New ways for energy systems in sustainable buildings

- increased energy efficiency and indoor comfort through the utilisation of low exergy systems for the heating and cooling of buildings -

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ABSTRACT: The necessity for a further increase in the efficiency of energy utilisation in buildings is obvious and indisputable. This is especially true regarding the great potential for the use of those measures in the building stock.

An optimisation of the energy flows in building, similar to other thermodynamic systems, such as power stations, can help in identifying the potential of increased efficiency in energy utilisation. This paper shows, through analyses and examples, that calculations based on the energy conservation and primary energy concept alone are inadequate for gaining a full understanding of all important aspects of energy utilisation processes. The high potential for a further increase in the efficiency of; for example, boilers, can not be quantified by energy analysis - the energy efficiency is close to 1; however, this potential can be showed by using the method of exergy analysis.

This research work is related to the international co-operation work in the IEA ECBCS Annex 37 “Low Exergy Systems for Heating and Cooling of Buildings”.

Conference Topic: 2 Design Strategies and Tools
Keywords: energy, exergy, thermal comfort, sustainable building

1 INTRODUCTION

Today’s discussion on rising energy prices and environmental problems arising from the use of fossil energy sources is highly followed. The consumption of primary energy in residential and commercial buildings accounts for about one third of the total world energy demand. Buildings represent a major contributor to that global problem [4] even though great efforts have been made to reduce energy consumption in buildings; for example, by improving the window glazing or constructing heavily insulated façades. Most of the energy is used to maintain constant room temperatures of around 20°C. In this sense, because of the required low temperature levels for the heating and cooling of indoor spaces, the so-called exergy demand for applications in room conditioning is naturally low. In most cases, however, this demand is satisfied with high quality sources, such as fossil fuels or electricity. Renewable energy sources, such as thermal solar power or using the ground as a cooling source, work very efficiently and are profitable for the regarded temperature levels.

To make energy use in buildings even more efficient and to open up the possibility of using renewable energy sources, and supplying energy with low quality, new low temperature heating and cooling systems are required. To allow for a better understanding of energy utilisation in buildings and how to implement more renewable energies into buildings, the method of exergy analyses is beneficial. A deeper understanding of the nature of energy processes in buildings would enable building designers and architects to achieve an improved overall design. Furthermore, it has been found that by applying so-called low temperature systems, thermal indoor comfort is improved at the same cost level as by using conventional, less comfortable building service systems.

In this paper, the method of exergy analyses and its applicability for those involved in building design is outlined and demonstrated with examples.

2 BACKGROUND

All calculations of heating or cooling loads of rooms and buildings, as well as temperature calculations, are based on energy balances. This is in reference to the commonly known first law of thermodynamics, which states that energy is conserved in every device or process and can not be destroyed or consumed. At the same time, the term “energy consumption” or “energy savings” is widely used. When such expressions are used, we implicitly refer to “energy” as energy available from fossil fuels or condensed uranium. These sources of energy are dissipated in everyday life. Over the last few decades, various, so-called “energy saving” measures, and their associated environmental control systems for heating, cooling and lighting, have been conceived, developed and also implemented in building envelope systems. National policies and codes have been influenced by these ideas, too. The question remains, what is consumed?

In order to enhance the understanding of the nature of energy flows in systems the second law of thermodynamics can be used in combination with the first law. The key concept of the second law of thermodynamics is entropy. In every process where energy or matter is dispersed, entropy is inevitably generated. In using both the first and second law of thermodynamics, the concept of exergy should be used. The exergy concept can explicitly show what is consumed in energy utilisation processes. In other words, exergy is the concept which quantifies the potential of energy to cause changes or to do work. It can be regarded as the valuable part of energy.

As illustrated thoroughly in this paper, the energy conservation concept alone is insufficient for gaining a clear understanding of some of the important aspects of energy resource utilisation. There are two fundamental concepts: energy and entropy. We believe that it is essential to articulate what is consumed and where such consumption occurs in all the processes of heating and cooling. Only then is it possible to improve the overall design of buildings and allow for the inclusion of more renewable energy sources into the supply of our houses.

The concept of 'primary energy use' may be reasonable in estimating the amounts of input in the systems in question. However, it can not be revealed where, within the systems, the consumption occurs and how the potentials of energy are used.

