New ways towards increased efficiency in the utilization of energy flows in buildings

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

1 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. National policies and codes have been influenced by these ideas, too. 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. Here, the concept of entropy is the key. In every process where energy or matter is dispersed, entropy is inevitably generated. 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 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 inadequate for an understanding of some important aspects of energy resource utilization. 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. 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). This method has been used for all cases included in this paper for the analysis of buildings. 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.

2 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. 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 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.

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

2.1 *Exergy balance*

The general expression of exergy balances is introduced using the above-mentioned 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:

$$E_{in} = E_{out} \tag{1}$$

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:

$$S_{in} + S_{gen} = S_{out} \tag{2}$$

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

$$\left(E_{in} - S_{in}T_0\right) - S_{gen}T_0 = \left(E_{out} - S_{out}T_0\right) \tag{3}$$

$$Ex_{in} - Ex_{consumed} = Ex_{out} \tag{4}$$

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.

2.2 *Exergy demand calculation of a heat emission system*

To demonstrate this method, one example of a system study is presented here. A commonly used radiator has been chosen to demonstrate how an exergy calculation on the component basis can be done. The combination of the two laws of thermodynamic is shown.

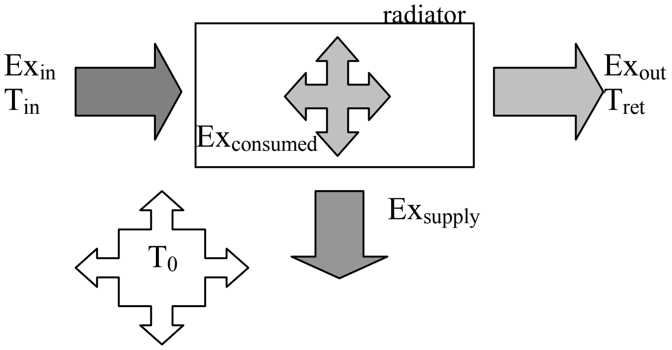

Figure 1. Exergy demand calculation of an emission system

Energy balance:

Energy flow contained by water, to radiator = Energy flow emitted by the radiator, supply to room + Energy flow contained by water, from radiator

$$\begin{aligned} c \cdot \dot{m} \cdot \left(T_{in} - T_0\right) &= A \cdot h_c \cdot \left(T_S - T_{ra}\right) \\ &+ A \cdot h_r \cdot \left(T_S - T_{rm}\right) + c \cdot \dot{m} \cdot \left(T_{ret} - T_0\right) \end{aligned} \tag{5}$$

An inflow of warm water is assumed on the left-hand side. The water heats the radiator and some heat energy is supplied to the room, heating the room. Thereby, entropy is generated and exergy consumed within the radiator. Somewhat chillier water exits the radiator on the right-hand side.

In equation (5) the first term represents the energy flow to the radiator, the second is the emitted heat from the radiator surface by convection, the third is the emitted heat by radiation, and the fourth term represents the remaining heat energy in the return line of the radiator.

Equally, an equation corresponding to the entropy balance (2) can be formulated. In addition to the terms of the energy balance, the entropy generation must be taken into consideration.

Entropy flow balance:

$$c \cdot m \cdot \ln\left(\frac{T_{in}}{T_0}\right) + S_{gen} = \frac{A \cdot h_c (T_S - T_{ra})}{T_S} + \frac{A \cdot h_r (T_S - T_{rm})}{T_S} + c \cdot m \cdot \ln\left(\frac{T_{ret}}{T_0}\right) \qquad (6)$$

The first term of the left hand side is the flow of entropy to the radiator. To estimate the entropy an internal reversible process is assumed, with the natural logarithm. In the first and second term of the right-hand side of the equation above, the surface temperature of the radiator is placed in the denominator. These terms represent the entropy flows leaving the radiator through the surface. This process happens at surface temperature (see also Moran & Shapiro 1998).

