Designing Low-"Exergy" Buildings

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SUMMARY:
There is an obvious and indisputable need for an increase in the efficiency of energy utilisation in buildings. Heating, cooling and lighting appliances in buildings account for more than one third of the world's primary energy demand. In turn, building stock is a major contributor to energy-related environmental problems. There are great potentials, which can be obtained through a more efficient use of energy in buildings.

Calculations in energy simulations and analyses of energy flows in buildings have commonly been based on the energy conservation principle, the first law of thermodynamics. A more holistic view of these calculations is attained by estimating the primary energy demand for all processes. As shown in the paper by way of analyses and examples, the energy conservation concept alone is not adequate to gain a full understanding of all the important aspects of energy utilisation processes. Thus, a method for exergy analyses based on a combination of the first and second law of thermodynamics is presented for a better understanding and design of energy flows in buildings. This concept of exergy is described. Although the basic principles had been stated as early as in the nineteenth century, it wasn't until the mid nineteen fifties that the term exergy was introduced.

A number of analyses have been performed using a pre-design tool for buildings. Using a typical case, the advantages of the analyses and the difference between energy and exergy analyses are demonstrated. In conclusion, some design guidelines deriving from all of the analyses are given. A number of so-called low-exergy demonstration buildings, both new constructions and retrofitted buildings, are presented. In order to achieve an exergy-optimised building design, loads on the building services system have to be reduced as much as possible. Generally, in the retrofit or new design of buildings, first priority should be given to creating an energy-efficient building shell. Then, improvements to the building service system, which should be next in priority, will be much more efficient.

The presented research work is related to the international cooperation work lately concluded under IEA ECBCS Annex 37 "Low-Exergy Systems for Heating and Cooling of Buildings" and to the established Network for "Low-Exergy Systems in Buildings - LowExNet". Further, an overview of ongoing German activities in the exergy collaboration project, involving industry partners and research institutions, is presented.

1. Introduction

The growing concern of environmental problems (such as global warming), which have been linked to the extended use of energy, has increased both the importance of all kinds of so-called "energy-saving measures" and the necessity for increased efficiency in all forms of energy utilisation. Numerous efforts have been undertaken to make buildings (and associated processes, such as domestic hot water production) more efficient and to reduce the use of fossil energy sources in the built environment. One aim was common to all these efforts, namely saving natural resources and fossil energy sources with the key of creating energy-conscious and comfortably built environments.

Today, all estimations of the energy use in buildings, i.e. calculations of heating or cooling loads of rooms and buildings, as well as temperature calculations, are based on so-called energy balances. This is in reference to the first law of thermodynamics, which states that energy is conserved in every device or process and that it can neither be destroyed nor consumed. To enhance the understanding of the nature of energy flows in systems, we can use the so-called principle of entropy generation or the second law of thermodynamics, in addition to the energy conservation principle. In every process where energy or matter is dispersed, entropy is inevitably generated. In combining these two important principles, the concept of exergy should be used. The exergy concept can explicitly show what is consumed in energy utilisation processes. In particular, the method of exergy analyses is found to provide the most correct and insightful assessment of the thermodynamic features of any process and to offer a clear, quantitative indication of both the irreversibilities and the degree of matching between the resources used and the end-use energy flows (Sciubba and Ulgiati 2005). The strongest point of the concept lies in the possibility of finding both the right energy source of the quality required for a certain use and the source for an increase in so-called energy efficiency.

2. Exergy analyses

Energy resources are used for nearly all kinds of activities, such as providing thermal comfort, transportation and industrial production. Some of these are wasted due to a variety of inefficiencies and poor practices. It is also of economic worth to be concerned about better energy utilisation. Improving the efficiency of energy utilisation is not purely a technical matter, as there are other barriers and constraints imposed by economics, politics, etc... . Nonetheless, there is an important technical view to this problem which is highlighted in this paper. The concept and tool of exergy analysis in buildings proposed here can be used effectively to develop and evaluate energy-use strategies. The use of the proposed concept will enhance the development and optimisation of energy systems in buildings.