A clear picture of where the potential for a further increase of an efficient energy use can be found can only be obtained by using an analysis which included both energy and exergy. This is done in other fields, such as the engineering of thermodynamics; for example, in the analysis of power stations (see [1] and [6]). This method has been used for all cases included in this paper in the analysis of buildings. The only differences are in the aim of the optimisation procedure. In the case of power stations, the electricity output from a given flow of primary energy/exergy is to be maximized as much as possible. In buildings where people live, the most important thing is to have rational energy utilisation patterns which enhance occupants' well-being within the built environment.

3 THE METHOD

For the following study of a building environmental control system, such as heating or cooling, steady state conditions are assumed. Energy and matter are supplied into the system to make it work. In- and outputs are the same, according to the laws of energy and mass conservation. The energy flow through the building envelope is constant in time under steady state conditions. In the case of heating, heat transmission occurs from the warm interior to the cold ambient environment, across the building envelope. This is accompanied by an increasing flow of entropy. The entropy of a substance is a function of the temperature and pressure. A certain amount of entropy is generated by this process, due to irreversible processes inside the building envelope. This generated entropy has to be discarded to the surroundings, i.e. the outdoor environment. It is important to recognise that the energy flowing out of the building envelope is not only accompanied by a destruction of exergy, but also by an increased flow of entropy. Disposition of generated entropy from a system allows room for feeding on exergy and consuming it again. This process, which underlies every working process, can be described in the following four fundamental steps. Heating and cooling systems are no exception here [11]:

Table I: Four steps of the exergy-entropy process.

1.	Feed on exergy
2.	Consume exergy
3.	Generate entropy
4.	Dispose entropy

3.1 Exergy calculations

All processes in nature, as well as in buildings, happen under the first law (energy conservation) and second law (entropy increase) of thermodynamics and both of them are equally important. The concept of exergy is the combination of these laws. This implies that a comparison of energy and exergy calculations only becomes meaningful once both laws are taken into regard.

For analysis purposes, a commonly known energy balance has to be set up and all incoming or outgoing energy flows have to be considered.

Secondly, an entropy balance has to be formulated for the entropy flows accompanying the energy flows, and a term for the internally produced entropy has to be set up.

As a last step, the energy and the entropy balance are combined and formulated as an exergy balance. See [8] and [9] for a detailed description.

4 DESCRIPTION OF A DESIGN TOOL

To increase the understanding of exergy flows in buildings and to be able to find possibilities for further improvements in energy utilisation in buildings, a pre-design analysis tool has been produced during the work for the IEA ECBCS Annex 37. Throughout the development, the aim was to produce a "transparent" tool, easy to understand for the target group of architects and building designers, as a whole. Other requirements were that the exergy analysis approach was to be made clear and the required inputs were to be limited.

All steps of the energy chain - from the primary energy source, via the building, to the sink (i.e. the ambient environment) - are included in the analysis.

The tool is built up in different blocks of sub-systems for all important steps in the energy chain (see Figure 1). All components, building construction parts, and building services equipment have sophisticated input possibilities. Heat losses in the different components are regarded, as well as the required auxiliary electricity for pumps and fans. The electricity demand for artificial lighting and for driving fans in the ventilation system is included. On the

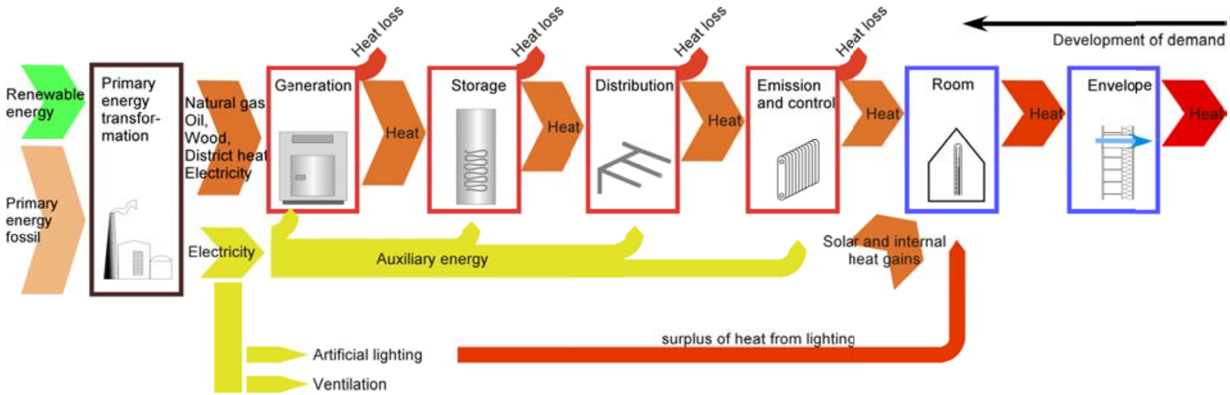

Figure 1. The modelling method, the energy chain in the tool from source to sink ([3], modified)

primary energy side, the inputs are differentiated between fossil and renewable sources. The calculation is made under steady state conditions.