Combining equation (5) and (6) gives the

Exergy flow balance:

$$c \cdot \dot{m}\left\{(T_{in} - T_0) - T_0 \cdot \ln\left(\frac{T_{in}}{T_0}\right)\right\} - S_{gen} \cdot T_0 = \left(1 - \frac{T_0}{T_S}\right) \cdot A \cdot h_c \cdot (T_S - T_{ra}) + \left(1 - \frac{T_0}{T_S}\right) \cdot A \cdot h_r \cdot (T_S - T_{rm}) + c \cdot \dot{m}\left\{(T_{ret} - T_0) - T_0 \cdot \ln\left(\frac{T_{ret}}{T_0}\right)\right\} \qquad (7)$$

In order to more simply explain the process, this equation can be formulated in the following shorter way:

$$Ex_{in} - Ex_{consumed} = Ex_{supply} + Ex_{ret} \qquad (8)$$

The exergy demand of the emission system is the difference between the supplied exergy and the exergy returning to the generation. This difference must be compensated by the boiler.

$$\Delta Ex = Ex_{in} - Ex_{ret} \qquad (9)$$

$$\Delta Ex = c \cdot \dot{m}\left\{(T_{in} - T_{ret}) - T_0 \cdot \ln\left(\frac{T_{in}}{T_{ret}}\right)\right\} \qquad (10)$$

To introduce the term for the heat energy supply to the room Q, the exergy difference can be written in this way:

$$\Delta Ex = \frac{Q}{(T_{in} - T_{ret})}\left\{(T_{in} - T_{ret}) - T_0 \cdot \ln\left(\frac{T_{in}}{T_{ret}}\right)\right\} \qquad (11)$$

$$Q = c \cdot \dot{m} \cdot (T_{in} - T_{ret}) \qquad (12)$$

This example is meant to demonstrate how exergy analyses can be done on a typical building service system.

3 DESCRIPTION OF THE USED 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 ongoing 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 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 2002).

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, as shown in Figure 2.

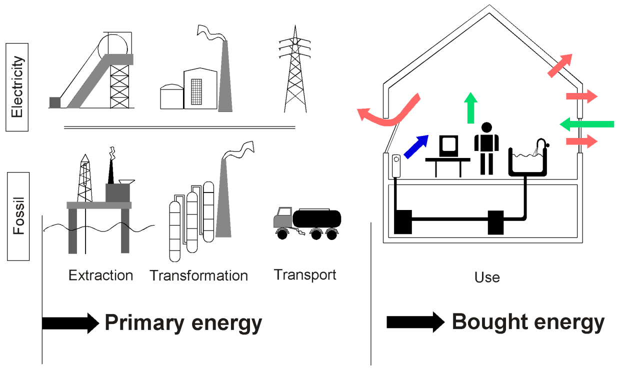

Figure 2. Energy demand in buildings, boundaries for the modeling (Maas, Hauser & Höttges 2002, modified)

The entire tool is built up in different blocks of sub-systems for all important steps in the energy chain (see Figure 3). 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

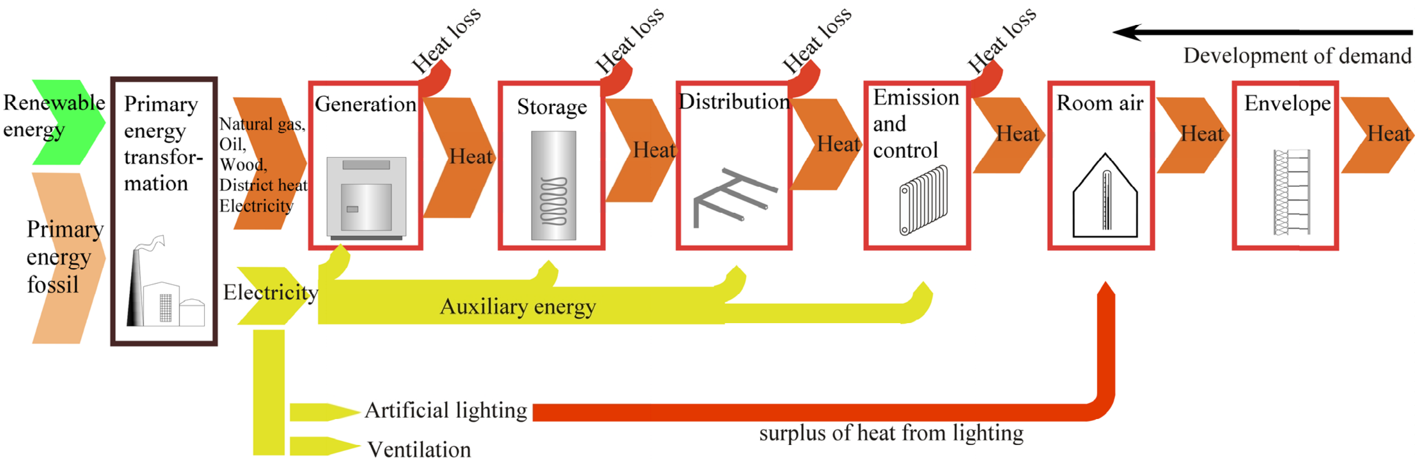

Figure 3. The modeling method, the energy chain from source to sink (see DIN 4701-10 2001, modified)

electricity demand for artificial lighting and for driving fans in the ventilation system is included. On the primary energy side, the inputs are differentiated between fossil and renewable sources.