In many cases, some improvements in energy utilisation can be achieved without any detailed or elaborate analysis, simply through common sense, good housekeeping, and leak-plugging practices. But, as system configurations become more complex and good engineering methods are needed, it becomes apparent that a more in-depth analysis is required, which goes far beyond simple energy bookkeeping (Moran 1989).

Calculations for all kinds of energy utilisation, including heating/cooling loads of rooms in buildings and temperature distributions, are commonly based on energy balances. This is done in reference to the first law of thermodynamics, which states that energy is conserved in every device and process and that energy can neither be destroyed nor consumed (Moran and Shapiro 1998). Although the first law of thermodynamics is one of the most widely used and best understood concepts in science, terms like “energy savings” or “energy consumption” are widely used in all energy-related discussions, even by professionals.

When we use such terms, we implicitly refer to “energy” as the energy available from fossil fuels or condensed uranium. These sources of energy are in fact dissipated in everyday life and all discussions on “energy savings” refer to this fact and experience. Over the last few decades, various “energy saving” measures have been conceived, developed and implemented, to a large extent in reference to building envelope systems and their associated indoor-environment control systems such as heating, cooling and lighting. A number of national policies, regulations, and commonly used analysis and optimisation procedures have been influenced by these ideas, and standards have been formulated.

To obtain a better understanding of the energy-flow processes, in addition to the first law of thermodynamics, the second law of thermodynamics, in which the entropy concept plays the key role, can be applied. It is stated that in every process where energy or matter is dispersed, entropy is inevitably generated (see also Gertis 1995 and Baehr 1980). All real and non-ideal processes are irreversible and there is an increase in the irreversibility of a closed system (Moran and Shapiro 1998). Also, it becomes obvious from the second law that something gets lost in energy-related processes. The fact that something can be destroyed is useful to know, but it should not be applied to the energy concept (Moran 1989). This “something”, which originates from the combination of the first and second law of thermodynamics, is named “exergy” or, in the USA, “availability”. This concept indicates to which extent a certain amount of energy is available to do mechanical work. It can explicitly show what is consumed, and it allows to quantify the potential of energy available to cause changes or to do work. Exergy can also be regarded as the valuable part of energy.

For the following study of building environmental control systems, such as heating or cooling, steady-state conditions are assumed. Energy and matter are supplied to 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 discharged to the surroundings, i.e. to 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 by the four fundamental steps summarised in Table 1. Heating and cooling systems are no exception in this case (Shukuya 1998; Saito and Shukuya 2001).

Table 1. The four steps of the exergy-entropy process (Shukuya 1998).

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

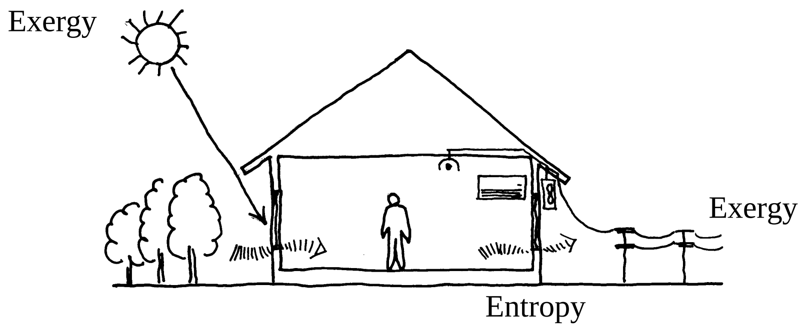

Figure 1: The exergy-entropy process on a building (Shukuya and Hammache 2002).

