. This means they cannot be thermodynamically improved and therefore should be avoided. Exergy destructive processes include:

- Combustion
- Resistance heating
- Mixing
- Throttling
- Processes with large driving forces (e.g. large differences in temperature or pressure).

NOTE

The principles are described from an exergetic point of view. However, for application into a building design other considerations are also (or even more) relevant, such as health and comfort aspects and technical boundary conditions (e.g. in case of floor heating).

Furthermore, the thermodynamic improvement and optimization of components itself (such as heat exchangers, heat pumps or thermal energy storage tanks) is not treated by these principles because they are outside the influence of building professionals, but many thermodynamic textbooks can be consulted on this (Bejan et al. 1996, Moran and Shapiro, 2004 and Woudstra, 2012).

Integral exergy principles:
Make exergetic optimal use of the situation and available options

In order to exergetically optimize an entire system an integral approach is necessary. The word 'integral' is used here to refer to the integration of the relevant situational characteristics for optimizing exergy performance[7].

In literature numerous handbooks and energy guidelines can be found for developing smart energy systems for buildings and improving the energy performance of buildings and their energy, by focussing on bioclimatic design or an integrated approach (e.g. Santamouris and Mumovic, 2009; Kristinsson, 2012). Also principles and guidelines for a larger – urban or regional - scale can be found, such as Tillie et al (2009), Stremke (2010), Gommans (2012) and Stremke and Dobbelsteen (Eds, 2012). The aim of the principles listed below is therefore not to present a complete list of energy-conscious design principles, but to provide additional considerations based on the exergy concept.

Principle B-1: Investigate all demands according to their exergetic value & potential of combining and reducing demands

The aim of this principle it to reduce the overall demand, especially the exergy value of the demand, by smart combination or synergy, of the different demands.

- On a building level:
  - Investigate possibilities to reduce the demand, not only by adding insulation and increasing air tightness but also by using smart and bioclimatic design.
  - Make sure the building is adapted to allow low-temperature heating and high-temperature cooling systems.
  - Take into consideration that reducing the - low-exergy - heat demand might be less favourable than reducing the demand for high-quality energy such as lighting.
- On a larger scale:
  - Map all demands including their exergetic value and investigate their profile.
  - Look for possibilities to combine demands, which can lead to exergetic optimization. For example: a concurrent demand for heat and cold or power and heat can increases the effectiveness of heat pumps or combined heat and power (CHP) units.
  - Use the cascading principle for demands at different temperature levels, as described by Gommans (2012) and Tillie et al. (2009), for a better use of heat networks. *(NOTE: the advantage of cascading depends on whether the heat 'generation' benefits from this cascade, see also previous page)*

Principle B-2: Investigate all possible sources and their exergetic value

An inventory of all the 'free' (waste and renewable) energy potential within a project boundary is indispensable to make -exergetic- optimal use of it. In addition to the energy

[7] Integral means 'necessary for completeness' (Oxford dictionary). In this book not a total completeness is meant, but completeness in terms of energy related aspects.

value the exergy value needs to be considered in order to gain insight into the true potential. The energy potential mapping method as developed by Dobbelsteen (Dobbelsteen et al. 2007a, Broersma et al. 2013) is a means to systematically investigate all local and regional potentials, also regarding the exergy value.

Principle B-3: Consider exergy in the overview of the total system

- **A total system approach** is important in order to make sure that avoided exergy destruction in one component is not abolished in one of the other components (for example using low-temperature heating is not helpful if the heat is still supplied by a component producing high-temperature heat).
- **An iterative approach** is needed to obtain the best connection between available resources, system components and the demand. It is not optimal to start at the demand side and finish with the resources, or work in the opposite direction. System components have to deliver the demand, but they also determine the required resource input. The availability of the surroundings have to be taken into account with respect to this; If living in a farm land with a lot of (sustainable) biomass available, a CHP might be a good option. In a region with a high solar PV potential, electricity driven HP is more relevant.
- **Also the available alternatives have to be considered.**
  When designing the system one is also dependent on the available options. This can for example mean that, even though PV may exergy wise be more efficient than solar thermal collectors, it is better to use solar thermal collectors if the only alternative of producing hot water is a boiler or electrical heater. In this way also the alternatives for meeting the required demand have to be considered. (Dobbelsteen et al. 2007c).
- **Compare 'energy saving' versus exergy-efficient supply in relation to other objectives**
  When considering the low exergetic value of the demand for space heating it may be more profitable to focus on the achievement of thermodynamically effective systems than on an extreme reduction of the heat demand by very thick insulation. In the end the choice between the two approaches must be made on end-objectives such as costs, use of space and environmental impact.
- **Consider the future**
  In general the visions of the desired and potential future have to be considered when designing an energy system, both when it incorporates choices at building level, due to the long life span of buildings as well as when it influences choices regarding spatial planning[8]. In exergy terms this means that for example the future possibilities of producing 'sustainable' electricity versus 'sustainable' gas should be considered in relation to the given project and considered system components. If in the near future the ratio of renewables in the electricity production will increase this will be a reason to opt for electricity-driven components rather than fuel-driven components. This point of attention is much related to the third item: consider the available options.

[8] The importance of taking into account the possible near and far futures in spatial planning is also mentioned by Stremke and Dobbelsteen (2012, p. 103).

5.2 Using exergy analysis

Exergy analyses can be used to obtain quantitative insight in the largest losses and explore and study possibilities to reduce these losses. As previously mentioned an exergy analysis does not automatically lead to solutions but the insight obtained can be helpful. The following three steps can be used, between which iterations take place as in any design or improvement process:

1) Provide an insightful presentation of the losses
2) Investigate possibilities to reduce these losses of individual components
3) Investigate interrelation between components

The steps are further discussed below.

Ad 1) Provide an insightful presentation of the losses

A very straightforward presentation of the losses is a component analysis overview, as used in the previous chapter. In this analysis all the inputs and output of each component are shown. As an example figure 5-2 (which was also shown in chapter 4) presents the component exergy analysis of Case 1 (the Dutch reference system).

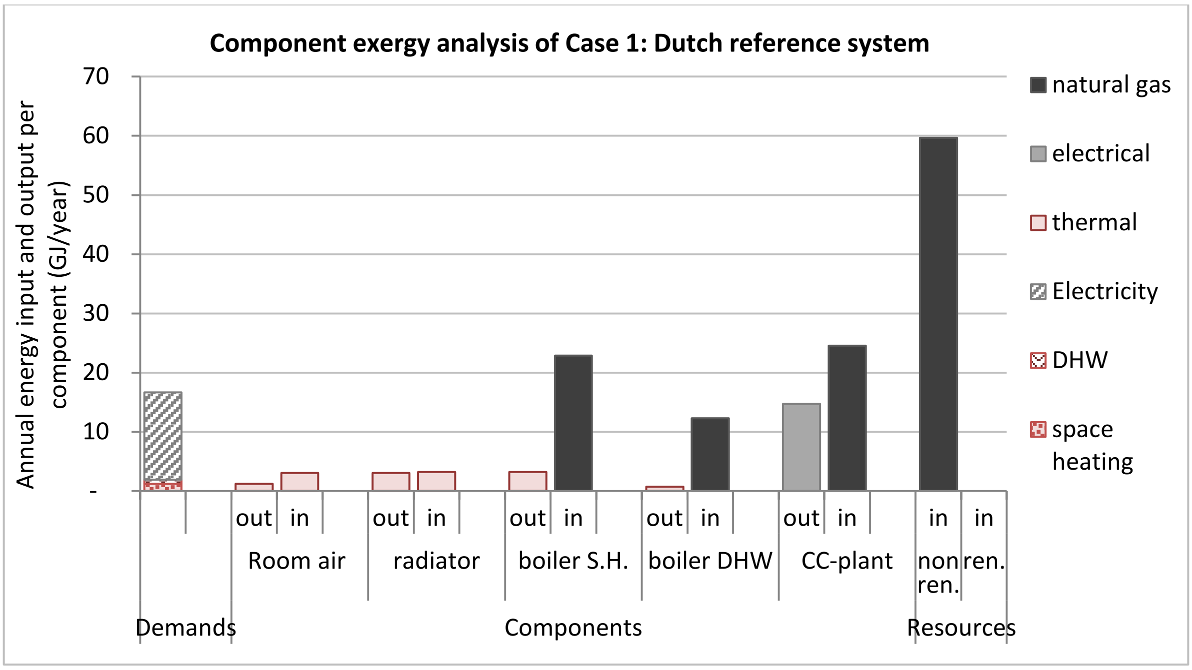

Figure 5-2: component exergy analysis of Case 1 (see chapter 4)
(legend: S.H.= space heating, DHW = Domestic hot water, CC-plant = combined cycle power plant)

