Exergy Use in the Built Environment
Basics and Analyses

D. Schmidt[1]

[1] *Fraunhofer-Institut für Bauphysik, Gottschalkstrasse 28a, 34127 Kassel, Germany*

ABSTRACT

It is often claimed that energy is consumed; this is not only done in everyday conversation but also in scientific discussions associated with energy and environmental issues. This claim conflicts with the first law of thermodynamics stating that the total amount of energy is conserved, even though forms of energy may change from one to another. This is why we need to use the thermodynamic concept, exergy, to fully understand what is consumed.

An optimization of the exergy flows in building, similar to other thermodynamic systems such as power stations, can help in identifying the potential of increased efficiency in energy utilization. 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 utilization 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 exergy analysis.

This research work is related to the finished international co-operation work in the ECBCS Annex 37 “Low Exergy Systems for Heating and Cooling of Buildings” and the newly started in ECBCS Annex 49 “Low Exergy Systems for High-Performance Buildings and Communities” (Annex 49 2006).

KEYWORDS

Energy efficiency, exergy analyses, heating and cooling systems.

INTRODUCTION

Every calculation of heating or cooling loads of rooms and buildings, as well as temperature calculations, is based on energy balances. This is in reference to the first law of thermodynamics, which states that energy is conserved in every device or process and it 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 decades various, so-called “energy saving” measures, and their associated environmental control systems such as heating, cooling and lighting systems, have been conceived, developed and also implemented in building envelope systems. The question remains, what is consumed?

To enhance the understanding of the nature of energy flows in systems we can use the second law of thermodynamics, in addition to the first law. In combining the first and second laws of thermodynamics, the concept of exergy should be used. The exergy concept can explicitly show what is consumed in energy utilization 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 in this paper, the energy conservation concept alone is inadequate for an understanding of some important aspects of energy resource utilization. For this, exergy, that is derived from the two basic concepts, and the associated environmental temperature must be used, in addition to energy calculations. The concept of 'primary energy use' may be reasonable in estimating the amounts of input to the systems in question. However, one cannot reveal 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 will be obtained by using a combined energy and exergy analysis only. This is done in engineering thermodynamics; for example, in analyzing power stations (see Ahern 1980 and Moran & Shapiro 1998). The only differences are in the aim of the optimization procedure: power stations shall maximize the electricity output as much as possible from a given flow of primary energy/exergy. In buildings where people live, the most important thing is to have rational energy utilization patterns which enhance occupants' well-being within the built environment.

BACKGROUND/APPROACH/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. 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 recognize 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 (Shukuya 1998):

Table 1. Four steps of the exergy-entropy process (Schmidt & Shukuya 2003).

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

The general expression of exergy balances is introduced using the case of a simple building envelope system. The concept is to conserve energy, so, under assumed steady state conditions, the energy flowing in has to be equal to the energy flowing out from the system:

$$E_{in} = E_{out} \quad (1)$$

Secondly, the entropy balance has to be formulated in consistence with the energy balance. Heat is an energy transfer caused by dispersion, thus, in the course of heat transmission, entropy flows into the system and some amount of entropy is inevitably generated within the system:

$$S_{in} + S_{gen} = S_{out} \quad (2)$$

By combining the energy and entropy balance, a general formulation of the exergy balance can be gained:

$$(E_{in} - S_{in}T_0) - S_{gen}T_0 = (E_{out} - S_{out}T_0) \quad (3)$$

$$\Rightarrow \quad Ex_{in} - Ex_{consumed} = Ex_{out} \quad (4)$$

This is the exergy balance equation for a system under steady state conditions (Shukuya & Hammache 2002). 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 both laws. This implies that a comparison of energy and exergy calculations only becomes meaningful once both laws are kept in mind.

DESCRIBTION OF THE TOOL

To increase the understanding of exergy flows in buildings and to be able to find possibilities for further improvements in energy utilization in buildings, a pre-design analysis tool has been produced during the work for the ECBCS Annex 37 (Ala-Juusela 2004). 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 are that the exergy analysis approach is to be made clear and the required inputs need to be limited. Today, the Microsoft Excel spreadsheet based tool has two input pages and results are summarized on two additional pages with diagrams (Annex 37 2006). 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.