By applying exergy analysis to buildings it can be shown that the greatest fraction of the total supplied exergy for heating in buildings is consumed when heat is generated from other sources, e.g. fossil fuels like natural gas. Parts of these losses occur during energy transformation, extraction, and transformation in power stations or in heat generation, e.g. in a boiler. Only a small fraction of the exergy consumption happens within the buildings (Schmidt and Shukuya 2003).

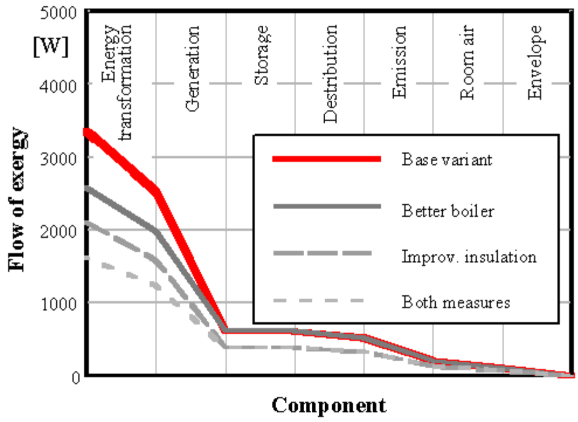

Figure 2: Exergy use in a building for different system alternatives. In all cases, the biggest losses occur within the boiler, whereas heat distribution and emission are of minor importance. The smallest fraction is used for heating the room space, but the entire exergy use in a building is influenced by that value (Johannesson 2004 and Schmidt 2004a).

This means that our known energy systems consume more exergy than needed for a certain purpose. It was clearly shown that there is a larger potential for exergy-saving measures than for energy “savings” (Johannesson 2004).

Since a great fraction of the supplied exergy is consumed within the heat generator, namely by the boiler in this case, one would suggest the use of a better or perfect boiler. This is done for the case boiler. Evidently, even with the best boiler possible, with an energy efficiency of 100 % (see Figure 2, dark thin solid line), the exergy consumption would still be large. In contrast, the energy analysis in Figure 3 presents some improvement (half dark dotted line) for the case of using more insulation, but the exergy analysis shows that this measure really helps to reduce the exergy consumption of the entire system, even if the improvement is hard to visualise (difference between dark solid and half dark dotted line) in Figure 2 (Schmidt 2004a; Schmidt and Shukuya 2003).

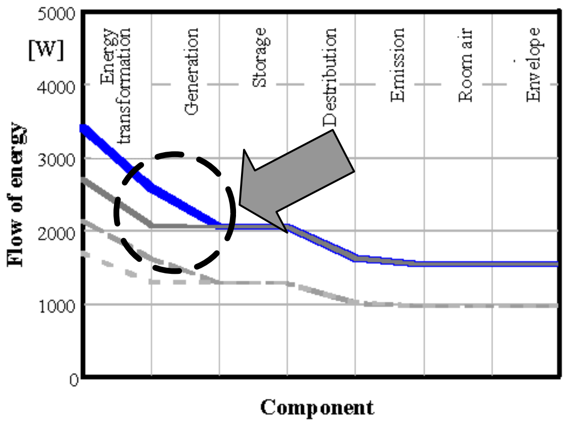

Figure 3: Energy use for the same cases and legend shown in Figure 2 (Schmidt 2004a).

To use the supplied exergy most efficiently, we have to design heating systems that will keep the supply temperatures as low as possible. In most cases, low exergy consumption within a component coincides with a low inlet temperature; that means that the energy is supplied at a low temperature level. There are examples of such systems already available on the market, such as thermally activated building constructions. There are some types of floor-heating systems or waterborne systems where heating or cooling pipes are inserted into the concrete slab construction. Another one is the airborne hollow-core deck system, where tempered air first circulates inside the construction, thereby heating or cooling the rooms, to be subsequently released as fresh supply air to the rooms (Johannesson 2004). There are many more system alternatives, which are showcased in the LowEx Guidebook (Ala-Juusela et al 2004 and Annex 37 2004).