5 DESCRIPTION OF THE EXAMINED CASE

In order to clarify the method for this analysis, a room in a typical commercial building has been chosen. For this simple model, a number of variations in the building envelope design and in the building service equipment have been calculated.

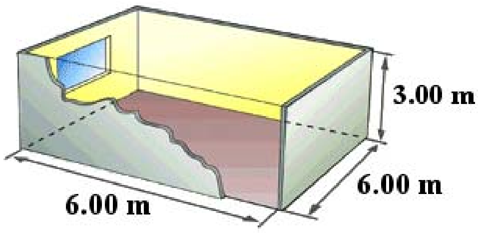

Figure 2. Examined room, from a typical office building

Table II. Facts and values of the base case

Building type:	Commercial building
Boiler:	LNG fired high temperature boiler
Emission:	High temperature radiators (70/60)
Ventilation:	Natural ventilation, n = 1.5 *ach*
Exterior wall:	$U_W = 0.4\ W/m^2K$, $A_W = 18\ m^2$
Window:	$U_w = 2.2\ W/m^2K$, $A_w = 9\ m^2$

(LNG: liquefied natural gas)

The base case has been chosen so that the building standards of a number of countries (e.g. in Central Europe, Japan, and North America) could be met in round terms. The insulation standard is moderate and the building service systems are somehow representative of the building stock in these countries.

To enhance the understanding of the exergy analysis method and to see the impacts of building design changes on the result, variations in the design have been calculated. For the base case, a number of different improvements and changes in the system design have been analysed:

Table III. Improvements and changes made on the system for the analysis

(1)	LNG Condensing boiler, $\eta_G = 0.99$
(2)	Ground source heat pump, COP = 2.5 or 4.3 dependent on supply temperature of emission
(3)	Direct electrical heating with convectors
(4)	Low temperature floor heating
(5)	Higher insulation standard, tighter envelope $U_W = 0.2\ W/m^2K$, $U_w = 1.2\ W/m^2K$, $n = 1$ *ach*

6 RESULTS OF THE ANALYSES

Numerical examples are shown for the whole process of space heating, based on a system design and the sub-systems shown in Figure 1.

Results of the analysis of the base case are shown in Figure 3 and Figure 4. These figures, which indicate where losses occur, are quantified by the sub-systems/components in Figure 4.

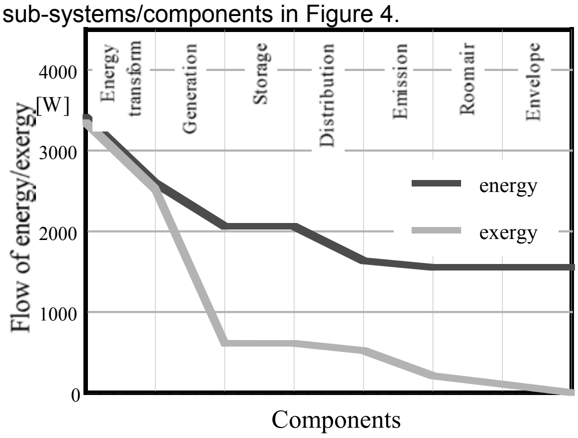

Figure 3. Absolute values of energy and exergy flows for the base case

In Figure 3, absolute values of the energy and exergy flows through the different components are given. The system is fed with primary energy/exergy, shown on the left side of the diagram. Because of losses and system immanent irreversibilities and inefficiencies in the heat and mass transfer processes in the components, energy, as well as exergy, dissipates to the environment. At the same time, exergy is consumed in each component. When the flow of energy leaves the building through the building envelope there is still a remarkable amount of energy left over (i.e. the sum of all building heat losses), but the same is not true for exergy. At the ambient environment level, energy has no potential of doing work and all exergy has been consumed. The exergy flow on the far right side of the diagram is equal to zero. This kind of diagram helps in comprehending the flow of exergy through building systems and enables further optimisations in the overall system design.