The steady state calculation for this heating case is done in the direction of the development of demand, as indicated in Figure 3.

4 DESCRIPTION OF THE EXAMINED CASE

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. As stated above, all calculations have been performed under steady state conditions.

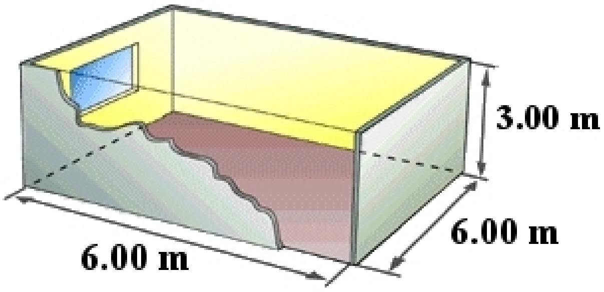

Figure 4. Examined room, from a typical multi-family house

Table 2. facts and values of the base case

Building type:	Residential multi-family house
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 in such a way that the building standards of a number of countries (e.g. 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 analyzed:

Table 3. 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) Balanced ventilation system with heat recovery $\eta_V = 0.8$

Some common boundary conditions have been defined for all cases. The impact of short wave solar radiation hitting building components and being transformed into heat has been neglected in the following considerations, as well as the effect of internal heat gains from occupants or equipment inside the room. Only the dependencies and implications from the building construction and service equipment are to be investigated.

Table 4. Common boundary conditions for the analyses

Indoor air temperature	20°C
Exterior air temperature	0°C
Solar radiation on window	neglected
Internal gains	neglected
Primary energy factor for electricity	3
Primary energy factor LNG	1.3

5 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. This is done based on a system design and the subsystems shown in Figure 3.

Results of the analysis of the base case described in Chapter 4 are shown in Figure 5 and Figure 6. These figures, which indicate where losses occur, are quantified by the sub-systems/components in Figure 6.

