Exergy Analysis in Buildings

A complementary approach to energy analysis
Exergy Analysis in Buildings
A complementary approach to energy analysis

Marco Molinari

Licenciate thesis
KTH-Stockholm, Sweden
November 2009

KTH The Royal Institute of Technology
School of Architecture and the Built Environment
Division of Building Technology
Act practically, think theoretically, live idealistic
Abstract

Though mandatory to be pursued, improved energy efficiency is not the only target to reach. The quality of energy has to be assessed as well. Most of the overall energy use in residential building is for low temperature heat, i.e. temperatures relatively close to the outdoor conditions. From a thermodynamic point of view, this is a degraded form of energy with low potential to be converted into work. On the other hand energy demand is mostly met with high quality energy, such as electricity and natural gas. There is a mismatch between supply and demand, which is not clearly shown by the sole energy analysis. Target of this thesis is to analyze the energy use in buildings from the point of view of its quality, to provide effective theoretical and calculation tools to investigate this mismatch, to assess its magnitude and to propose improvements aiming at a more rational use of the energy. The idea behind the quality is clarified with the concept of exergy.

The potential for improvement in space heating is shown. In no heating system the overall exergy efficiency is above 20%, with fossil fuels. Using direct electricity heating results in exergy efficiency below 7%. Most of the household appliances processes have low-exergy factors but still are supplied with electricity. This results in poor exergy efficiencies and large exergy losses.

Systems are poorly performing because little consideration is explicitly given to energy quality. Policies to lower the energy demand, though vital as first step towards an improved use of energy, should not neglect the exergy content.

The problem is then shifted to find suitable supplies. Electricity can be exploited with low exergy losses with high-COP heat pumps. Use of fossil fuels for heating purposes should be avoided. District heating from cogeneration and geothermal proves to be a suitable solution at the building level. The issues connected to its exploitation forces to shift the boundary layers of the analysis from the building level to the community level. A rational use of energy should address the community level. The system boundaries have to be enlarged to a dimension where both the energy conversion and use take place with reduced energy transportation losses. This is a cost-effective way to avoid the waste of the exergy potential of the sources with exergy cascade and to make it possible the integration of with renewable sources. Exergy efficiency of the buildings is a prerequisite for a better of energy in this field.

Keywords

Exergy; Energy; Building systems performance; Built environment.
Aknowledgements

This thesis is the result of my work at the Division of Building Technology at KTH – The Royal Institute of Technology in the past two years. Two years full of experiences and people. It would be too demanding to remember all the persons that directly or indirectly took part in this work, from a professional and –more important- personal point of view. Also, it is reductive to summarize in one name what persons signify for us.

In this context I would like to acknowledge the financial support of the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (FORMAS) and of the European Science Foundation COST C24.

I would like to express my gratitude to Prof. Jóhannesson for this chance and, moreover, for the witty and inspiring night talks. My thankfulness is also for Dr. Schmidt, Dietrich, Prof. Björk, Prof. Zecchin and Prof. de Carli.

A special thought is for my family, always supporting me with sense of humor.

I would like also to remember here my friends, the evergreen ones in Venice, the ones that made colorful the life in Stockholm and the ones from those two wonderful years in Kassel who are now quite everywhere. They all, though physically distant sometimes, are always close. To this people I dedicate this thesis, because, directly or indirectly, they are all here.
List of enclosed papers


II Molinari M., Exergy efficient space heating systems: analysis of different solutions. To be submitted.


# Table of contents

Abstract ........................................................................................................ i

Keywords ....................................................................................................... i

Acknowledgements ....................................................................................... iii

List of enclosed papers ................................................................................ iv

Table of contents ........................................................................................ vi

1. Introduction .............................................................................................. 1
   World energy use ......................................................................................... 1
   Buildings energy use .................................................................................. 1

2. Exergy method .......................................................................................... 4
   Assessing the potential: the theory of exergy ........................................... 4
   Evaluating the performance: the exergy of the different forms of energy and the exergy efficiency ................................................................. 6
   Exergy analysis in buildings ...................................................................... 8

3. ANNEX 49 & COST Projects ................................................................. 10

4. Previous studies ....................................................................................... 12
   Theoretical issues in exergy ....................................................................... 12
   Exergy in buildings .................................................................................... 12
   Exergy in geothermal, district heating & heat pumps .................................. 13
   Exergy in storage systems ......................................................................... 14
   Exergy and sustainability .......................................................................... 15

