High performance buildings with optimized energy systems based on exergy principles

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Abstract. Optimising buildings and energy systems with a focus on mitigation of greenhouse gas emission is not an easy task: first, principles are necessary to be established and then the steps to be followed. Exergy efficiency can show the best issues: building envelope insulation and air tightening, low-valued energy sources, low-exergy heating and cooling systems, avoiding destructive exergy-processes like boilers burning fossil fuels, systems and grids for low-temperature heating and for high temperature cooling, renewable energy sources, daylight, and passive solar energy use supported by control strategies of building systems can contribute to a better future when considering global warming and comfort.

1. Introduction

The energy demand for heating and cooling in the building sector is responsible for more than one third of the final energy consumption in Europe and worldwide, energy commonly resulting from combustion processes using different fossil fuels. The resulting greenhouse gas (GHG) emissions are the core challenges in fighting climate change considering its large contribution from the built environment. Two issues exist: a more efficient use of energy and burning fewer fossil fuels. Increased efficiency is related to optimization and the concept of exergy can help a better understanding and evaluation of the processes and systems quality. An increased efficiency in energy use is possible when investigating the exergy flows in buildings. While energy is conserved – First Law of Thermodynamics – the exergy, as the entirely convertible energy into other types of energy, can be destroyed, i.e., converted in anergy, as shown in figure 1. The heat transferred through a wall separating the warm space from the cold exterior is the same on the inside face and the outside one, 1035 W. But the exergy entering the inside-warm face, 93,15 W is different from the exergy leaving the outside-cold face, 0 W, meaning that the entire exergy was destroyed during the heat transfer through the wall.

The destroyed exergy is:

\[ I = Q_{\text{wall}} \left( 1 - \frac{T_0}{T_1} \right) - Q_{\text{wall}} \left( 1 - \frac{T_0}{T_2} \right) = 1035 \left( 1 - \frac{273}{300} \right) - 1035 \left( 1 - \frac{273}{273} \right) = 93.15 \text{ W} \]  

Buildings destroy more input exergy than they lose and produce, (84....93% of exergy consumed by buildings are destroyed by irreversibility) [1].
Figure 1. The flow diagram for the energy (a) and for the exergy (b).

Minimizing the irreversible dissipation of low-value energy into the environment is possible if the heat transferred through the wall $Q_{\text{wall}}$ is reduced: insulating the wall not only the heat transferred is diminished but the temperature of the inside face of the wall will become higher. In figure 2 is presented an example where the design heat loss for the space is initially 8600 W for an outdoor design temperature of -21°C resulting in a heat loss per degree of 210 W/K in case of an indoor design temperature of 20°C. Considering an average internal heat gain $Q_g$ of 540 W the balance temperature will be diminished, about 2.5°C. Insulating the envelope with 10 cm of expanded polystyrene the balance temperature will be diminished with 5.3°C. In case of a better insulation, say 20 cm and having a better glazing almost a difference of 9°C between the indoor design temperature and the balance one will result. Lowering the balance temperature means shortening the time of the heating period and of course a reduced amount of energy supplied for the house heating.

Figure 2. Insulating the envelope, the balance temperature is becoming lower in case of the same internal heat gains.
But insulating the envelope results in a higher temperature on the inside surface of walls, i.e., from 12 to 18 or even 19°C, which has as an effect the decrease of the heat radiated by humans to these surfaces and finally the inside air temperature can be dropped 1…3°C.

The exergy factor \((1 - \frac{T_0}{T_1})\) resulting if the inside air temperature, \(T_1\) is diminished, caused by the insulation, will be affected 5 to 10% depending on the outside temperature, as shown in figure 3.

\[
\frac{1 - T_0}{T_1} = \eta_{ex} = \frac{E_{x,res}}{E_{x,in}}
\]

Exergy efficiency illustrates how far the efficiency of a conversion process is from its theoretical maximum.

An exergy-optimized building design must follow the steps:
1. Reduction of the energy use;
2. Temperature levels harmonization;
3. Intelligent storage of exergy;
4. Efficient use of high-quality sources;
5. Avoid destructive exergy-processes;
6. Avoid long components chains.

2. Energy versus exergy efficiency of systems and equipment

A substantial decrease of CO₂ emissions for the building stock can be realized through a better and exergy optimized building design. Additionally, enhanced heating and cooling systems lead to a lower exergy demand of buildings. Figure 4 illustrates the energy efficiency together with the exergy efficiency in case of four usual equipment: the energy efficiency for liquid fuel-based boilers and cogeneration systems are quite similar, less than 100% as it is in case of electrical boilers, in which nearly all electrical energy is converted into heat, while heat pumps can reach values over 300%. On the other hand the corresponding exergy efficiency do not exceed 4 to 5 per cent in case of boilers, fossil fuel based or electrical; these low values are due to the large temperature difference between the flame (more than 1000°C) and the heated water (about 60°C) in case of fossil fuel boilers; the electrical boiler is transforming the extremely high-quality electrical energy into a low-quality thermal energy aiming to cover the gap between the inside temperature (20°C) and that of the outside air (5°C or less).
The exergy efficiency of a heat pump is significantly greater than that of an electric heater because of the fact it transfers the energy from the environment to the interior space by means of a smaller amount of electrical energy, resulting in a lower cost. Heat pumps can use the low-valued energy delivered by sustainable energy sources (from the environment) to supply the heating energy necessary for the comfort inside buildings. Saving energy is in fact an exergy saving. The focus in case of heat pump systems design for individual buildings is to adjust its capacity to the heating load of the building including the DHW provision.