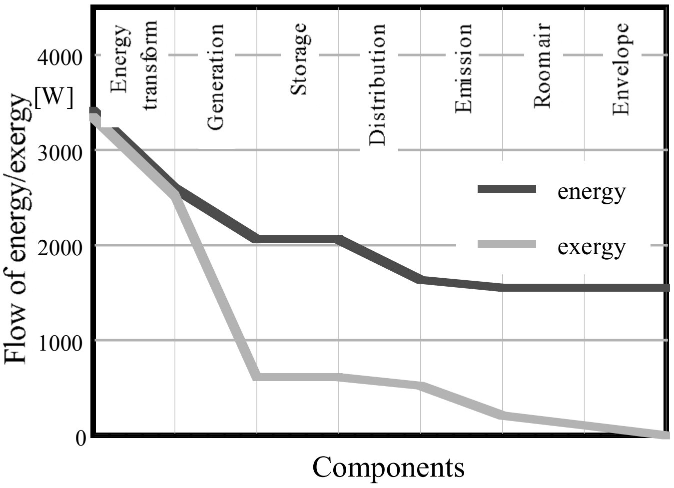

Figure 5. Absolute values of energy and exergy flows for the the base case

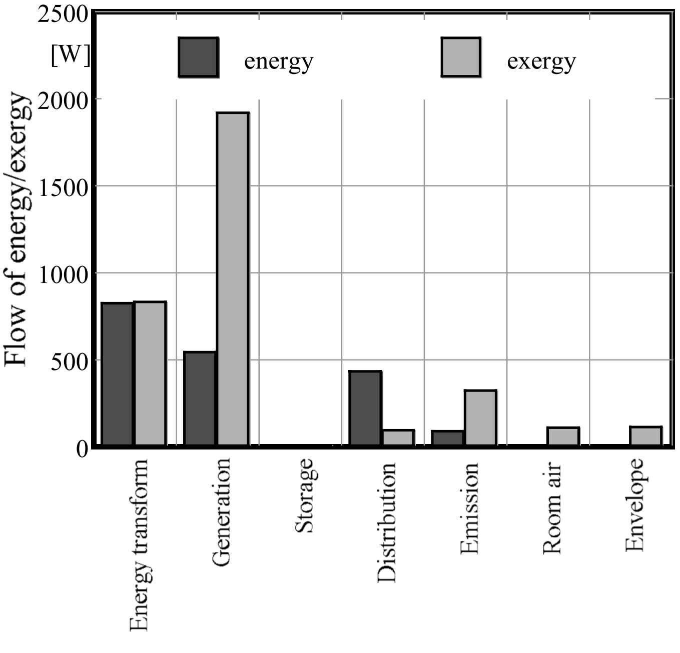

Figure 6. Relative energy loss and exergy consumption of components for the base case

In Figure 5, 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.

To achieve improvements in the system design and a reasonable optimization procedure, it is mandatory to know where losses and inefficiencies occur. Some losses are needed to make the system work. For example, for all heat transfer processes, exergy is consumed because of the needed temperature difference between one medium and the other.

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 (liquefied natural gas), 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 when extracting 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 C, 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 in the potential of the capability to do mechanical work. In the theory of thermodynamics, this is quantified by the carnot efficiency:

$$W_{\max} = Q \cdot \left(1 - \frac{T_0}{T_{source}}\right) \qquad (13)$$

As indicated by equation (13), the temperature levels of the in- and out-coming heat flows are important. They should be kept at a comparable level to prevent an increased exergy consumption or destruction.

5.1 *Impact of improvements in the building envelope versus improvements in the service equipment*

Four numerical results of exergy consumption during the whole process of space heating, from the power plant to the building envelope in steady state, are presented in Figure 7 and Figure 8.

Starting with the base case described above, improvements on the design have been made and calculated. As already shown in Figure 6, exergy consumption within the heat generation, i.e. the boiler, 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 $\eta_G = 0.8$ to 0.99, has been reached with improvement (1) (see Table 3). The results are shown by the solid gray line in the following figures. The decrease in exergy consumption is marginal.

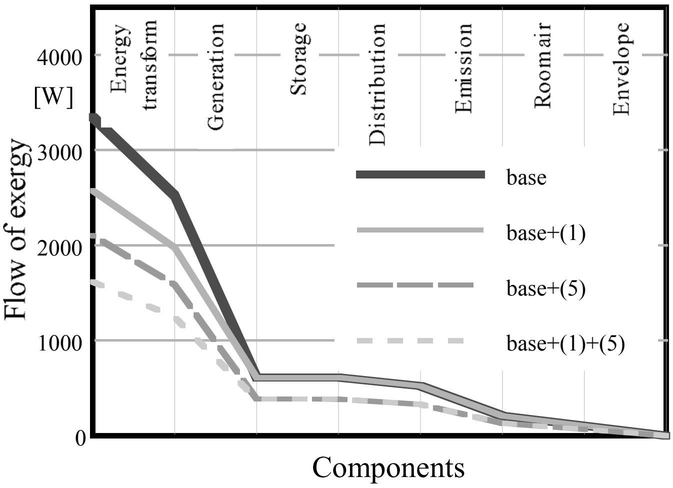

Figure 7. Comparison of exergy consumption for improvements on the building envelope or the equipment, as described in Table 3.

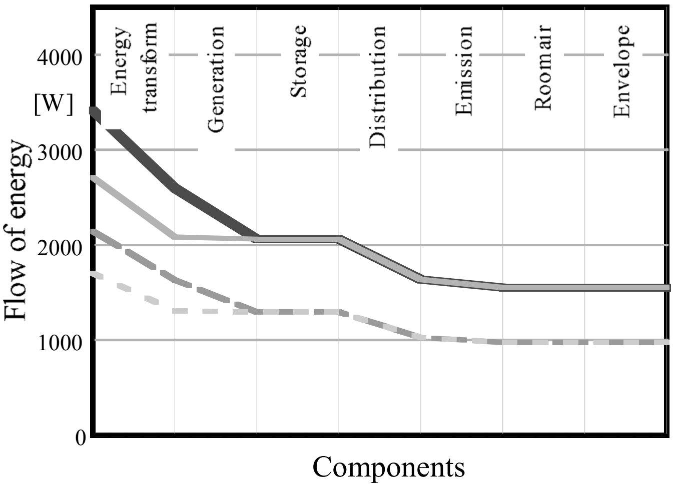

Figure 8. Comparison of energy utilization for improvements on the building envelope or the equipment. For legend, see Figure 7.