The presentation of component in- and output has the following advantages:

- It can be understood intuitively.
- The losses become clear from the difference between output and input, while the relative contribution of the component is also clear from the amount of output created (e.g. the boiler has large losses for little output, while the combined cycle plant has large losses for large output). This is an advantage over using only exergy efficiencies or exergy losses.

By being simple, the overview lacks information about how different components influence each other. Sometimes a reduction of losses in one component creates additional losses somewhere else; sometimes it reduces losses somewhere else. These effects are not visible in this presentation. For this the energy system scheme needs to be consulted.

Ad 2) Investigate possibilities to reduce these losses at component level

Once the losses are identified and quantified, possibilities to reduce these losses can be investigated. Finding solutions to reduce losses is a creative process which is greatly helped by experience with energy systems and knowledge of available alternatives, as well as by the exergy principles presented in section 5.1. However, the insight from the exergy analysis of the system itself is also helpful. The following question is helpful to explore potential solutions:

Question: What is causing the losses?

a) A mismatch in temperature
b) Poor component properties (e.g. a heat pump with a COP much lower than COP_{Carnot})
c) A fundamentally flawed process (e.g. combustion)

The solution in these cases can be sought in the following directions:

a) Is it possible to reduce the temperature difference?
   NOTE: Take into account how this influences losses in other components, see next item (Ad 3).
b) Is the same type of component available with better - more exergy efficient – properties?
c) Can the employment of this component be further reduced by transferring (part of) the output to another component?

Ad 3) Investigate interrelations between components

The interconnection between components is also very important for the overall performance. In the first place a large chain of components inevitably leads to relatively large losses even though the losses per component are moderate. Secondly, the increased efficiency in one component may influence the losses of another in a positive or negative way (see note 1 below)

In principle it is possible to quantify all potential effects of changing one component, however this is very time consuming and not all potential effects are relevant. It is recommended to examine the losses of the components and investigate potential solutions by keeping in mind the interrelation between the components according to the energy concept scheme (as for example shown in figure 5-3 on the next page). Three points of attention to keep in mind are described below.

Note 1: Different efficiency improvements

Increased exergy efficiency in one component may influence exergy losses in another component. This has to do with the type of efficiency improvement. As explained in chapter 2 the exergy efficiency (ψ) is a result of the energy efficiency (η) and the ratio of the exergy factor of the output ($f_{ex,product}$) to the exergy factor of the input ($f_{ex,source}$) (see chapter 2).

$$\psi = \eta \cdot \frac{f_{ex,product}}{f_{ex,source}} \qquad (5\text{-}1)$$

When the exergy efficiency is increased by increasing the *energy* efficiency, the exergy factor of the required input remains equal which means simply less input of the same exergy factor is needed. The exergy efficiency of the subsequent component is then likely to remain equal and simply less output has to be delivered.

However, if the exergy efficiency is increased by reducing the exergy factor of the input, this means the same amount of energy has to be delivered by the subsequent component, but with a lower exergy factor. In theory this will also require less input, but it has to be ensured that the subsequent component is *able* to provide this output of a lower exergy factor. If not, there will be losses introduced in the subsequent component or between the components and the overall system is not improved. (e.g. a radiator can be replaced by a floor heating system, but if the heat is still supplied by a condensing boiler the losses are only shifted to another component)

Note 2: Effect of efficiency improvement of components in series

When a demand is not delivered by using one component but by a series of components (as is usually the case), the total losses are the sum of all losses and the total efficiency for this 'chain of delivery' is the product of all component efficiencies involved. An example of a component chain for delivering heat is shown in figure 5-3, where the components highlighted in grey form one chain of delivery.

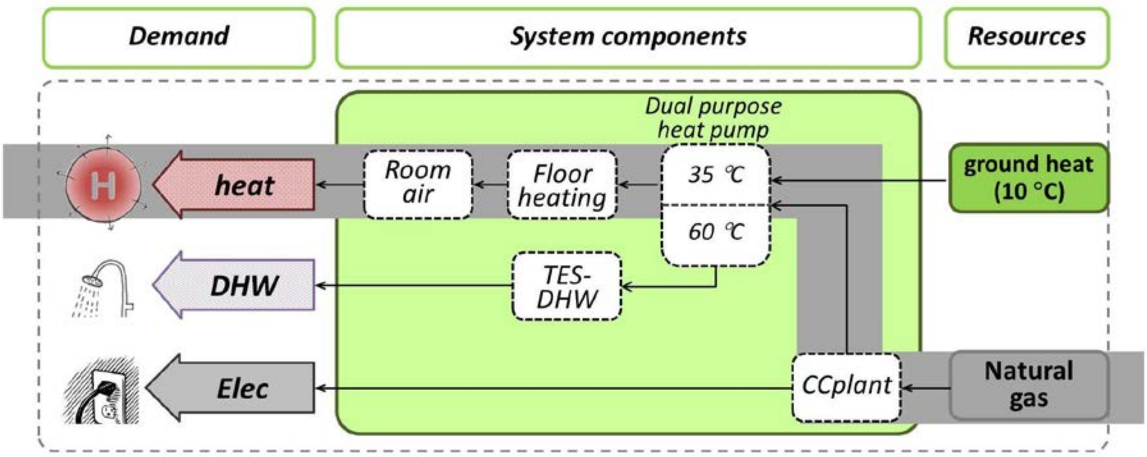

Figure 5-3: Energy system scheme of case 3 (chapter 4) with chain of components for delivering space heating highlighted in grey.

The total efficiency of this chain of components is the product of all efficiencies, i.e. $\psi_{room\_air} \cdot \psi_{floorheating} \cdot \psi_{heat\ pump} \cdot \psi_{power\ plant}$. An example of component exergy efficiencies resulting from Case C (Chapter 4) are shown below:

Component chain:	Room air	Floor heating	Heat pump	Power plant	Overall efficiency
Exergy efficiency ψ	67%	87%	42%	60%	**14%**

The first conclusion that can be draw from this figure and table is that the overall efficiency is quite low even though all separate components perform relatively well. This demonstrates the importance of keeping the chain of components short.

Secondly, the following mathematical rules apply for improving a component chain like this one:

- A *relative increase* of efficiency of N% (i.e. current efficiency multiplied by 1+N) of any component leads to the same improvement of the overall efficiency.
- An *absolute increase* of efficiency of M % of a component (i.e. current efficiency + M) leads to the best results when applied to the component with the lowest efficiency.

Consequently, in cases of a component chain the absolute losses are less important than the component efficiencies and the above rules apply.