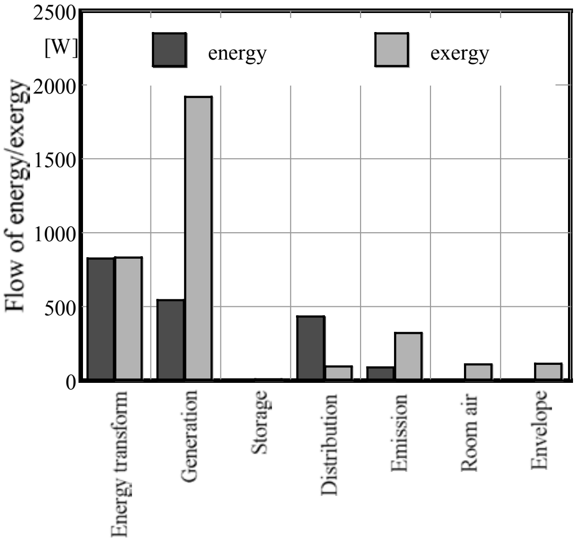

Figure 4. Relative energy loss and exergy consumption of components for the base case

To achieve improvements in the system design, it is mandatory to know where losses and inefficiencies occur (Figure 4). Major losses occur in both transformation processes. This happens namely in the primary energy transformation, where a primary energy source is transformed into an end-energy source, such as LNG, and in the generation, where the named end-energy source is transformed into heat by, for example, a boiler.

The difference between an energy and an exergy analysis becomes clear when observing the losses in the generation sub-system. The energy efficiency of this system is high, but the exergy consumption within the boiler system is the largest of all regarded sub-systems. When using a combustion process, consuming a lot of exergy is indispensable in the extraction of thermal exergy from the chemical exergy contained in LNG. As for the process in the generation, the supply of energy is of a high quality factor, as it is for LNG, with 0.95. The core inside the generation is a combustion process with flame temperatures of some thousand degrees celsius, leading to the output of the process being a heat carrier medium of about 80°C. Even at this point, the temperature levels indicate a great loss.

6.1 Impact of improvements in the building envelope versus improvements in the service equipment

Four numerical results for the process of space heating in steady state, are presented in Figure 5 and Figure 6.

Starting with the base case described above, improvements on the design have been made and calculated. As already shown, exergy consumption within the heat generation is the largest among all sub-systems. This is unavoidable when generating heat for space heating through the use of a combustion process. Because of this, it may be considered that it is essential to improve the efficiency of the boiler. Thus, an increase in boiler efficiency from η_G = 0.8 to 0.99 has been reached with improvement (1) (see Table III). The results are shown by the solid gray line in the following figures. The decrease in exergy consumption is marginal.

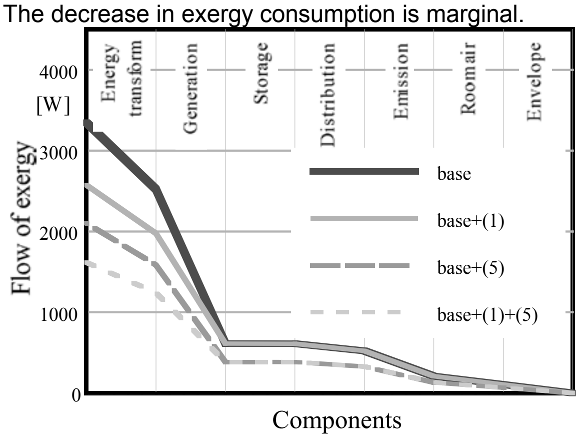

Figure 5. Comparison of exergy consumption for improvements on the building envelope or the equipment, as described in Table III.

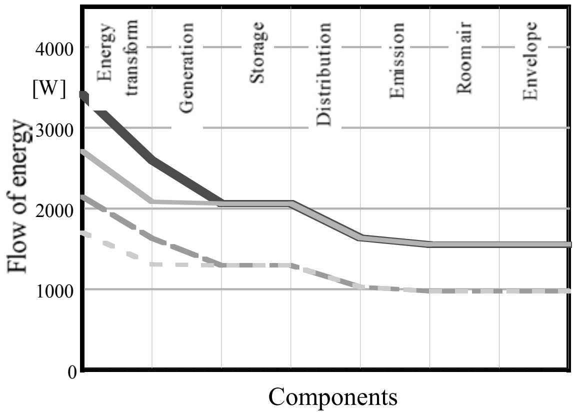

Figure 6. Comparison of energy utilisation for improvements on the building envelope or the equipment. For legend, see Figure 5.