5. Exergy analysis tools: SEPE .................................................................. 16
   Program logic ............................................................................................ 18
   Models description ..................................................................................... 19

6. Papers ....................................................................................................... 21
   Energy management in buildings: matching supply and demand by means of exergy ....................................................................................... 21
   Exergy efficient space heating systems: analysis of different solutions ..... 22
An exergetic analysis and potential for improving the rational energy use in dwellings. (Proceedings of the 8th Symposium on Building Physics in the Nordic Countries, Copenhagen, 2008) ................................................................. 22

A pressure and thermal exergy analysis of a waterborne and an airborne system. (Proceedings of the 15th „Building Services, Mechanical and Building Industry Days” International Conference, Debrecen 2009) ....... 23

SEPE: an excel calculation tool for exergy-based optimizations. (ECBCS Annex 49 newsletter 6, September 2009) ............................................................................................................. 23

7. Results........................................................................................................................................ 24
8. Discussion and conclusions ................................................................................................. 26
9. Bibliography............................................................................................................................ 27
1. Introduction

World energy use

In the last decades energy use in the world has become a crucial point in everyday agenda. The forecast energy supplies shortage and excessive CO₂ levels are of growing concern. Most developed countries strongly rely on fossil fuels, such as oil, natural gas, coal and nuclear fuels for fission. As of 2008, in the USA petroleum was the major source with 40% of the overall supply, natural gas and coal were slightly over 20%, electricity from nuclear around 10%, and the remaining part was supplied by hydroelectric power and wood (DOE/EIA, 2008). In 2007, 34% of the primary supply in the world was based on oil, 21% on gas, 26.5 coal and peat and 6% on nuclear; hydropower, waste and combustible renewables accounted for 12%, while other sources like geothermal, solar and wind were a negligible fraction (IEA, 2009).

This clear energy dependency on fossil fuels has effects on the environment as well and generates growing concerns on the sustainability of the current energy balance both for the environment and the possible shortage resources. Energy use is constantly increasing in greatly populated countries. Regional shares of primary energy demand for developing and developed countries was respectively 13% and 69% in 1971 and it is expected to be 39% and 51% in 2020, the overall energy demand being increasing in the world (International Energy Agency, 2002). For the period from 1973 to 2007 the total energy use has doubled (IEA, 2009).

The trend is of a generalized energy demand over the world. Energy has then to be used in the most efficient way. An interesting strategy to the problem is the so-called Trias Energetica (Lysen, 1996), which defines a strategy of addressing energy efficiency and use of renewable energy at the same time by reducing the demand by avoiding waste, by exploiting sustainable sources and converting and using energy as efficiently as possible.

Buildings energy use

In this context, there are three main sectors where the energy is used: transport, industry and buildings. In the European Union, residential and tertiary, i.e. office buildings, together are the largest demanding sector (Commission of the European Communities, 2006).
In developed countries like USA buildings account for about 41% of the end-use energy share (DOE/EIA, 2008). 22% is used in residential buildings and 19% in commercial buildings. A similar trend is shown in EU countries.


Figure 1: Energy use by sector in European Union, 2005. (Commission of the European Communities, 2006).

Figure 2: Energy use in residential buildings in EU countries.
Different policies have then been put into force to reduce the energy demand. The building codes put restrictions on the energy demand for heating. Improved building envelope performance has decreased the demand for space heating in many EU countries. The European directive 91/2002 EC in order to reduce the energy use in buildings, provides the adoption of a common calculation methodology at regional or regional level, and of an energy certificate; it sets minimum energy performance requirements for newly constructed buildings and regular inspections of the heating and cooling systems to verify their energetic performance.