Note 3: Effect of efficiency improvement of components in parallel

In case a demand is supplied by two separate chains of components, such as the heating demand of the above is delivered by the chain described above and by a second chain consisting of the heat recovery unit and the electricity production, the absolute contribution is of importance. Improving the chain with the largest input will have the largest overall results.

General note on the exergy analysis approach

The exergy analysis approach to minimize exergy losses can be regarded as an exergy insight supported design process. The exergy analysis identifies which components can be improved and quantifies the theoretical improvement potential. When exploring solutions for improvements the available improvements per component of available alternatives need to be considered and applied with respect to the overall interrelations between components in order to obtain the largest reduction of losses. This section has provided some central points of consideration which can support this development process.

5.3 Exergy based idea for an improvement

Example: Exergy smart storage strategies

Chapter 4 presented the detailed analysis of the space heating demand. This analysis showed a rather large variation between the exergy factors for space heating within the total heating season as well as within shorter time periods. For instance, during two weeks in February the space heating demand showed exergy factors between 3% and 9%. If the total space heating demand could be supplied at an exergy factor of 3% instead of 9%, this would greatly reduce the ideal minimum amount of high-quality energy input required. The variation between exergy factors within the seasonal heating period indicate that in principle there is potential to further optimize storage systems in line with the exergy demand. In combinations with heat pumps an optimal use of the highest possible COPs can be achieved resulting in a reduced input of high-quality energy.

In principle the lowest exergy input is required if *all* the energy is provided at the lowest exergy factor occurring during a given period, which means at the highest outdoor temperature (= reference temperature). [9] Such a solution would not result in a demand 'profile' but in one single hour of heat 'production' and the release of this heat at the profile of the building demand. With a limited heat production capacity and limited storage the heat will be produced at a range of the lowest exergy factors, e.g. the exergy factors between 3% and 6% when the total range is between 3% and 9%. Figure 5-4 shows a scheme of the principle.

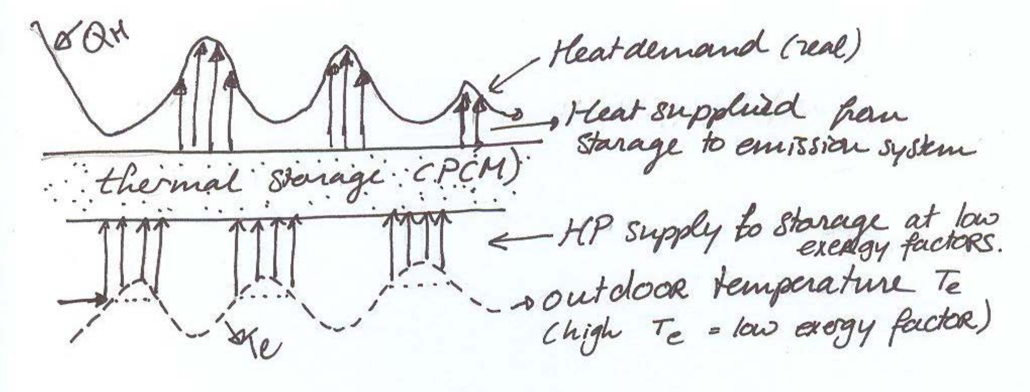

Figure 5-4: scheme of the principle of using storage to produce heat at lower exergy factors (higher outdoor temperatures) and emit the heat when needed.

The ideal heat demand can be studied for various periods of time. To demonstrate the idea, this section presents a one day optimization. This means the entire heat demand of one day needs to be produced in the previous day, but this can be produced during the most 'profitable' hours.

For this study, the following assumptions are used:

[9] When using thermal storage the heat 'production' is not directly connected to the demand profile anymore, which means an optimization using all exergy factors during a given period of time can be used, not only those occurring during the original heat demand.

- Heat is ‘produced’ as soon as the exergy factor is lower than the average factor of the period assumed.
- The power of the ideal heat pump is adjusted in such a way that the real heat demand *plus* an additional 3% (for storage losses) are produced.
- In the examples the calculations are based on outdoor temperatures and heat demands known beforehand, which in reality of course is not the case. The calculations are meant to explore the ideal potential of using storage in this way. In real situations intelligent building operation systems are required which also include weather forecasts and building information.

Optimized profile

According to the assumtions described above an optimized heat profile per day was calculated. It was assumed that the heat demand of one day was produced during the previous day. The resulting exergetically optimized heat demand profile is presented for each day as well as the average day in figure 5-5. In figure 5-6 the average ideal heat demand and the average real heat demand are presented in the same graph.

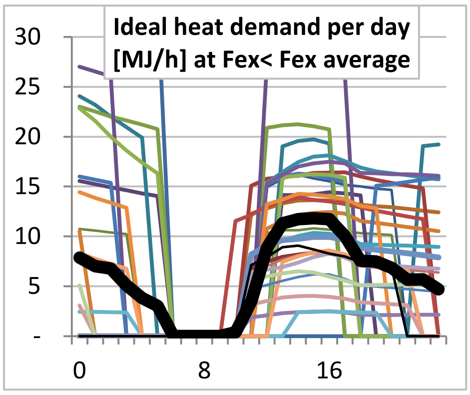

Figure 5-5: Ideal daily heat demand

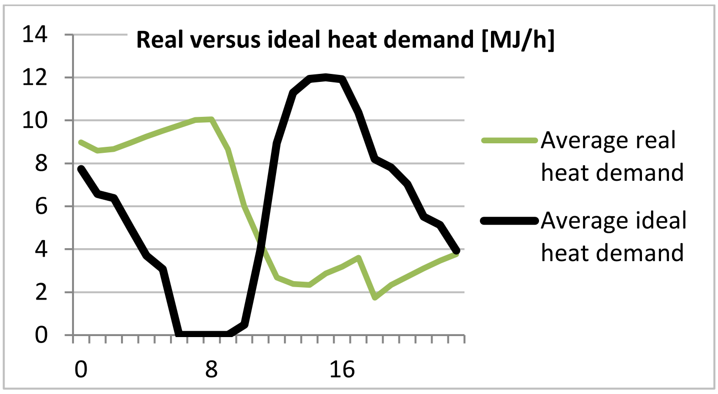

Figure 5-6: real versus ideal average daily heat demand

In table 5-1 the total monthly resulting heat and exergy demands, when using the daily optimization, are presented. This means for each day a different optimization was made.

Table 5-1: Results of daily optimized heat profile for ideal heat ‘production and storage

Results of daily optimization for the month of February	Heat demand [MJ/Feb]	Exergy of heat demand [MJ/Feb]
Real heat profile (2-28 Feb.)	3,700	238
Ideal heat profile (1-27 Feb.)	3,811	208
Change of ideal profile versus real profile	+ 3%	-13%

As can be seen this daily optimization ideally leads to an exergy demand reduction of 13%. The calculation however is performed assuming a very ideal situation, which means in practice a much smaller reduction will be achieved. On the other hand, when assuming larger storage or larger heat pump capacity, the reduction of the demand may be larger. The potential ‘savings’ assuming more realistic simulations (based on wheather forecast for example) has to be further investigated.

Sketch of an energy concept for a dwelling including exergy-smart storage

In figure 5-7 the energy concept of a dwelling including 'exergy smart storage' is sketched. The processes numbered in both figures are described below.