To increase the exergy output of the boiler, an increase of the outlet water temperature may 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 cannot 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 (from 0.4 to 0.2 W/m²K) and the windows (from 2.2 to 1.2 W/m²K) have been improved. The heating exergy load, which is the exergy output from the room air and the exergy input to the building envelope is 105.98 W for the base case, and 66.56 W for the improved construction. It represents only 4.2 % of the chemical exergy input to the boiler. This reduction measure could be regarded as marginal, or of 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 of the building enveope's thermal insulation.

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

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. 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 9.

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 (see also Chapter 5.3). 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 10.

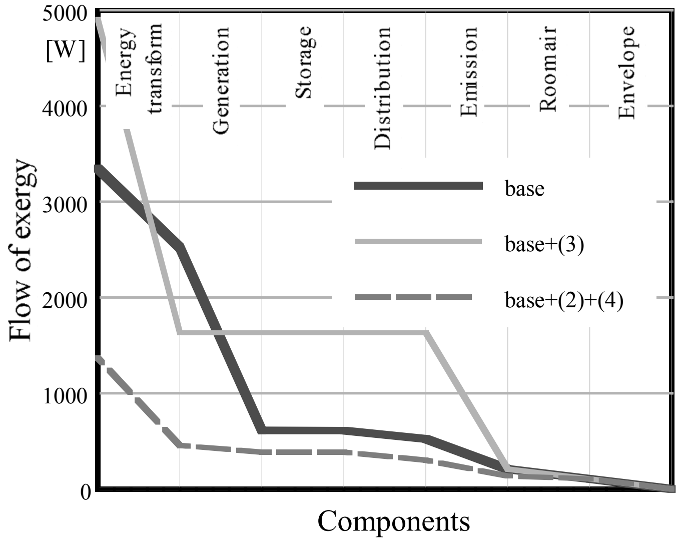

Figure 9. Comparison of exergy consumption for different system configurations with regard to overall system design flexibility. Cases described in Table 3.

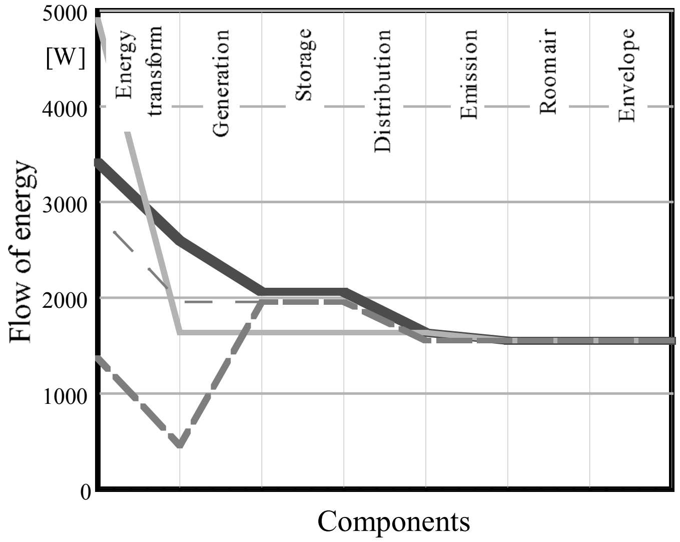

Figure 10. Comparison of energy utilization for different system configurations with regard to overall system design flexibility. For legend, see Figure 9. Thin line indicates the energy flow including extracted heat from the surroundings.

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 could only be fed with high exergetic sources, and the system design is locked, not flexible. The implementation of renewable sources, with their great potential for a reduction in CO_2, could not be realized.

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 (see Table 4).

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 could be fed, like the low temperature floor heating system depicted in Figure 9. Discussing the issue of the integration of renewable energy sources on a larger scale and in buildings opens new possibilities by utilizing the potential of exergitically optimized service designs.