Though mandatory to be pursued, improved energy efficiency is not the only target to reach. The quality of energy has to be assessed as well. As previously discussed, most of the overall energy use in residential building is for low temperature heat, i.e. temperatures relatively close to the outdoor conditions. From thermodynamic point of view, this is a degraded form of energy with low potential to be converted into work. On the other hand energy demand is mostly met with high quality energy, such as electricity and natural gas. There is obviously a mismatch between supply and demand, which is not clearly shown by the sole energy analysis. A well insulated electric boiler producing hot water can be highly energy efficient but at the same time presents the same energy quality mismatch. Target of this thesis is to analyze the energy use in buildings from the point of view of its quality, to provide effective theoretical and calculation tools to investigate this mismatch, to assess its magnitude and to propose improvements aiming at a more rational use of the energy. The idea behind the quality is clarified with the exergy concept.
2. Exergy method

Assessing the potential: the theory of exergy

Exergy is a concept that stems from both the first and the second law of thermodynamics and can be defined as the part of the energy which has the potential to be fully converted into mechanical work, which is the thermodynamic most valuable form of energy. Valuable explanations of the exergy theory have been given by (Bejan, Advanced Engineering Thermodynamics, 1997), (Cavallini & Mattarolo, 1992), (Kotas, 1995) and (Çengel & Boles, Thermodynamics: an engineering approach, 2006).

The first law of thermodynamics states the equivalence between heat, internal energy and work in a system. The second law of thermodynamics, on experimental basis, adds some constraints to the first statement and introduces the concept of entropy. By stating that the entropy of the universe is always increasing in the actual processes, the concept of irreversibility and the idea of a “spontaneous direction” in a process are therefore introduced. Anergy derives from entropy and it represents the non-valuable part of energy, i.e. the part that cannot be converted into work, even with a virtual reversible engine. It is therefore:

\[ \text{Exergy} = \text{Energy} - \text{Anergy} \]

This can be explained more in detail: for an open system with flow mass and exchange of heat and work the first law of thermodynamics is:

\[
\frac{dE}{dt} = \sum_{i=0}^{n} \dot{Q}_i - \dot{W} + \sum_{in} m_i h^0_i - \sum_{out} m_i h^0_i \tag{1}
\]

where \( \frac{dE}{dt} \) represents the variation in time of the system energy, \( \sum_{i=0}^{n} \dot{Q}_i \) and \( \dot{W} \) the heat and the work exchanged between the considered system and the surroundings and \( \sum m_i h^0_i \) the enthalpy of the inlet and outlet flows. The second law of thermodynamics for the same system is:

\[
\dot{S}_{\text{gen}} = \frac{dS}{dt} - \sum_{i=0}^{n} \frac{\dot{Q}_i}{T_i} - \sum_{in} m_i s_i + \sum_{out} m_i s_i \geq 0 \tag{2}
\]
where \( \frac{dS}{dt} \) is the variation of entropy in the system, \( \sum \dot{m} s_i \) is the entropy of the inlet and outlet flows and \( \sum_{i=0}^{n} \frac{\dot{Q}_{i}}{T_i} \) is the entropy connected to the heat flows; \( \dot{S}_{gen} \) is the overall entropy generation, which accounts for system and surroundings and which in actual processes is always positive. By multiplying (2) times \( T_0 \), subtracting it to (1) and rearranging we obtain:

\[
\dot{W} = - \frac{d}{dt} \left( E - T_0 S \right) + \sum_{i=0}^{n} \left( 1 - \frac{T_0}{T_i} \right) \dot{Q}_{i} + \sum_{m} \dot{m} h^0 - T_0 s - \sum_{out} \dot{m} h^0 - T_0 s - T_0 \dot{S}_{gen} \tag{3}
\]

The maximum work obtainable from such a system is depending on the variation of the exergy of the system itself \( (E-T_0 s) \), on the exergy of the heat sources, \( \sum_{i=0}^{n} \left( 1 - \frac{T_0}{T_i} \right) \dot{Q}_{i} \), on the exergy of the in- and outflows \( \sum \dot{m} h^0 - T_0 s \) and on the irreversibility generated \( T_0 \dot{S}_{gen} \).

\( T_0 \) is the so-called reference temperature: a peculiarity in the exergy analysis is that reference conditions have to be determined, for pressure, temperature and chemical composition, which has been here neglected due to the targets of this work. \( T_0 \) is actually the temperature of the heat sink. According to the second law of thermodynamics no cycle can produce work without a sink where the heat is disposed of.

It is important now to focus on a very important concept. The first law of thermodynamic states, that in all processes energy is conserved. What changes is its form and status. So, strictly speaking, it is not proper to talk about energy conservation policies or energy consumption. What is actually consumed is the exergy content of a given energy quantity. Heat transfer, for instance, is generated by temperature difference between a medium and its environment, i.e. the exergy content. Once the medium reaches the environment state, i.e. the dead state, no further exchange is possible because the exergy content is finally destroyed, but no energy has been consumed.
Evaluating the performance: the exergy of the different forms of energy and the exergy efficiency

Energy appears in many forms: chemical, mechanical and thermal. Its exergy content varies and needs to be properly defined for an effective exergy analysis.