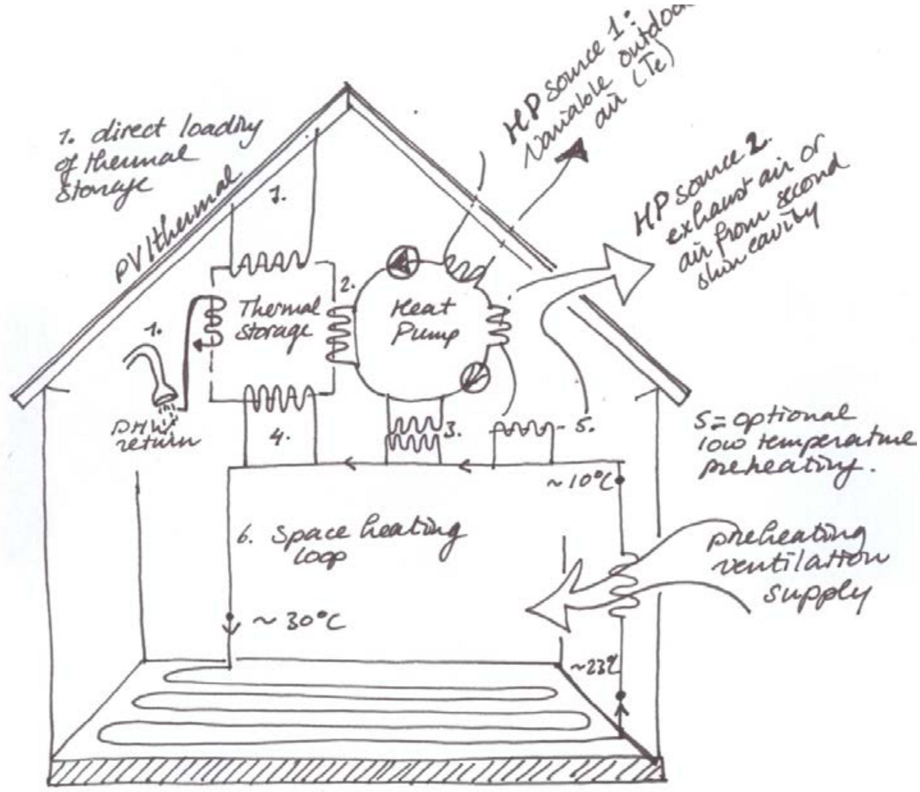

Figure 5-7: Sketch of energy concept making use of smart thermal storage and preheating of ventilation air, as discussed in sub-sections 5.5.1 and 5.5.2.

The numbered processes are:

1) The smart storage is directly charged by using medium temperature heat available (~40°C), for example from domestic hot water or thermal solar heat (e.g. PV/thermal).
2) The storage is actively charged by the heat pump when suitable heat sources for the heat pump are available; this can be the outdoor air when it is relatively high (as studied in the previous section), as well as other sources, such as exhaust air from ventilation.
3) If needed, the space heating loop can be directly heated by the heat pump. Preferably the heat pump is used for 'producing' the heat at the lowest temperatures, while the heat at higher temperatures is obtained by discharging the storage as much as possible. An optimal operation requires intelligent control of the system as whole.
4) The space heating loop will be heated by the thermal storage as much as possible.
5) When including the preheating of ventilation air in the space heating loop preheating at lower temperatures is needed to actually exploit the exergy potential. Potential sources include many 'return' flows of the other sources displayed at the right of the figure, of which the temperature can be lowered further (e.g. the return flow of DHW)
6) The space heating and ventilation preheating loop makes use of cascading within the dwelling: the floor heating system requires a higher temperature than preheating the ventilation supply air.

5.4 Discussion on using exergy to develop improved systems

The exergy approach does not lead to instant solutions nor does it provide a step by step procedure to come to solutions. Improving or developing an energy system is a design process and exergy can only support this process by giving meaningful insights.

The approaches presented in this chapter can be helpful to develop promising energy concepts and to avoid 'fundamentally flawed' systems or processes.

The studies underlying this book (Jansen, 2013; Jansen et al., 2012 and Teres-Zubiaga et al., 2013) also presented several case studies that were developed based on the approaches described (i.e. using exergy principles to develop an energy system and using exergy analysis to further improve and optimize the system). These examples showed that these can lead to improvements compared to existing options, resulting in reduced input of high-quality energy. However, even though the improvements are significant compared to a traditional system, they are rather moderate compared to state-of-the-art energy systems (i.e. heat pump based systems) and the exergy efficiency of heating systems is still rather low. It was shown that further improvement of essential system components is needed for improving the overall system efficiency. This is further discussed in the next and last chapter.

- ***The exergy approach is very helpful to develop improved systems, but it is very difficult to achieve very high exergy efficiencies.***
- ***Some thoughts on the achievable efficiencies and related desired developments are discussed in the next chapter.***

6 Outlook: What to expect from the exergy approach?

All the previous chapters demonstrated the added value of using exergy: Firstly, exergy gives a much more meaningful insight into the performance of energy systems than an energy approach. Secondly, it can be used to support the development of improved systems. The exergy approach thus seems a very promising 'tool' to support the development of smarter (and more sustainable) energy systems.

However, it was also discussed that it is difficult to obtain exergy efficiencies that are really higher than the current best practice energy systems (such as a modern heating system based on floor heating and a heat pump.)

Therefore, the following questions may be asked to explore what really can be expected from the exergy approach:

- How exergy efficient can real energy systems become?
- Can significant improvements compared to best practice system be developed?
- If so, what developments are needed to further improve the exergy efficiency of energy systems for the built environment?

These questions are discussed in this chapter.

6.1 Improvement potential: ideal versus practical achievable

The state of the art case studies presented in chapter 4 showed exergy efficiencies for providing space heating between 5% for a Case 1 (traditional condensing boiler based system) and 14% for case 3 (state of the art heat pump system). These results suggest that there is a very large improvement potential of these systems, between 86% and 95%. However, the improved options developed by Jansen (2013) proved to obtain a maximum exergy efficiency of 22% for an adapted version of case 3. (These examples are not presented in this book, but only in the original thesis).

Thus, it may be a little too simple to state that the improvement potential of current systems for heating lies between 86 and 95%. In this section a rough estimate of the scope of a highest technically possible exergy efficiency is made. For this aim the necessary components for providing the required heating, consisting of one component at building level for emitting heat and a component for 'producing' (generating or distributing) this heat. A scheme of the approach to estimate the maximum technically achievable exergy efficiency is shown in figure 6-1. Minimal driving forces are assumed. It is noted that the values chosen are a little bit arbitrary, but they do provide an estimation of what is technically achievable.