More detailed and extended exergy analyses of buildings can be found in (Schmidt and Shukuya 2003; Schmidt 2004a).

3. Examples of low-exergy buildings

Today, a number of so-called Low-Exergy Buildings are already existing. Careful planning (including coordinated building envelope and services, the use of passive effects to heat, cool or ventilate the buildings) in combination with the reduction of internal (e.g. by low-energy office equipment) and external loads (e.g. by efficient external sunshading), are characteristics of successful building concepts.

3.1 New demonstration buildings

Twenty-seven new constructions featuring different uses are showcased and described in detail in the final report, the LowEx Guidebook, of IEA Annex 37 (Ala-Juusela et al. 2004).

Figure 4: Left: A new office building in Germany (Hauser et al. 2005, Meyer 2001), equipped with thermally activated floor and ceiling systems and an ground-heat exchanger for cooling; right: residential buildings in the Netherlands, provided with wall and floor heating systems (Annex 37, 2004).

The case examples presented here or in the IEA Annex 37 report, respectively, reflect the wide variety of applications of LowEx systems. They also demonstrate the flexibility of the systems with regard to the exergy source. The heating or cooling systems of these buildings use exergy from the sun, the ground, the district heating network as well as the electricity or gas networks. Together with the findings from literature studies and occupant surveys, the case examples give strong evidence that in addition to the desired heating or cooling effect, LowEx systems can provide occupants with a comfortable, clean and healthy indoor environment.

3.2 Retrofitted demonstration buildings

The existing building stock is very important to focus on, but the renewal of the building stock is actually very slow. If we neglect the possibilities of retrofitting existing buildings with low-exergy systems, the total effect will not be as substantial as we hope for. There are some examples of LowEx systems to be found in existing buildings; also, there are a few examples of historical buildings with a cultural heritage, which pose an even greater challenge.

Figure 5: A retrofitted church building in Slovenia, equipped with a wall tempering system, and a wooden residential building in Norway, equipped with advanced waterborne floor, wall and ceiling heating systems (Annex 37 2004).

Some special issues must be taken into consideration when implementing LowEx systems in existing buildings. Actually, the age of the building is not that important when considering the possibilities of applying LowEx systems. Rather, important aspects include the building's degree of protection, the building type, the scale of renovation, replacement of installations and the type of LowEx system to be applied.

When we are talking about retrofits, we need to keep in mind that there are some technical limitations, even though low-temperature heating systems are functional systems with lots of advantages. For instance, the walls of old houses are not always that good, and one can encounter really poor U-values, i.e. bad insulation standards. If this is the case, floor heating is not efficient enough to meet the heating demand (Schmidt and Ala-Juusela 2004).

4. Ongoing and further activities

A number of LowEx activities are currently going on, both on an international and a national level.

4.1 International collaboration – the network LowExNet

Since the IEA Annex 37 working group experts considered it very important to continue working with the topics described above, the International Society for Low Exergy Systems in Buildings was formed to further promote the use of the exergy concept and to pursue more sustainable buildings.

In order to reach these objectives, the LowExNet organises activities, such as workshops, seminars and presentations, in combination with other international events, such as conferences in the field of energy use in buildings and sustainable buildings.

At present, members from 13 countries from all over the world are promoting the low exergy approach in building. Announcements of all activities, comprehensive material, the LowEx Guidebook and all other Annex 37 deliverables are also available via the internet homepage of the LowExNet (**www.lowex.net**).

4.2 German national LowEx activities

Based on research projects conducted earlier in the field of thermally activated building constructions with so-called capillary tubes and regarding the use and performance of phase change materials (PCM) in buildings, a national research network project has been established with the objective of further investigating low-exergy strategies and systems in buildings. New products, systems and strategies for the use of low-valued and renewable energy sources in the built environment are developed by research institutes in close collaboration with industries from different fields (HVAC components and systems design, building material, chemistry, etc.).