The exergy of heat is evaluated by means of the equation (3) in reversible, steady-state conditions and when there is no mass flow. Not all the heat can be converted into work but only a fraction \(1 - \frac{T_0}{T_i}\), which is given by the so-called Carnot factor. The higher is the temperature \(T_i\) compared to \(T_0\), the closer this fraction is to 1, the quality of the heat increases and the work that can be extracted is greater. The specific exergy of flow of a flowing medium is given by \(h^0 - T_0s\), where \(h^0\) is the specific enthalpy [J/kg], \(s\) the specific entropy [J/(kg K)], and \(T_0\) is the reference temperature [K].

Kinetic and potential energy are forms of mechanical energy: as such, since no entropy is involved, they are equivalent to exergy. Referred to the unit mass, they are respectively:

\[
\frac{v^2}{2}
\]

And

\[
g \Delta z
\]

Where \(v\) is the fluid velocity [m/s], \(g\) is the standard gravity [m/s\(^2\)] and \(\Delta z\) is the height of the fluid above a considered reference height.

The evaluation of the exergy of fossil fuels and energy carriers used in buildings as energy supplies such as natural gas or fuel oil is usually carried out by means of a quality factor \(\varepsilon_i\), which quantifies the relative exergy content for a given energy quantity. (Schmidt, Design of low exergy buildings - Method and a pre-design tool, 2004) and (Jóhannesson, Low exergy systems, 2001) suggest the following values for fuels and energy carriers (Table 1).
Table 1: Exergy factor values of selected fuels (Reference conditions: $T_0=293$ K, $P_0=101000$ Pa).

<table>
<thead>
<tr>
<th>Fuel</th>
<th>$\varepsilon_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas</td>
<td>0.9</td>
</tr>
<tr>
<td>Fuel oil</td>
<td>0.9</td>
</tr>
<tr>
<td>Liquefied natural gas</td>
<td>0.9</td>
</tr>
<tr>
<td>Mineral coal</td>
<td>0.9</td>
</tr>
<tr>
<td>Wooden pellets</td>
<td>0.9</td>
</tr>
<tr>
<td>District heating at 100 °C</td>
<td>0.21</td>
</tr>
<tr>
<td>Electricity</td>
<td>1</td>
</tr>
</tbody>
</table>

A useful tool to evaluate the exergy performance in a system is the exergy efficiency. Different definitions can be given (Kanoglu, Dincer, & Rosen, 2007), depending on the different targets of the analysis: here an introduction of the so-called simple exergy efficiency and some examples will be given.

Simple exergy efficiency is defined as the ratio between the desired exergy output and the required exergy input, i.e. the exergy recovered and supplied (Çengel & Boles, Thermodynamics: an engineering approach, 2006); in formulas:

$$\eta_{ex} = \frac{\text{Exergy}_{\text{recovered}}}{\text{Exergy}_{\text{supplied}}} = 1 - \frac{\text{Exergy}_{\text{destroyed}}}{\text{Exergy}_{\text{supplied}}} \quad (6)$$

In case of working-producing devices, this becomes

$$\eta_{ex} = \frac{\eta_{th,rev}}{\eta_{th}} = \frac{W_u}{W_{rev}} \quad (7)$$

$\eta_{th,rev}$ is the thermal efficiency of a machine working reversibly, such as a Carnot machine, while $\eta_{th}$ is the actual thermal efficiency of the considered machine.

Exergy efficiency quantifies which is the amount of work extracted by a device out of the overall available, which would be exchanged in virtual, reversible conditions. As a consequence, it gives a potential of the degree of irreversibility that take place.

The same expression can be expressed for work-consuming devices, such as compressors:

$$\eta_{ex} = \frac{W_{rev}}{W_u} \quad (8)$$
and for cyclic devices like heat pumps:

$$\eta_{ex} = \frac{COP}{COP_{rev}}$$  \(9\)

The generality of the definition (9) is suitable for analysis of more complex systems. In this form it is often found in literature.