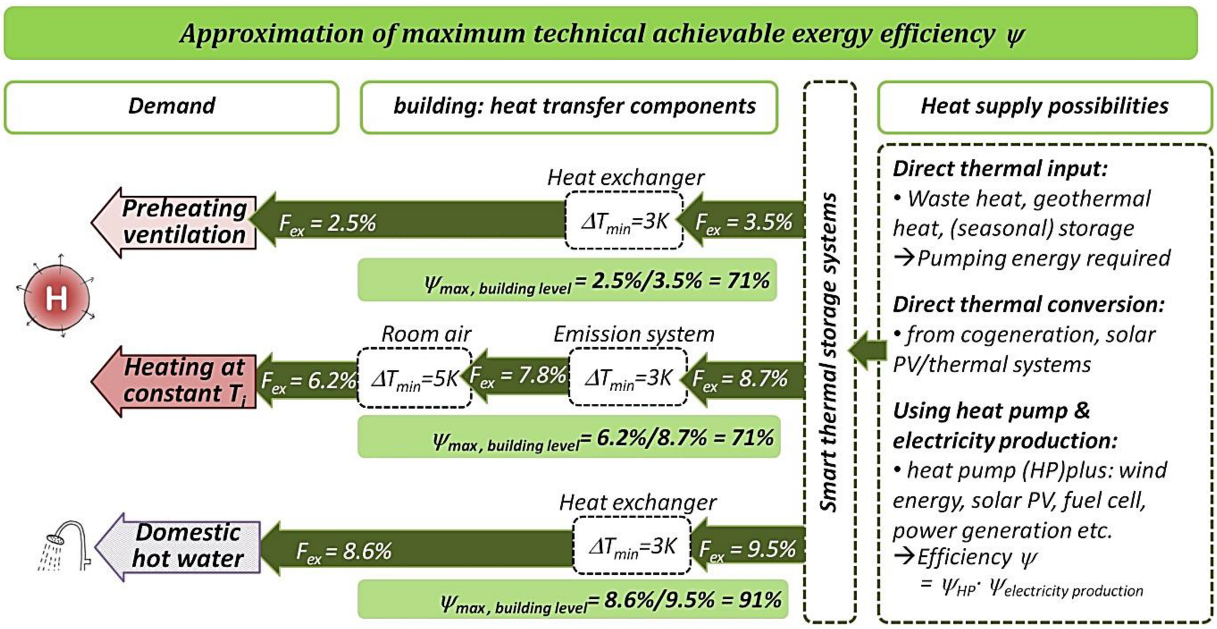

Figure 6-1: Approximation of the minimum technically required exergy losses and maximum technically achievable exergy efficiencies for providing heating and domestic hot water.

At building level the following components are at least required to supply the heat demand:

- a heat exchanger for preheating ventilation air.
- for the remaining heat demand: a 'room air' component, which accounts for the required temperature difference between emission system and the room (see methodology section chapter 4) and an emission system

- a heat exchanger for heating domestic hot water.

Due to the required temperature differences the exergy factor of the heat required as input into these components (heat exchangers and emission system) is higher than the exergy factor of the demand. When assuming a minimum temperature difference of 3 K for heat exchange and of 5 K for the component 'room air', the exergy factors of the different demands increase as presented in figure 6-1: from 2,5% to 3,5% for preheating ventilation air and from 6,2% to 8,7% for providing the remaining space heating. This means the maximum exergy efficiency for space heating is already only 71% after the first step of emission.

For generating the heat for these building level components there are several possibilities, which cannot be all described in this section. However, when based only on renewables, they include mainly the following options, which are also presented in figure 6-1:

- Directly available heat sources: for example from waste heat or geothermal sources. In this case pump energy is required for distributing the energy. The energy input depends on the amount of pump energy and (in case no windmills or other direct pumping mechanisms are used), on the electricity production process.
- Heat is directly generated from a primary resource: for example using biomass cogeneration plants or PV-thermal solar cells (combustion for heating purposes only is not considered as an option, since it is an intrinsically exergy-destructing process)
- The heat is produced using a heat pump. In case of a compression heat pump this means the efficiency of the heat generation is the product of heat pump efficiency and electricity production efficiency.
- To optimize the use of (renewable) heat sources and the use of a heat pump, a smart storage system as explained in section 5.3 could be considered.

All these options for sustainable and efficient production of heat and electricity represent extensive fields of study (e.g. Woudstra, 2012; Toonssen, 2010 and many more) and it is not possible to estimate an accurate technically maximum achievable exergy efficiency for these possibilities. It can be concluded, however, that the maximum achievable exergy efficiency of 71% at building level needs to be multiplied by the exergy efficiency of the heat generation or supply system. This will lead to maximum values between approximately 71%·60% = 43% (assuming directly generated heat from a biomass cogeneration plant with an exergy efficiency of 60%) and 71%·60%·60% = 26% (assuming the heat to be produced by a heat pump with 60% exergy efficiency and electricity production process with 60% efficiency). This 'technically obtainable ideal' is thus much lower than the 100%. Especially for a total system consisting of a chain of components, the ideal thermodynamic efficiency of 100% is quite far from achievable.

- ***It is impossible to make an accurate estimation of the technically achievable maximum exergy efficiency. However, it is certain that this is much lower than the ideal 100%, especially for a total system consisting of a chain of components.***
- ***Based on minimal driving forces, the maximum exergy efficiency for providing heating is estimated around 35%, unless heat is directly (and freely) available.***

6.2 Desired developments of essential system components

Even though the technically achievable maximum exergy efficiency may be far from 100%, there is still room for improvement. However, several system components are essential for highly exergy efficient energy systems. A further development and improvement of these components is needed to achieve significant improvement of energy systems as a whole.

The following components demonstrated to be essential for highly exergy-efficient systems:
1) Heat pumps (HP)
2) Combined heat and power systems (CHP)
3) Thermal energy storage (TES)
4) Ventilation preheating systems and heat recovery
5) Intelligent building control systems
6) Very-low-temperature emission systems for heating / high-temperature for cooling.

All these components present extensive fields of study and scientific research. In this section some important characteristics and points of attention in the light of the exergy approach presented in this book are given. The discussions do by no means pretend to provide a comprehensive overview of all scientific developments in these areas.

Ad 1) Heat pumps (HP)

Heat pumps are the only components that can produce low-quality heat or cold by using high-quality input in an exergy-efficient way. This means that if no or not enough waste heat or other 'free' low-quality heat is available, the remaining demand for heating or cooling can only be exergetically efficiently supplied by a heat pump. In addition, a heat pump is the only means to provide cooling, apart from thermal storage systems. Therefore, as also shown by the examples in this thesis and mentioned by Meggers et al. (2010), a heat pump is often essential in 'LowEx' energy systems for buildings. (see section 2.7 for more technical information on heat pumps).

There are some ways to improve the performance of a heat pump, including:
- To minimize the required temperature lift (between T_H (condenser) and T_C (evaporator)) (e.g. by a flexible operation of the heat pump, enabling flexible use of available sources together with the use of thermal storage. See example section 5.3)
- To maximize the exergy performance of these low-temperature-lift heat pumps.
- To use both the cold and the warm side of the heat pump (cooling and heating).

Ad 2) Combined heat and power production (CHP)

Also CHPs can provide low-quality heat in an exergy-efficient way, but only as a by-product of electricity production. This type of component is only interesting in case both outputs can be used. Furthermore, the exergy performance of a CHP depends very much on the efficiency of electricity production. For exergy efficient solutions only CHP's with a high electrical efficiency should be used.

Ad 3) Thermal storage

As shown by the example in section 5.3, thermal storage is very important to make optimal use of available waste flows, available changes in outdoor temperature or available renewable energy, especially in combination with a heat pump. For energy systems solely based on renewables efficient thermal storage is also essential. From an exergetic point of view thermal storage should take place at a temperature near the temperature finally required, otherwise additional exergy losses are introduced. Therefore in exergetically ideal thermal storage systems large amounts of thermal energy can be stored at the same temperature. This kind of storage is possible by using phase change materials (PCM).

Ad 4) Ventilation preheating systems and heat recovery

As discussed in chapter 2 and section 3.5 the exergy demand (minimum required work) of heating ventilation air from the outdoor temperature to the indoor temperature is much lower than the exergy demand of heating at a constant temperature T_i. In principle preheating ventilation air therefore is more exergy efficient than mixing this air with the warmer indoor air at T_i. However, the fan energy of heat recovery systems (HRU) can be significant. Possibilities to avoid large fan capacities while still preheating ventilation air should be further developed. This could for example be local heat recovery systems in facades, or preheating by other heat sources with a good match in temperature level. The latter can for example be done by using the return flow of low-temperature floor heating systems, as shown in the exemplary energy concept illustrated in figure 5-7.

Ad 5) Intelligent building services control systems

Many exergy-efficient systems as well as systems that make optimal use of available renewable energy flows require intelligent building services control. These are more outdoor temperature dependent or hybrid systems, where the choice of the best performing component at each time-step depends on many parameters. Ideal building services control systems should also be 'self learning' concerning the building behaviour, and include weather forecasts. Further investigation of intelligent building services control systems in relation to exergy optimization is recommended.