In order to clarify the method for this analysis, a room in a typical residential 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. All calculations have been performed under steady state conditions (Schmidt & Shukuya 2003).

RESULTS OF THE ANALYSES

Numerical examples of energy utilization and exergy consumption are shown for the whole process of space heating, beginning with the power plant, through the generation of heat (the boiler), via a storage and distribution system, to the heat emission system and from there, via the room air, across the building envelope to the outside environment. Results of the analysis of a base case are shown in Figure 1. These figure, which indicate where losses occur, are quantified by the sub-systems/components.

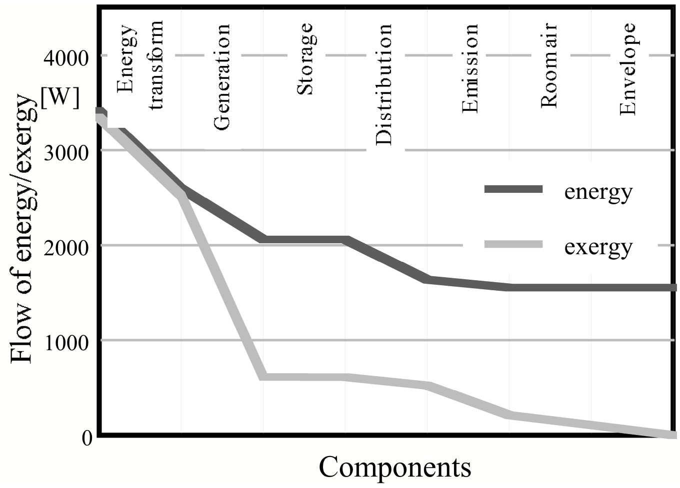

Figure 1. Absolute values of energy and exergy flows for a base case (Schmidt & Shukuya 2003)

In, 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 (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 to comprehend the flow of exergy through building systems and enables us to do further optimizations in an overall system design.

One major point in the overall discussion on sustainable building or building with a low impact on the natural environment is the necessity for flexible building service systems. This means flexibility in the utilization of different energy sources, of course, mainly the possible use of renewable sources, and also flexibility to satisfy broad variations from the demand side. Utilizing exergy analysis could help to quantify the degree of system flexibility. 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 2.

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 are satisfying the same heat demand, but with totally different exergy needs. This difference can not be clearly shown in an energy analysis, see Figure 3.

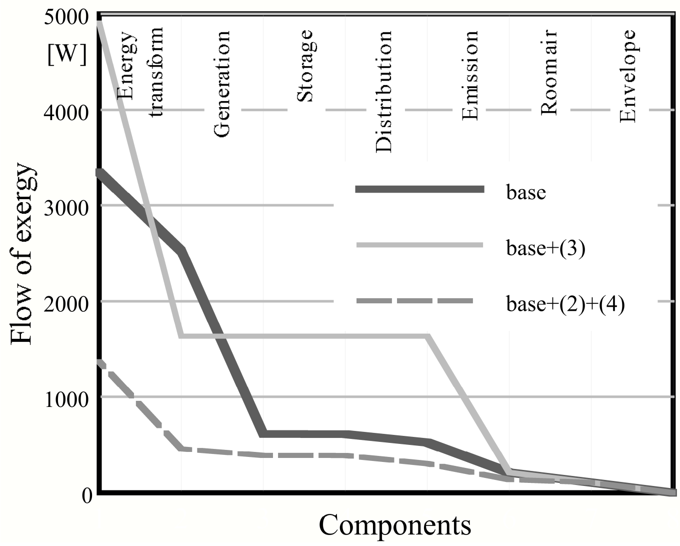

Figure 2. Comparison of exergy consumption for different system configurations with regard to overall system design flexibility (Schmidt & Shukuya 2003).