**Exergy analysis in buildings**

Buildings use a great amount of energy but have the potential to consume small amounts of exergy. Most of their demand is for low- and medium temperature energy, such as space heating and cooling and domestic hot water. With a reference temperature of 0 °C, space heating at 30 °C has a Carnot Factor of 0.01 and domestic hot water at 55 °C of 0.17. This demand is mostly supplied with electricity and natural gas or oil boilers, with energy quality factor of the source close to the unity. As it will be further shown, this results in a poor exergy performance which also is common to many processes in buildings.

Exergy analysis and efficiency provide a very effective tool to improve the energy use for buildings. Exergy explains univocally the concept of energy quality. Exergy and its counterpart anergy give also a physical meaning to the concept of entropy, which anergy derives from. Reducing the exergy losses in either a system or a process and increasing its exergy efficiency means to use energy in a more rational way. High exergy overall efficiencies mean exploiting all the available exergy content and using energy in the most rational way.

It is important to stress the word “overall”. A low-temperature emission heating system, such as a floor heating, supplied by high-exergy sources would shift the exergy loss in the generation system, with little or no improvement from an exergy point of view with respect to higher-temperature emission systems like radiators. To perform the best results, a low exergy approach has to be holistic.

Exergy analysis in buildings aims at reducing the exergy input, having in this a different target than in the utility case, where exergy analysis was first applied. Exergy optimization aiming at increasing the exergy efficiency in power plants can lead to a step-up in the electricity, i.e. the output. In buildings the exergy output is defined by the energy demand and set-point temperatures for the different functionalities where energy is provided. The exergy optimization here must address the input. The exergy efficiency can be increased only by reducing the exergy input (Figure 3 and Figure 4).
Figure 3: Power plant optimization aims at increasing the power output.

Figure 4: Building exergy optimization aims at decreasing the power input.

The definition of the exergy demand strongly affects the input results. To obtain the best out of the exergy analysis a wide screenshot of the current energy use, with particular reference to the previous work has to be made. The next two paragraphs are about two international projects focused on the application of the exergy approach to buildings and an extensive bibliography of the most relevant papers about exergy analysis in buildings, in heating and cooling systems, in innovative solutions.
3. ANNEX 49 & COST Projects

Exergy analysis has been applied to many research fields, such as power plants and utilities, industry processing and transportation sector. A systematic application to the built environment dates back to the last two decades. The first International Energy Agency project on exergy conservation in buildings was IEA ECBCS Annex 37, “Low Exergy Systems for Heating and Cooling of Buildings”, which covered a time span of four years, from 1999 to 2003. Its focus was mainly on heating and cooling systems. Its final guidebook provided several examples of best practice buildings (IEA ECBCS Annex 37, 2003). In 2005 this project was followed by the IEA ECBCS Annex 49 “Low Exergy Systems for High Performance Buildings and Communities”, which this Ph. D. is part of. The research fields of the Annex 49 are split into four subtasks: methodology, building level, community level and dissemination (see Figure 5).

![Figure 5: IEA ECBCS Annex 49 subtasks (Schmidt, 2009).](image)

The philosophy behind this different, broader approach compared to the previous ECBCS Annex 37 is to insert the building stock in the community level to make it possible to exploit the exergy content of the sources available, as shown in Figure 6.

![Figure 6: Desirable energy/exergy flow to the building stock and industry (IEA ECBCS Annex 49, 2007).](image)

Similar targets are shared with the European Science Foundation COST action C24 “Analysis and Design of Innovative Systems for LOW-Exergy in the Built Environment”, a European project which is closely linked to the ECBCS Annex 49 and which this thesis is also part of. Aim of the COST 24 is the dissemination of new knowledge and practical design support to facilitate the use of the exergy concept applied to the built environment.
The COST C24 is also divided into four research areas, named working packages. They comprise the definition of the practical applicability of exergy analysis, the use of insights from exergy analysis to develop innovative concepts, the application of exergy to human body and indoor environment and the dissemination, with coordination targets (see Figure 7). An entire working group addresses the correlation between comfort and human body exergy consumption. Possible future outcomes could result in finding an optimization of the exergy consumption in space heating systems allowing best comfort conditions.