Ad 6) Very-low-temperature emission systems

Very-low-temperature emission systems enable the use of very-low-quality heat and increase the performance of heat pumps. As the exergy factor strongly increases near the environment temperature (see figure 2-20) the first losses are easily introduced by the temperature of the emission system (for instance, for an environmental temperature of 5°C the exergy factors of heat at 20°C, 25°C, 30°C and 35°C are 5%, 7%, 8% and 10% respectively). This means that even with low-temperature heating systems the exergy factor of an emission system is twice as high as the exergy factor of the demand, reducing the ideal COP of a potential heat pump by 50% and thus doubling the required primary energy input. The emission system is thus the first component to potentially result in high or low exergy performance of a system. Very-low temperature heating system should therefore be investigated.

6.3 Other desired developments

The exergy approach for a larger (neighborhood to regional) scale

The larger scale incorporates much more possibilities for exergy optimization than only the building level, as was also discussed in the exergy principles section in chapter 5. The multiple functions and energy resources encompass more possibilities for matching quality levels and using waste flows. Currently much research is being done on including energy and exergy considerations in the spatial design of larger areas. Important works include publications on the Energy Potential Mapping methodology developed by Dobbelsteen (e.g. Dobbelsteen et al., 2007; Broersma et al 2013), 'Sustainable energy landscapes' by Stremke and Dobbelsteen (2012) and many publications resulting from the SREX project (www.exergieplanning.nl).

The larger scale is also the focus of the IEA (International Energy Agency) Annex 64 "*LowEx Communities: Optimised Performance of Energy Supply Systems with Exergy Principles"*[10]*.* This all shows the current interest in the potential of the larger scale, where exergy can be a very useful tool to support the development of smart energy systems.

Exergy in energy legislation

Current energy laws are generally based on energy (i.e. the first law of thermodynamics), not on exergy. Some laws can be implicitly using the exergy concept by suggesting some exergy effective solutions. E.g. article 6 of the EPBD states that "*For new buildings, Member States shall ensure that, before construction starts, the technical, environmental and economic feasibility of high-efficiency alternative systems such as those listed below, if available, is considered and taken into account: [including cogeneration, heat pump and district heating]"* (EPBD, 2010). However, without exergy analysis this is no assurance that exergy losses will indeed be minimized.

Possibilities of including exergy analysis in energy legislation

The exergy analysis approach needs to be further developed and the added value in daily practice needs to be studied before an exergy performance indicator could be required. As a first step however, the prerequisite of performing an exergy analysis for large projects, without any further implication, could be tested. This way the energy system developers will become aware of exergy losses and improvement potentials and potentially this will lead to improvements of the system, which is to the advantage of the designers, the owners of the building and the environment. Also for planned market introduction of new components, such as the micro CHP, an exergy analysis could be required in order to evaluate the exergetic performance and potential in relation to desired developments.

[10] This is a proposal for a new Annex to take place within the IEA (International Energy Agency) Energy Conservation in Buildings and Community Systems (ECBCS) Programme (www.ecbcs.org), as a follow-up of Annex 49 "Low Exergy Systems for High-Performance Buildings and Communities" (www.annex49.com)

As a second step the justification of large losses could be required. This may stimulate the further effort to reduce losses. This may for example give more insight in the performance of small combined heat and power units (CHP) and this might accelerate the development of better performing CHPs.

A third step may be to set minimum standards. An essential advantage of exergy efficiencies over energy efficiencies is the fact that the exergy efficiency is an indicator of the achieved performance to the ideal, which means the ideal is the reference. However, determining the minimum standards may be very complicated, especially since the technically achievable ideal is far from 100% for an entire energy supply chain for heating. Possibly standards at component level are more realistic.

A more 'prescribing' approach could be very effective, for example by prohibiting the use of gas-fired boiler in newly built houses (e.g. Danish agreement (KEMIN 2012)) or by requiring heat pumps to have a minimum COP of 50% of COP_{Carnot}. However, in order to increase the insight of energy consultants the exergy approach itself should also be applied to support the design of exergetically optimized integrated systems.

Increase awareness of exergy (e.g. in education)

Lastly, building professionals and other professionals involved in designing energy systems for buildings should be more aware of the exergy concept and its implications. This is also the main aim of this book. And, as was one of the propositions made by Woudstra in his doctoral thesis (2012), at least an understanding of the exergy concept should be included in higher education programmes teaching sustainable energy systems.

6.4 Closure

Exergy gives a much better insight in the performance of energy systems and provides strategies to develop better systems

This book showed that exergy provides a better indicator of thermodynamic performance of a system than energy and additionally provides insight that can support the development of improved energy systems for the built environment. The analysis methods and the approaches described – including qualitative principles and quantitative analysis – provide ways of using the exergy concept that can support the design and development of exergy efficient energy systems for the built environment. Although they do not provide a complete step by step procedure, they provide sufficient considerations and guidelines to be applied in daily practice.

But.. it is hard to improve best practice current systems

Currently, the exergy concept is hardly used in daily practice of energy consultants in the built environment and far from being fully integrated in this field. The exergy concept as a whole is still relatively unknown. Possibly for this reason, the exergy concept is sometimes considered to be unnecessarily complex and not providing sufficient added value. An argument for this can be that many state-of-the-art systems already include principles that are in fact based on exergy and lead to 'highly efficient' systems, such as the use of seasonal storage, district heating, combined heat and power and especially the use of low-temperature heating and high-temperature cooling in combination with heat pumps. These arguments do have some legitimacy since well-designed state-of-the-art energy systems indeed show a relatively good exergy performance which is hard to improve using available technologies, even though these energy systems are developed with no conscious use of exergy analyses or of exergy principles.

Thus: why use exergy?

Even though it is hard to significantly improve current systems, there is still considerable room for improvement, based on the estimated technically achievable maximum as discussed in the previous chapter.

- ***Therefore, it can still be expected that the use of the exergy concept does lead to better systems that fully exploit the potential of resources and reduce the wasteful use of these.***

Firstly, the exergy concept is the umbrella that links all the principles for thermodynamically-efficient design as well as the guidelines following from these principles (such as the ones mentioned in chapter 5) together. When *understanding* exergy, these guidelines (such as 'use low-temperature heating') can be understood as an integrated unity and not as separate items to be remembered.

Secondly, when being able to identify *and calculate* exergy losses and related improvement potential, the system can be changed or optimised. The advantage of alternatives can also be quantified, such as the use of low-temperature heating (e.g. 30°C) over very-low-temperature heating (e.g. 25°C) (and compared to the additional investment of larger emission surfaces etc.) Related to a quantitative exergy analysis the saying that 'the numbers tell the tale' is very true. The quantification is essential for the development of highly exergy-efficient systems.

Lastly, even though current energy systems are possibly implicitly based on (some) exergy principles and perform relatively well, not explicitly using the exergy concept and especially, not using a quantitative exergy analysis of systems encloses two risks:

- There is a chance of failing to spot opportunities.
  - The energy concept is unable to determine what is possible and what is not, since it does not consider the convertibility of different forms of energy or the need for driving forces; The exergy concept is needed to determine what is ideally achievable, but also what is *technically* achievable. Exergy insight can stimulate investigation of further improvements and innovations beyond what is currently available.
- Mistakes are more easily made when not calculating the exergy losses.
  - Some exergy losses are obvious, such as those resulting from combustion for low-quality heat. But if losses are not quantified it is difficult to really know where the biggest losses occur. Or even, for some (new) processes it may be unknown whether they involve exergy losses, and mistakes can easily be made if these are not explicitly calculated.