To increase the exergy output of the boiler, an increase of the outlet water temperature can be taken into consideration. This, however, results in the consumption of more exergy within the following systems, from the storage to the emission system. Also, the exergy consumption within the room air would be higher because the desired room temperature is just 293 K or 20°C. These facts imply that an extremely highly efficient boiler alone can not necessarily make a significant contribution to the reduction of exergy consumption in the whole process of space heating.

The picture changes when the heating exergy load of the room - the standard of the building shell - is taken into consideration. This has been done with improvement (5), where the insulation standards of the walls and the windows have been improved. The heating exergy load, which is the exergy output from the room air and the exergy input to the building envelope which represents only 4.2 % of the chemical exergy input to the boiler. This reduction measure could be regarded as marginal, or as having a limited impact on the total exergy consumption of the system. But, as can be seen by the difference between the whole exergy consumption profile of the base case and the base case with improvement (5), in order to decrease the rate of total exergy consumption, it is more beneficial to reduce the heating exergy load by installing thermally, well-insulated exterior walls and glazings than to install thermally, extremely highly, efficient boilers.

A further reduction in exergy consumption of the boiler sub-system, as indicated by the base case with improvements (5) and (1), i.e. the light grey dotted line, becomes essentially meaningful together with the improvement in the thermal insulation of the building envelope.

6.2 System flexibility and the possible integration of renewable sources into building systems

One major point in the overall discussion on sustainable building is the necessity for flexible building service systems. This means flexibility in the utilisation of different energy sources, of course, mainly the possible use of renewable sources, and also flexibility in satisfying broad variations from the demand side.

Utilising exergy analyses could help to quantify the degree of system flexibility. As already stated, a reduction in the exergy load of the room is important. However, it is equally important to consider how to satisfy the remaining demand. This is done in the analysis shown in Figure 7.

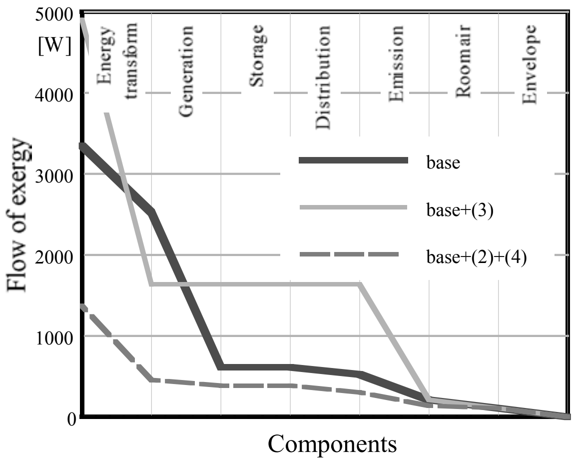

Figure 7. Comparison of exergy consumption for different system configurations with regard to overall system design flexibility. Cases described in Table III.

Three system solutions have been chosen to satisfy the heat demand for the same room. The base case represents a high temperature LNG boiler and high temperature radiators (solid dark line), a system where direct electrical heating by convectors is used, as is common in a number of Nordic countries (base+(3), light grey solid line), and a system where a heat pump supplies a low temperature floor heating system (base+(2)+(4), dotted line). The thin dotted line indicates the energy extracted from the environment by the heat pump. All three system designs satisfy the same heat demand, but with totally different exergy needs. This difference can not be clearly shown in an energy analysis, see Figure 8.

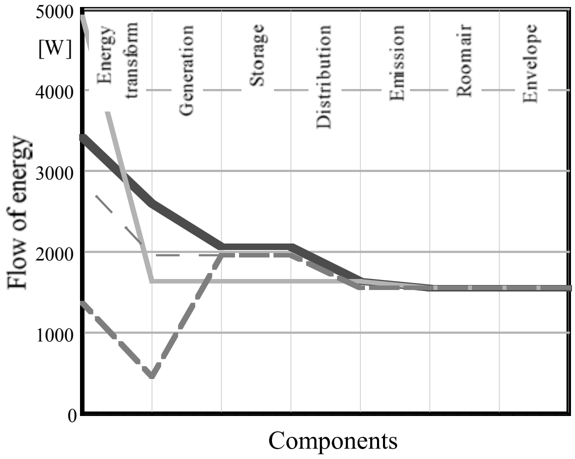

Figure 8. Comparison of energy utilisation for different system configurations with regard to overall system design flexibility. For legend, see Figure 7. The thin line indicates the energy flow including heat extracted from the surroundings.