Figure 7: Cost C24 framework, (Boelman, 2009).
4. Previous studies

Theoretical issues in exergy

A controversial theoretical aspect in the exergy approach applied to buildings is the choice of the reference (dead) state, for basic parameters such as temperature, pressure and specific enthalpy of a medium. While for power plants this proved not to be a very sensitive parameter, the choice of the reference state can greatly affect the results in buildings, were heating and cooling temperatures are close to the ambient temperature, which is usually chosen as reference. This is exemplified in (Rosen & Dincer, Effect of varying dead-state properties on energy and exergy analyses of thermal systems, 2004), (Al-Muslim, Dincer, & Zubair, 2005) (Utl & Hepbasli, A study on the evaluation of energy utilization efficiency in the Turkish residential-commercial sector using energy and exergy analyses, 2003) and (Sakulpipatsin, Exergy efficient building design, 2008). Chemical issues such as exergy losses in combustion processes are treated by (Som & Datta, 2008) and (Taniguchi, Mouri, Nakahara, & Arai, 2005); the exergy content in moist air is given by (Liley, 2002).

Exergy in buildings

The core of the application of exergy analysis to the built environment and the entropy-exergy mechanism are clearly explained by Shukuya, a pioneer in the exergy approach in buildings, in (Shukuya, 2009) and (Shukuya & Komuro, 1996).

Overview studies on the exergy consumption in residential and commercial sector have been performed by different authors for Greece, Japan and Turkey (Xydis, Koroneos, & Polyzakis, 2009), (Kondo, 2009), (Utl & Hepbasli, 2005), (Utl & Hepbasli, 2006) and (Utl & Hepbasli, 2003). In those countries the overall efficiency proved to be low, between 5% and 9%, and, in particular, lower than the one found for similar analyses in other sectors.

Available resources play a fundamental role in the decision making process, both for policies and for design: (Hermann, 2006), (Valero, Valero, & Martinez, 2009) and (Koroneos, Spachos, & Moussiopoulos, 2003) gave a wide overview on the energy sources available and on their exergy content. A wide review of renewable sources for climatisation has been given by (Torio, Angelotti, & Schmidt, 2009), with particular regard to methodology and reference state. (Niewlaar & Dijk, 1993) stressed the better behavior of district heating and cogeneration with respect to traditional solutions like boiler heating.
As heating and cooling processes play an important role in the overall energy use in buildings, several papers on exergy optimization are dedicated to HVAC systems. (Sakulpipatsin, Itard, van der Kooi, Boelman, & Luscuere, 2009) and (Yıldız & Güngör, 2009) focused their study in the whole heat generation chain and found in both cases exergy efficiencies below 10%. Another low-exergy system was analyzed from the generation to the building envelope by (Tolga Balta, Kalinci, & Hepbasli, 2008).

Absorption machines, which present a certain degree of complexity analysis, have been investigated by (Morosuk & Tsatsaronis, 2008), (Ravikumar, Suganthi, & Anand, 1998), (Iquerdo, Hernández, & Martín, 1996) and (Prídasawas & Lundqvist, 2004) and (Şencan, Yakut, & Kalogirou, 2005).

Solar collectors optimization and exergy delivery were addressed by (Bejan, Extraction of exergy from solar collectors under time-varying conditions, 1981), (Altfeld, Leiner, & Fiebig, 1988), (Kar, 1985) and (Suzuki, 1988); (Tyagi, Wang, Shingal, Kaushik, & Park, 2007) dealt with the problem of parametric solar concentration. Air solar heaters and their exergy performance and costs drew the attention of (Kurtbas & Durmuş, 2004), while (Xiaowu & Ben, 2005) studied domestic scale water heaters. A solar parabolic cooker, whose exergy efficiency was around 1%, was the object of a paper by (Öztürk, 2004). An innovative type of hybrid solar heating, cooling and power generation system was the object of (Zhai, Dai, Wu, & Wang, 2009).

Different types of cooling devices too were analyzed from the exergy point of view. (Guadalupe, Heard, Best, & Rojas, 2005) focused in desiccant cooling and its suitability in hot humid climates. (Taufiq, Masjuki, Mahlia, Amalina, Faizul, & Saidur, 2007), (Chengqin, Nianping, & Guangfa, 2002) and (Niksiar & Rahimi, 2009) dealt with evaporative cooling. The latter found that while the energy efficiency of such a process is high, the relative exergy efficiency is low and a remarkable portion of the exergy is destroyed. Traditional vapor compression refrigeration and the relationship of COPs and exergy efficiency with condenser and evaporator temperatures were examined by (Yumrutaş, Kunduz, & Kanoğlu, 2002).