The above reasons affirm that it is good to understand why some systems are better than others and to understand the 'law' of nature that determines why some processes are efficient and others are not, and to be able to calculate this.

We are used the concept of energy, but now we have also seen that the energy concept alone gives an incomplete and sometimes even misleading representation of the performance of an energy system. We can use all kinds of additional guidelines or advices in order to improve system (such as ' use low temperature heating, use heat pumps with a COP higher than 5', etc).

Or we can also start using exergy. This will enhance the insight in the performance of energy systems and in potential ways of further improving them. Hopefully this book has inspired you to start thinking about exergy and will be helpful to start using it.

7 References

Agentschap_NL (2012). EPN en Nieuwbouw - Kenmerken tussenwoning.Retreived: January 2012, from www.agentschapnl.nl

Ala-Juusela, M., Ed. (2003). *Annex 37 Guidebook - Low exergy systems for heating and cooling of buildings,* VTT - Finland.

Annex_37 (2003). Annex 37 Low Exergy Systems for Heating and Cooling, International Energy Agency (IEA).

Annex_49 (2011). Annex 49 Low Exergy Systems for High Performance Buildings and Communities, International Energy Agency (IEA). (www.annex49.com)

Baehr, H. D. and Bergmann, E. (1965). *Energie und Exergie. Die Anwendung des Exergiebegriffs in der Energietechnik (IN German).* durch H.D. Baehr und E. Bergmann und F. Bosnjakovic. Dusseldorf, VDI.

Bejan, A., Tsatsaronis, G. and Moran, M. (1996). *Thermal design and optimization*. New York, Wiley.

Broersma, S., M. Fremouw and A. A. J. F. v. d. Dobbelsteen (2013). "*Energy Potential Mapping: Visualising Energy Characteristics for the Exergetic Optimisation of the Built Environment.*" Entropy 15: 490-506.

C24 (2011). CosteXergy - Analysis and Design of Innovative Systems for LOW-EXergy in the Built Environment, Cost - European Cooperation in Science and Technology.

Carnot, S. (1824). *"Reflections on the motive power of fire and on machines fitted to develop that power*" (translated and edited by R.H.Thurston. Original title: ' Réflexions sur la puissance motrice du feu et sur les machines propres a développer cette puissance'.

Carnot, S. and E. Mendoza (1960). *Reflections on the motive power of fire and other papers on the Second law of thermodynamics by E. Clapeyron and R. Clausius*. New York, Dover Publ.

CEN-EN_15603 (2008). CEN-EN 15603 (en): *Energy performance of buildings - Overall energy use and definition of energy rating*s. 15603. CEN. Brussels, CEN - european committee for standardization.
Cornelissen, R. L. (1997). *Thermodynamics and sustainable development; the use of exergy analysis and the reduction of irreversibility.* Doctoral thesis, Delft University of Technology. Febodruk.

Commoner, B. (1971). *"THE CLOSING CIRCLE; nature, man, and technology".* New York, Knopf.

Dincer, I. (2002). "*The role of exergy in energy policy making.*" Energy Policy 30(2): 137-149.

Dincer, I. and M. A. Rosen (2007*). Exergy energy, environment and sustainable development*. Amsterdam, Elsevier.

Dobbelsteen, A. A. J. F. vd., Jansen, S. C. and Timmeren, A. v. (2007). *"Naar een energiegestuurd omgevingsplan groningen"* (In Dutch). Delft, Delft University of Technology.

Eurostat (2010). Statistics Database - Energy statistics - supply, transformation, consumption, Eurostat (http://epp.eurostat.ec.europa.eu/portal/page/portal/statistics/search_database, accessed aug 2012).

EPBD (2010). " *DIRECTIVE 2010/31/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 May 2010 on the energy performance of buildings (recast).* Official Journal of the European Union, 18.6.2010.

Favrat, D., F. Marechal and O. Epelly (2008). *"The challenge of introducing an exergy indicator in a local law on energy."* Energy **33**(2): 130-136.

Gaggioli, R. A. and Wepfer, W. J. (1981). *"Second law analysis of building systems."* Energy Conversion and Management 21(1): 65-75.

Gommans, L. (2012). *gebiedsgerichte energetische systeemoptimalisatie.* Doctoral thesis, Delft University of Technology.

Gong, M. and Wall, G. (2001). *"On exergy and sustainable development—Part 2: Indicators and methods."* Exergy, An International Journal **1**(4): 217-233.

Gool, W. v. (1997). *"Energy Policy: Fairy Tales and Factualities"*. In: Innovation and Technology — Strategies and Policies. Springer Netherlands: pp. 93-105.

Hameetman, P. et al. (2006). *Toolkit Duurzame Woningbouw - 2e editie (In Dutch)*. Aeneas.

Haskoning (1994). *Exergie-Proefproject knooppunt Arnhem-Nijmegen (in Dutch),* Royal Haskoning.

Hermans, L.J.F.(Jo) (2009). *Energie Survival Gids (in Dutch)*.Jo Hermans (i.s.m. Technologiestichting STW).

ISO_13790 (2008). *Energy performance of buildings - Calculation of energy use for space heating and cooling (ISO 13790:2008)*. CEN, EUROPEAN COMMITTEE FOR STANDARDIZATION.

ITHO (2013a). ITHO HRU ECO 4 datasheet, available from http://www.ithodaalderop.com/wp-content/uploads/2011/02/HRUDataSheet1.pdf , accessed march 2013, ITHO Daaldrop.

Jansen, S.C. (2013). *Exergy in the built environment. The added value of exergy in the assessment and development of energy systems for the built environment.* Doctoral thesis delft university of Technology.

Jansen, S. C., Terés-Zubiaga, J. and Luscuere, P.G. (2012). "*The exergy approach for evaluating and developing an energy system for a social dwelling.*" Energy and Buildings **55**(0): 693-703.

Jansen, S.C., Luscuere, P.G. and Linden, A.C. vd (2011). *"Exergy Demand of Heating in Buildings - Steady State Versus Dynamic Approach"*. 2nd International Exergy, Life Cycle Assessment, and Sustainability Workshop & Symposium (ELCAS-2), Nisyros, Greece.

Jansen, S.C. and Woudstra, N. (2010). *"Understanding the exergy of cold: theory and practical examples."* International Journal of Exergy 7(6): 693-713.

Jong, A. d., Gastel, M. v., Bakker, E.J.,Jeeninga,H., Dam, J. and Wolferen, H. v. (2006 (update 2008)). *Energie- en CO2-besparingspotentieel van micro-wkk in Nederland (2010-2030). (In Dutch)*

KEMIN (2012). "*DK Energy Agreement, March 22 2012*", Danish Ministry of Energy, Climate and Building - Klima og energiministeriet.

Kristinsson, J. (2012). Integrated Sustainable Design (Volume 1). Delftdigitalpress

Meggers, F., V. Ritter, P. Goffin, M. Baetschmann and H. Leibundgut (2012). "*Low exergy building systems implementation.*" Energy **41**(1): 48-55.

MIT (2006). *The Future of Geothermal Energy* . Boston, Massachusetts Institute of Technology.

Molenbroek, E., Stricker, E. and Boermans, T. (2011). *Primary energy factors for electricity in buildings - Toward a flexible electricity supply,* Ecofys.

Moran, M.J. and Shapiro, H.N. (2004). *Fundamentals of Engineering Thermodynamics*. New York, John Wiley & Sons Inc.

Muller, I. (2007*). A history of thermodynamics the doctrine of energy and entropy* Online resource. Berlin, Springer.

Nieuwlaar, E. and Dijk, D. (1993). "*Exergy evaluation of space heating options*." Energy 18(7): 779-790.