5.3 *Integration of heat pumps into the building design*

Two cases where a heat pump has been integrated into the heating system design have been investigated and compared to the base case. In the first system solution, an electrically driven ground source heat pump is the heat generator and high temperature radiators are the heat emission system. The radiators regarded are designed with a supply temperature of 70°C. Because of this unfortunately high temperature level, the heat pump works with a moderate COP of only 2.5 (base+(2), solid gray line). A better system design uses the combination of a heat pump with a low temperature emission system, as has been done in the second case. The same ground source heat pump has been coupled with a low temperature floor heating system with a supply temperature of 35°C and has, therefore, an increased COP of 4.3 (base+(2)+(4); dashed gray line). The room, and the exergy and energy load of the system is, in all cases, identical.

Both cases with an integrated heat pump have lower exergy and energy demands. An optimized design shows a much better performance than the other one.

As for the results of the energy analysis, the apparent “energy production” of the heat pump is remarkable (see Figure 10). According to the first law of thermodynamics, energy production is impossible. The explanation here is found in the extraction of heat from the surroundings (indicated by the thin lines).

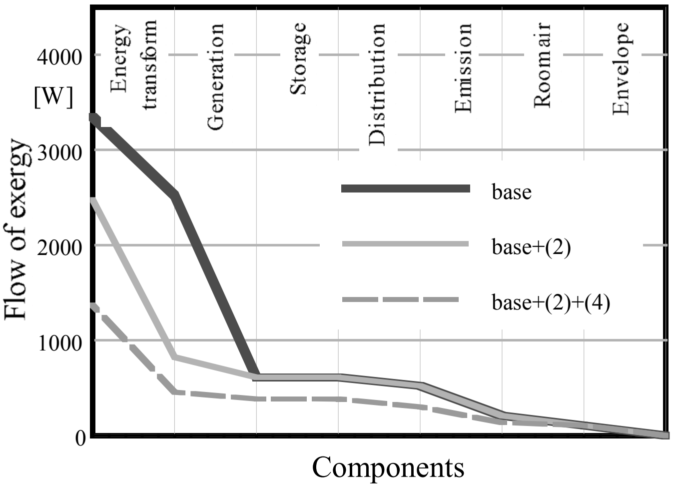

Figure 11. Comparison of exergy consumption for different system configurations with heat pumps integrated. Cases described in Table 3.

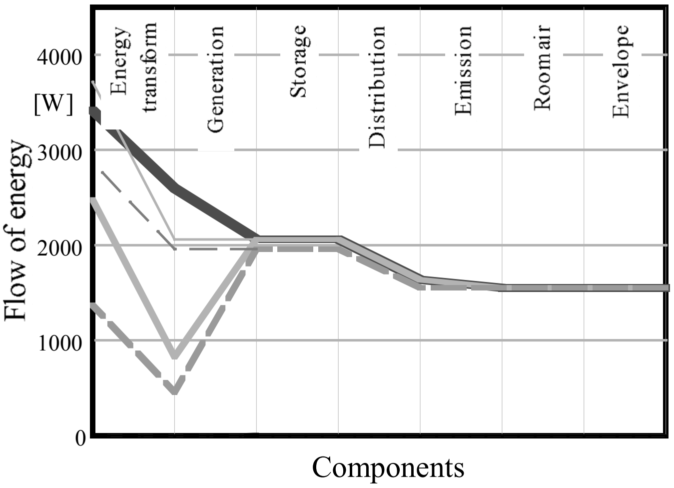

Figure 12. Comparison of energy utilization for different system configurations with heat pumps integrated. For legend, see Figure 11. Thin lines indicate the energy flow including extracted heat from the surroundings.

The difference between the thick and thin line is the amount of renewable environmental heat included into the process. The required input of fossil primary energy is shown on the left-hand side of the diagram, where the thick lines hit the y-axis.

The differences in the two heat pump designs become obvious in an exergy analysis (Figure 11). The possible saving potential in non-consumed exergy during the entire process is shown there. In the energy analysis (Figure 12), this difference is not definitely shown. Yet, the effect of the increased COP on the overall energy utilization is clear.

In the following figure, the energy and exergy losses by components are shown for the optimized heat pump design. Compare this Figure 13 with Figure 6, the same diagram which represents just for the base case.