5. 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 using these measures in building stock, as indicated by examples provided throughout this paper. Approximately one third of primary energy is consumed in non-industrial buildings such as dwellings, offices, hospitals, and schools, where it is utilised for space heating and cooling, lighting, and the operation of appliances (ECBCS 2002). New national codes, restricting energy use in buildings (based on the first law of thermodynamics) only apply to the use of primary energy. The German Energy Conservation Regulation EnEV is an example of this approach. As set out in this paper, the energy conservation concept alone is not enough to gain full understanding of all the important aspects of energy utilisation processes (Weber 2003). From this aspect, the method of exergy analyses facilitates clearer understanding and improved design of energy flows in buildings. The proposed method allows for the possibility of choosing energy sources according to the quality needed for a certain application. One of these options is energy cascading, where the flow of energy is used several times, despite a quality decrease in each step.

From this general statement, a number of conclusions can be drawn from the cases analysed. The following design guidelines for building designers can be extracted from the recommendations:

- Reducing the loads on building service equipment is an efficient and mandatory step towards good, exergy-saving design, as shown by the analyses in Figure 2 and Figure 3. Utilising passive means - like good insulation standards, tight building envelopes and passive gains (solar or internal) – is an excellent starting point for optimised design. All measures offered by modern building physics in this field are highly efficient in this process and generally accepted. In a second step, building

services appliances should be taken into consideration. Use of these appliances should be kept to a minimum and be restricted to cases in which passive means are insufficient. This decision depends on the building owner's preferences and on the standards or limits considered acceptable for indoor environments.
Related problems (such as overheating or increased cooling needs due to excessive solar gains, for instance) must also be taken into account. Even in the case of cooling, which has not been especially addressed in this paper, the reduction of loads by e.g. efficient solar shadings is mandatory.

- Flexibility in system configurations is important for future “more sustainable” buildings. Exergy analysis can help in quantifying the degree of flexibility in a system design. Low exergy loads from the enclosed spaces and from 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, see (Schmidt 2004) for a more detailed analysis. Here, the possibility of integrating all kinds of renewable sources of heat and coolness should be kept in mind. 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 simple flat-plate collectors or solar walls, for instance. If these sources are efficiently used to cover the heating-energy demand of a building, the entire service system will run with decreased amounts of environmental loads, such as CO_2 emissions and other greenhouse gases.
  High exergy sources like electrical power should be left to special appliances that require a high exergy content, such as artificial lighting, computers and machines. These sources should not be used for heating purposes. Even though some advantages (like low installation costs for direct electrical heating) may seem beneficial, exergy analysis proves the opposite. High primary energy transformation factors in a lot of countries can explain the same fact, through an energy analysis. If high exergy sources are to be used nonetheless, efficient processes are needed, for example heating with heat pumps in combination with low-temperature emission systems (Schmidt 2004).

- Other systems that will reduce exergy loads in simple components are beneficial, too. The integration of a mechanical ventilation system (preferably a balanced ventilation system with heat recovery in the air-handling unit) will reduce the exergy consumption, equal to measures like those specified in higher insulation standards. Storing heat during summertime, and utilising these gains when they are needed in wintertime, might be another possibility. Most of these measures imply larger investment costs, hence they are not always applicable. Most of the effects due to these additional measures to increase energy efficiency can also be shown by the energy approach.

- It is already possible to build a “low-exergy house” using today’s technology, as the presented examples of demonstration building projects show. Careful planning and good design of all systems are mandatory in achieving this goal, since some of the methods implemented are not yet everyday building practice.

More emphasis should be placed on the importance of exergy and on preventing its destruction in the energy utilisation processes in our homes and working places. In the same sense, communities could limit the exergy consumption of buildings and specify requirements for low-exergy buildings, by analogy with limits for primary energy use that already exist. The proposed analysis method offers the background for doing this.

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