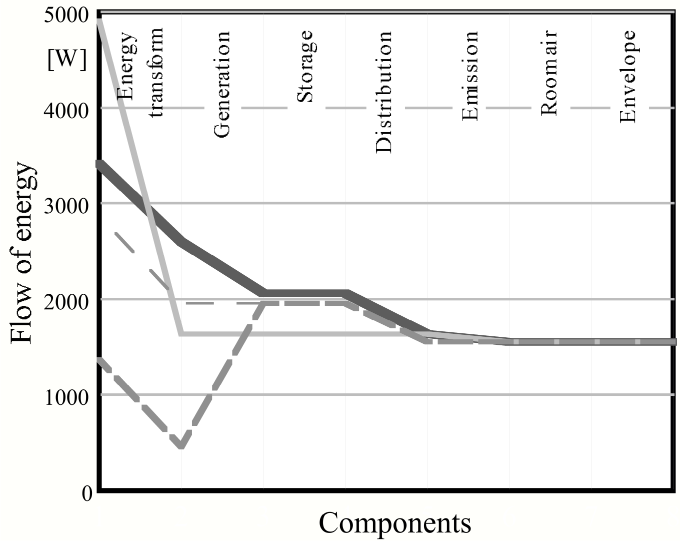

Figure 3. Comparison of energy utilization for different system configurations with regard to overall system design flexibility. Thin line indicates the energy flow including extracted heat from the surroundings (Schmidt & Shukuya 2003).

CONCLUSIONS

The necessity for a further increase in the efficiency of energy utilization in buildings is obvious and indisputable. This is especially true regarding the great potential for the use of those measures in the building stock. Approximately one third of primary energy is consumed in non-industrial buildings such as dwellings, offices, hospitals, and schools, where it is utilized for space heating and cooling, lighting and the operation of appliances (ECBCS 2006). 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 utilization 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.

Reducing the loads on the building service equipment is an efficient step towards a good and exergy saving design. Utilizing 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 optimized design. All measures that modern building physics can offer in this field are highly efficient in this process.

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 utilizing a number of different energy sources. Here, the possibility of the integration of all kinds of renewable sources of heat and coolness should be recognized. All renewable sources are utilized 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 to be beneficial, exergy analysis shows the opposite. High primary energy transformation factors in a lot of countries explain the same fact, through an energy analysis. 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.

REFERENCES

Ahern J. 1980. *The Exergy Method of Energy System Analysis*. New York: Wiley-Interscience Publication, John Wiley and Sons.

Ala-Juusela, M. et.al. 2004. Heating and Cooling with Focus on Increased Energy Efficiency and Improved Comfort. Guidebook to IEA ECBCS Annex 37. VTT Research notes 2256, VTT Building and Transport, Espoo, Finland, 2004

Annex 37. 2006. *International Energy Agency – Low Exergy Heating and Cooling of Buildings – Annex 37,* Web Homepage, http://virtual.vtt.fi/annex37/

Annex 49. 2006. *International Energy Agency – Low Exergy Systems for High-Performance Buildings and Communities – Annex 49,* Web Homepage, http://www.annex49.com

ECBCS 2006. *Energy Conservation in Buildings and Community Service Programme*. International Energy Agency. Web Homepage: http://www.ecbcs.org

Moran M.J. & Shapiro H.N. 1998. *Fundamentals of Engineering Thermodynamics.* 3rd Edition, John Wiley & Sons, New York, USA.

Schmidt, D. & Shukuya, M. 2003. *New ways towards increased efficiency in the utilization of energy flows in buildings.* Proceedings to the Second International Building Physics Conference 2003, September 14-18 2003, Leuven, Belgium: pp. 671-681.

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

Shukuya, M. & Hammache, A. 2002. *Introduction to the Concept of Exergy – for a Better Understanding of Low-Temperature-Heating and High-Temperature-Cooling Systems,* VTT research notes 2158, Espoo, Finland.

Shukuya, M. 1994. *Energy, Entropy, exergy and Space Heating Systems.* Proceedings of the 3rd International Conference "Healthy Building '94", Vol. 1, 1994, pp. 369-374.

Shukuya, M. 1998. *Bioclimatic design as rational design of exergy-entropy process.* Proceedings of PLEA '98. Lisbon, Portugal, June 1998, pp. 321-324.