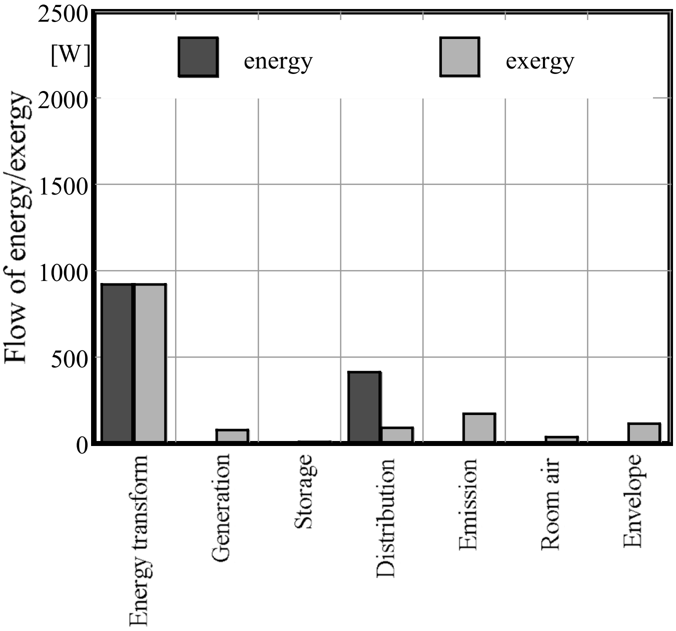

Figure 13. Relative energy loss and exergy consumption by components for the base case including improvements (2)+(4), heat pump and low temperature floor heating (compare with Figure 6).

In both cases, the biggest losses in energy take place in the primary energy transformation. Although these losses occur even before the flow of energy enters the building, they are caused by the building operation. This represents a great potential for the needed increase in energy utilization efficiency. Sources with a primary energy factor lower than electricity (here with 3.0) should be chosen.

For the exergy analysis, the picture changes. In the classical system design, shown by Figure 6, the highest exergy losses occur during generation. In the heat pump design, this happens in the primary energy transformation sub-system. All other components show approximately the same performance.

5.4 *Integration of balanced ventilation systems*

Another way to improve the system design is through the integration of balanced ventilation systems with heat recovery. A ventilation system with a thermal heat exchanger efficiency of 0.8 has been assumed for this case and compared to the base case.

Although ventilation systems for residential buildings are quite unusual in a number of European countries, they are quite common in Scandinavia, where mainly exhaust air systems with and without heat recovery are used. However, in commercial buildings it is different. In this case, mechanical ventilation systems are widely and commonly used.

The impact on the results of the analysis is similar to the one resulting from an increased building envelope standard (compare also with Figure 7 and Figure 8).

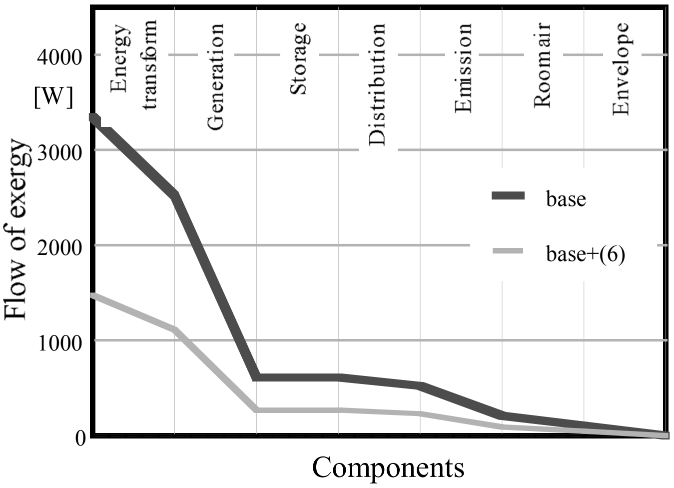

Figure 14. Comparison of exergy consumption for different system configurations including balanced mechanical ventilation with integrated heat recovery. Cases described in Table 3.

As shown by the results of the exergy analysis, there is a drastic reduction in the exergy load of the room to be satisfied by the service equipment, from 105.98 W without mechanical ventilation to 46.74 W with mechanical ventilation. This is also shown by the results of the energy analysis presented in the following figure:

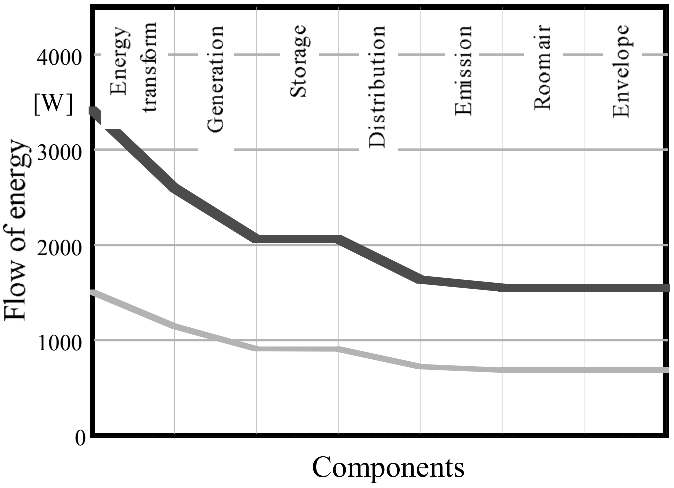

Figure 15. Comparison of energy utilization for different system configurations including balanced mechanical ventilation with integrated heat recovery. For legend, see Figure 14.

6 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 2002). 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.

A number of general conclusions can be drawn from all of the cases analyzed. 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, as shown in Chapter 5.1. 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. In the second step, the building service appliances should be taken into consideration. Their use should be minimized as much as possible and only when all passive means are no longer sufficient. This is also important to keep in mind. Designing rationally well-insulated windows and other building envelope systems is equivalent to installing a mechanical boiler free of charge, which implies that solar exergy is consumed rationally rather than spontaneously. This equivalence to a mechanical boiler does even more, namely, to provide a well-conditioned, thermally comfortably built environment. The mechanical boiler alone is not able to do this. Problems related with utilizing 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 optimization. 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 utilizing a number of different energy sources (see Chapter 5.2). 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 (see Chapter 5.3).

- Other system reducing exergy loads in simple components are also beneficial. The integration of a mechanical ventilation system, preferably a balanced ventilation system with heat recovery in the air handling unit, reduces the exergy consumption, equal to measures like a higher insulation standard. These impacts can be shown by the energy approach, too.

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 (Saito & Shukuya 2001 and Isawa, Komizo & Shukuya 2002)).

Furthermore, one should not only think about what is consumed in energy utilization 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 neighbors' 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.

7 ACKNOWLEGEMENT

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8 SYMBOLS

Symbol	**Quantity**	**unit**
η	Efficiency	-
A	Area	m^2
c	Specific heat	kJ/kgK
COP	Coefficient of performance	-
E	Flow of energy	W
Ex	Flow of exergy	W
h_c	Convective heat transfer coef.	W/m^2K
h_r	Radiative heat transfer coefficient	W/m^2K
m	Mass flow	kg/s
n	Air changes per hour (ach)	$1/h$
Q	Flow of heat	W
S	Flow of entropy	W/K
T_0	Ambient/reference temperature	K
T_{ra}	Room air temperature	K
T_{rm}	Radiative mean temperature	K
T_S	Surface temperature	K
U	U-value	W/m^2K
W	Mechanical work flow	W

REFERENCES

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

Annex 37. 2002. *International Energy Agency – Low Exergy heating and Cooling of Buildings – Annex 37,* Web Homepage, http://www.vtt.fi/rte/projects/annex37/Index.htm.

DIN 4701-10. 2001. *Energy Efficiency of Heating and Ventilation Systems in Buildings – Part 10: Heating, Domestic hot Water, Ventilation.* German national standard. Berlin: Deutsches Institut für Normung e.V.

ECBCS 2002. *Energy Conservation in Buildings and Community Service Programme*. International Energy Agency. Web Homepage: http://www.ecbcs.org

Isawa, K; Komizo, T. & Shukuya, M. 2002. *Low Exergy Systemswill provide us with the Lowest Human-Body Exergy Consumption and Thermal Comfort.* LowEx News, publication of IEA Annex 37, No. 5: pp 5-6.

Maas, A; Hauser, G. & Höttges K. 2002. *Die Energieeinsparverordnung.* Bauphysik, 24, No. 1: pp. 26-38

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

Saito, M. & Shukuya, M. 2001. *The Human Body consumes Exergy for Thermal Comfort.* LowEx News, publication of IEA Annex 37, No. 2: pp 6-7.

Schmidt, D. 2001. *Models for Coupled Heat and Mass Transfer Processes in Buildings – Applications to Achieve Low Exergy Room Conditioning*. Tekn. Lic. Thesis. ISRN KTH-BYT/R-01/185-SE, KTH, Stockholm ,Sweden.

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.