The role of the emission system is mandatory. If the exergy demand of the emission system is low it can be satisfied by a number of different sources, either high exergetic ones such as electricity, or low exergetic ones such as low temperature and highly efficient thermal solar power. Emission systems with high exergy requirements for the same amount of transported energy can only be fed with high exergetic sources, and the system design is locked, i.e. not flexible. The implementation of renewable sources, with their great potential for a reduction in CO_2, can not be realised.

Also, from an energy point of view, the solution of using direct electricity does not lead to the best possible choice with the highest demand on primary energy. This result naturally depends on the high primary energy factor of 3.

As for the possibility of implementing renewable sources into building systems, the major prerequisite is that of flexible storage, distribution, and emission systems in buildings. Renewable sources are highly efficient within moderate temperature ranges, like low temperature thermal solar power. Heat could easily and efficiently be produced at temperatures of about 40°C. At this temperature level, with this low level of exergy, only building service equipment with a low exergy demand can be fed, like the low temperature floor heating system depicted in Figure 7. Discussing the issue of the integration of renewable energy sources on a larger scale and in buildings opens new possibilities by utilising the potential of exergitically optimised service designs.

7 CONCLUSIONS

The necessity for a further increase in the efficiency of energy utilisation in buildings is obvious and indisputable. This is especially true regarding the great potential for the use of those measures in building stock. As shown in this paper, through analyses and examples, the energy conservation concept alone is not adequate enough to gain a full understanding of all the important aspects of energy utilisation processes. From this aspect, the method of exergy analyses is the missing link needed to fill the gap in understanding and designing energy flows in buildings.

A number of general conclusions can be drawn from all of the cases analysed. The following design guidelines for building designers can be extracted from these recommendations:

Reducing the loads on the building service equipment is an efficient step towards a good and exergy saving design. Utilising passive means - like a good insulation standard, tight building envelopes and also the use of passive gains, like solar or internal gains – is an excellent starting point for an optimised design. In the second step, the building service appliances should be taken into consideration. Their use should be minimised as much as possible and only when all passive means are no longer sufficient. This is also important to keep in mind.

Problems related to utilising passive means, such as overheating or increased cooling needs due to; for example, too much solar gain, also have to be regarded in an overall design optimisation. Even in the case of cooling, which has not been addressed in this paper, the reduction of loads by; for example, efficient solar shadings, is mandatory.

Flexibility in system configurations is important for future “more sustainable” buildings. Exergy analyses can help in quantifying the degree of flexibility in a system design. Low exergy loads, not only from the enclosed spaces, but also from the emission, distribution and storage systems, enable an open configuration of the generation and the possible supply of the building utilising a number of different energy sources. Here, the possibility of the integration of all kinds of renewable sources of heat and coolness should be recognised. All renewable sources are utilised more efficiently at low temperature levels. In the case of heating, this is true for thermal solar power, generated by; for example, simple flat plate collectors or solar walls.

High exergy sources, such as electrical power, should be left to special appliances that require a high exergy content, such as artificial lighting or driving computers and machines. These sources should not be used for heating purposes. Even though some advantages, such as low installation cost for direct electrical heating, may seem beneficial, exergy analysis shows the opposite. If high exergy sources are to be used anyway, efficient processes are needed, like heating with heat pumps in combination with low temperature emission systems.

In addition, exergy analyses offer more possibilities for investigating buildings; for example, in the area of thermal comfort. The conditions of good indoor thermal comfort coincide with the environmental conditions where the human body consumes the least amount of exergy to maintain comfortable conditions [5], [7]

Furthermore, one should not only think about what is consumed in energy utilisation processes, as discussed above. Another question is: what should we buy to satisfy our demand on energy services? Energy or exergy? If we bought energy, we could buy the transmission heat losses from our neighbours' houses to heat our houses. Yet, that is not possible. We have to buy high quality energy with the potential to do work, …exergy! Save exergy rather than energy.

8 Acknowlegement

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