Rant, Z. (1956). "*Exergie, ein neues Wort für technische Arbeitsfähigkeit*" (In German) Forschung Ing.Wesens **22**(1): 36-37.

Sakulpipatsin, P. (2008). "*Exergy efficient building design"*. Doctoral thesis, Delft University of Technology. Delft, VSSD.

Santamouris, M. and D. Mumovoc (2009). *A handbook of sustainable building design and engineering*, Earthscan.

Schmidt, D. (2004*). "Design of Low Exergy Buildings- Method and a Pre-Design Tool."* The International Journal of Low Energy and Sustainable Buildings 3: 1-47.

Sciubba, E. and Wall, G. (2007). "*A brief Commented History of Exergy From the Beginnings to 2004."* International Journal of Thermodynamics **10**(1): 1-26.
Scott Cato, M.. (2009) *Green Economics: An Introduction to Theory, Policy and Practice*, Earthscan.

Senternovem (2006). *Referentiewoningen nieuwbouw (in Dutch),* Agenschap NL (voorheen Senternovem). 2KPWB0620.

Shukuya, M. (2009). "*Exergy concept and its application to the built environment.*" Building and Environment 44(7): 1545-1550.

Shukuya, M. (2013). Exergy - Theory and Applications in the Built Environment. London, Springer Verlag.

Stremke, S. (2010). "*Designing sustainable energy landscapes - concepts, principles and procedures*". Doctoral thesis, Wageningen University.

Stremke, S. and Dobbelsteen, A. A. J. F. vd. Eds. (2012). *Sustaianble Energy Landscapes*, CRC Press, Online resource.

Szargut, J. (2005). Exergy method technical and ecological applications. Southampton, WIT Press.

Techneco (2012). *Toros combiwarmtepomp - ontwerphandleiding* (www.techneco.nl/producten/warmtepompen/toros), Techneco.

Terés-Zubiaga, J., Jansen, S.C., Luscuere, P.G. and Sala, J.M. (2013). *"Dynamic exergy analysis of energy systems for a social dwelling and exergy based system improvement"* Energy and Buildings (**64**(0): 359-371).

Tillie, N., Dobbelsteen, A. A. J. F. vd., Doepel, D. and Joubert, M. (2009). "*Towards CO2 neutral urban planning – presenting the Rotterdam energy approach and planning (REAP)."* Journal of Green Building 4(3): 103-112.

Toonssen, R. (2010). *Sustainable power from biomass comparison of technologies for centralized or decentralized fuel cell systems*. Doctoral thesis, Delft University of Technology.

Torío, H. (2012). *"Comparison and optimization of building energy supply systems through exergy analysis and its perspectives*". Doctoral thesis, Technische Universitat Munchen.

Torío, H., A. Angelotti and D. Schmidt (2009). *"Exergy analysis of renewable energy-based climatisation systems for buildings: A critical view."* Energy and Buildings 41(3): 248-271.

Torío, H., D. Schmidt, S. C. Jansen, M. Shukuya, A. Angelotti, P. Benz-Carlstrom, T. Iwamatsu, G. Johannesón, M. Molinari, F. Meggers, M. d. Carli, P. G. Cesaratto, L. Kranzl, P. Caputo, P. Op 't Veld, M. Ala-Juusela and D. Solberg (2011b). *IEA ECBCS Annex 49 Final Report - Low Exergy Systems for High-Performance Buildings and Communities - Detailed Exergy Assessment Guidebook for the Built Environment.* Stuttgart, Germany, Fraunhofer Verlag (available online from www.annex49.com).

Wall, G. (1977). *Exergy - A Useful concept withing resource accounting*. Göteborg, Sweden, Institute of Theoretical Physics, Chalmers University of Technology and University of Göteborg, S-412 96 Report no. 77-42.

Wall, G. and M. Gong (2001). *"On exergy and sustainable development--Part 1: Conditions and concepts."* Exergy, An International Journal 1(3): 128-145.

WCED (Brundtland report), World Commission on Environment and Development (1987). *"Our common future".* Oxford, Oxford University Press.

Wheeler, L. P. and J. Willard-Gibbs (1951). Josiah Willard Gibbs*. "history of a great mind".* New Haven, Yale University.

Wisman, W.H. (1990). *Inleiding thermodynamica (in Dutch*). Delft, NL, VSSD.

Woudstra, N. (2012). *Sustainable energy systems - Limitations and chalanges based on exergy analysis*.Doctoral thesis. Delft University of Technology.

8 Nomenclature

A	[m^2]	area
c_p	[J kg^{-1} K^{-1}]	isobaric heat capacity
E	[J]	electricity
En	[J]	energy
Ex	[J]	exergy
f_{ex}	[-]	exergy Factor (Exergy to energy ratio)
m	[kg]	mass
$\dot{m}$	[kg/s]	mass flow rate
P_{elec}	[W]	electric power
Q	[J]	heat
Q_0	[J]	heat transfer at environmental temperature
Q_H	[J]	heat transfer to or from the hot reservoir or at temperature higher than T_0
Q_C	[J]	heat transfer to or from the cold reservoir or at temperature lower than T_0
Q_s	[J]	hensible heat
S	[J/K]	entropy
T	[K]	temperature (°C if explicitly mentioned)
T_0	[K]	temperature of the reference environment
T_C	[K]	temperature of the cold reservoir
T_H	[K]	temperature of the hot reservoir
$\bar{T}$	[K]	(thermodynamic) mean temperature
U	[W m^{-2} K^{-1}]	heat transfer coefficient
V	[m^3]	volume
W	[J]	work

Greek symbols

η	[-]	energy Efficiency
λ	[W m^{-1} K^{-1}]	thermal conductivity
μ_j	[-]	frequency distribution of variable j
ψ	[-]	exergy Efficiency

Subscripts

0	related to the reference environment
Carnot	related to the Carnot process
dem	demand
e	outdoor
i	indoor
inf	infiltration
inl	inlet

int	Internal gains
ret	return
rev	reversible
sol	solar gains
sup	supply
trans	transmission
vent	ventilation

Abbreviations (also used as subscript)

CHP	combined heat and power (Cogeneration)
COP	coefficient of performance
DHW	domestic hot water
EER	energy efficiency ratio (referring to the heat pump performance for cooling)
HRU	heat recovery unit
HP	heat pump
HT	high temperature
LT	low temperature
PEF	Primary Energy Factor
PV	Photo Voltaic (energy)
SH	space heating
ST	Solar thermal (energy)
TES	Thermal energy storage
VLT	very low temperature

Exergy is a thermodynamic concept that can be used to evaluate the performance of energy systems. It provides additional insight by showing how far energy process are from the theoretically ideal process. Due to this added value, the application of the exergy concept to energy systems for the built has increased in the last decades. This is however primarily in scientific publications; the application in practice is still very rare.

This book aims to provide a clear handbook on the use of exergy in the built environment as well as on its added value in addition to an energy approach. It provides:

- An introduction and explanation of the concept of exergy
- Instructions on how to calculate exergy for processes relevant for the built environment
- Exemplary case studies demonstrating the exergy performance of current systems as well as the difference between energy and exergy assessment
- Guidelines on how to use the exergy concept to develop improved systems
- Outlook: What to expect from the exergy approach

This publication is based on the doctoral thesis by the same author, entitled ‘Exergy in the built environment: The added value of exergy for the assessment and development of energy systems for the built environment’, which was published in November 2013. This means that apart from the general introduction and explanations on the exergy concept, this book also presents the most important findings and conclusions from this research. Where possible additional simplifications are provided.

This publication is realised with the financial support of RVO (Rijksdienst voor Ondernemend Nederland). This support is gratefully acknowledged.