Additionally, heat pumps can operate in a reversible mode, cooling for comfort in the interior space, working as low-temperature heating and high temperature cooling systems.

Heat pumps and thermal collectors as decentralized supply technologies together with centralized options like thermal grids at different temperature levels can be future issues for communities. Increasing the exergy efficiency because of the temperature lowering of supply and/or return district heating network is a low-exergy approach leading to energy use reduction especially from fossil fuels.

Low-valued local energy sources and renewable ones are a flexible alternative able to meet different demands. Low-temperature heat from geothermal sources supplying communities can be a possible low-exergy approach to be solved at a local level.

3. **Envelope insulation or renewable energy sources use**

Minimizing GHG emissions being directly associated with the energy performance of the building and with the use of renewable energy sources a question arises: what the contribution of each of the two components is.

An exergy analysis can show that a house with 20 to 30 cm thick insulated walls heated with a heat pump having a coefficient of performance COP = 3…4, supplying a low temperature radiant system will have about the same energy use as that required by a passive house, as shown in figure 5. The development of low temperature heating and high temperature cooling systems is a prerequisite for the usage of alternative energy sources. Low thermal losses of buildings with high standards having a low energy demand can benefit the renewable energy with a better exergy efficiency as that specific for traditional thermal systems. Old district heating systems can be improved in terms of exergy efficiency if they are transformed in ultra-low temperature ones being assisted by local electric boosters.
Figure 5. A heat pump supplying a 20…30 cm insulated house needs almost the same energy for heating as a passive house.

4. Low temperature heating and high temperature cooling systems
A wide variety of possibilities exists for low exergy heating and cooling systems, but heat sources of lower temperature for heating require a thermally well-insulated envelope making use of building materials with an appropriate heat capacity. For the cooling season a combination of night ventilation with shading devices for windows and a mitigation of internal heat gains added to previous mentioned insulation materials for walls having a corresponding heat capacity represent the prerequisite condition for high temperature cooling systems. The exergy factor (efficiency) for an isothermal heating process lies between 1.4 and 22 per cent, but is only about half if the heat carrier does not remain at a constant temperature, as can be seen in figure 6 a) and b). The same for a cooling process, figure 7 a) and b).

Figure 6. Exergy efficiency as a function of the heat carrier temperature for isothermal processes (a) and for non-isothermal ones, (b) in case of heating.

Buildings having a low energy demand for space heating / cooling require increased demand for domestic hot water, DHW. It must be noticed that the exergy factor for DHW is about twice as high as that of space heating systems, i.e., 13%.

Buildings with systems working with low-level temperatures have advantages:
- Integration of renewable heat sources is much easier;
- Pumping costs can be reduced as a decreased mass flow in the network, for a constant power input. Additionally, transport lines having smaller dimensions will result in a lower investment cost.
- Lower temperature results in reduced heat losses to the surroundings.
Figure 7. Exergy efficiency as a function of the heat carrier temperature for isothermal processes (a) and for non-isothermal ones, (b) in case of cooling.

5. Conclusions

The optimization process as a combination of energy efficiency measures and renewable energy use is aimed to lead to the nearly-zero energy target, i.e., a reduction of approx. 90% of CO₂ emissions, considering the cost-effectiveness rather than cost-optimality. The overall exergy efficiency based on the analysis of every component losses is the way to improve the performance of the system leading to a progressive mitigation of GHG emission. The exergy concept used when developing a sustainable community offers a holistic understanding of the optimization process resulting from successive improvements. An exergy efficient building supply depends primarily on low exergy sources to be exploited. First-of-all, combustion processes should be avoided in an exergy efficient energy system based on low temperature heat. Low exergy sources, like solar thermal heat, geothermal-heat, or process waste heat (wastewater or exhaust ventilation air) should be used for space heating and cooling applications in buildings via heat recovery systems. Making use of more effective low exergy sources surface heating and cooling systems operate at lower temperature levels than conventional units like radiators or fan coils. Low exergy emission systems being more flexible, as they can be used for higher supply and return sources or can be coupled with low exergy systems like ground source heat pumps must be integrated in building for a better efficiency. Electricity required by pumps and fans being a high-exergy resource can be minimized by heat recovery systems connected to highly efficient energy systems, such as heat pumps. Chances offered by the renewable electricity production, PV or wind, [3] must be considered too as a challenge resulted from its fluctuating supply. The high potential of buildings to lessen the input exergy destroyed by irreversibility (84 to 93% of the exergy consumed) can be exploited through low-exergy heat-sources like the geothermal ones. Lowering the temperature of the heating agent will improve the exergy efficiency of the system.

A reduced energy demand of the building resulting from a good envelope insulation and an improved air tightness, daylight, and passive solar energy use supported by control strategies of building systems are important factors to minimize exergy losses.

An improved thermal comfort and indoor air quality together with a reduced energy consumption are feasible when applying low-exergy systems.

References

[1] LOWeX communities - optimised performance of energy supply systems with exergy principles. In EBS News Issue 69, Pag 83

[2] Dincer I and Yunus A. 2001 Energy, Entropy and Exergy Concepts and Their Roles in Thermal Engineering in Entropy, 3, 116-149

[3] Dragomir G, Șerban A, Năstase G and Brezeanu A I 2016 Wind energy in Romania: A review from 2009 to 2016, In Renew. Sustain. Energy Rev., vol. 64, pp. 129–143, ISSN: 1364-0321