Emission systems performances were treated by (Wei & Zmeureanu, 2009), (Zmeureanu & Yu Wu, 2007) and (Wang & Li, 2009) as regards the ventilation devices; (Wang, Morimoto, Soeda, & Yamashita, 2008) focused on the radiant exergy exchange in cooling systems.

**Exergy in geothermal, district heating & heat pumps**

Geothermal energy draw the attention of researchers due, among the other reasons, to the stable supply parameters and to the relatively lower environmental impact compared to traditional fossil fuels. A classification of
the geothermal by their exergy content can be found in (Lee, 2001). A similar study was made by (Etemoglu & Can, 2007) for Turkey. Exergy losses for district heating and geothermal distribution nets were quantified respectively by (Comakli, Yüksel, & Comakli, 2004) and (Bettagli & Bidini, 1996).

District heating is attractive as it offers the possibility to make benefit of surplus low quality waste energy from power plants. Detailed exergy performance description are found in (Ozgener, Hepbasli, & Dincer, 2006), (Ozgener, Hepbasli, & Dincer, Energy and exergy analysis of the Gonen geothermal district heating system Turkey, 2005), (Ozgener, Hepbasli, & Dincer, Exergy analysis of geothermal district heating systems: an application, 2005) and (Ozgener, Hepbasli, & Dincer, 2007), both from simulation and from experimental data. Exergy efficiencies in the different examples were found to range from 46% up to about 60%. (Kato, 2000) proposed a low-exergy nuclear reactor to be used for cogeneration.

Heat pumps represent an interesting solution for both heating and cooling systems from an exergy point of view. General analyses from the first and second-law point of view have been done by (Labidi, Boulet, & Paris, 2000), (Lorentzen, 1986) and (Bilgen & Takahashi, 2002). The latter found from simulations results COP for domestic purposes varying from 7.40 to 3.85 and exergy efficiencies ranging from 0.37 to 0.25. (Bejan, 1997)

(Tunç, Uysal, & Özmen, 1988) performed a simulation study on solar assisted heat pumps, while (Kaygusuz & Ayhan, 1993) and (Cervantes & Torres-Reyes, 2002) based their results on an experimental approach. (Dikici & Akbulut, 2008), still in an experimental study, found overall exergy and energy efficiencies of 65.6% and 30.8%. A wide review on the studies on solar assisted heat pumps systems can be found in (Ozgener & Hepbasli, 2007). The performance of Ground-coupled heat pumps (GCHP) was issued experimentally by (Hepbasli & Akademir, 2004), in a heating and cooling system for a university building. In another paper (Esen, Inalli, Esen, & Pihtili, 2006) found exergy efficiencies for shallow horizontal ground heat exchangers with heat pumps overall exergy efficiencies above 50%, with a slight increase with depth.

**Exergy in storage systems**

The possibility of exploiting renewable sources and to use waste exergy is strongly depending on the ability to accumulate it. Storage systems, in particular seasonal ones, are an essential task to be addressed: (Rosen, 2001) (Bjurström & Carlsson, 1985), (Koefoed, 1977) analyzed different aspects of the theoretical aspects of thermal energy storages (TES). (Koca, Oztop, Koyun, & Varol, 2009) studied a TES with phase change materials (PCM), finding energy and exergy efficiencies of 45% and 2.2% respectively. Similar
results were also found by (Öztürk, 2005) in a TES with PCM for seasonal storage.

**Exergy and sustainability**

Several connections between exergy, sustainability and environmental impact have been made. Indirect links have been made by means of exergy efficiency of regional and global areas, (Nakićenovic, Gilli, & Kurz, 1996), by means of a Carbon exergy tax (CET), (Massardo, Santarelli, & Borchelli, 2003) and (Santarelli, 2004) or exergy indicators in local laws, (Favrat, Marechal, & Epelly, 2008) and policy making perspectives, (Dincer I., 2002). The target here is to improve the sustainability of the systems (building, urban areas, communities) by means of an improved second-law efficiency and, consequently, by penalizing policies for exergy inefficiencies.

A more direct connection between exergy and sustainability was the matter of (Rosen, Dincer, & Kanoglu, 2008), with the introduction of a sustainability index, of (Dewulf, van Lagenhove, & Dirckx, 2001), with the evaluation of the sustainability of waste gas treatment systems, and (Balocco, Papeschi, Grazzini, & Basosi, 2004), with the evaluation of an urban area by means of the extended exergy analysis method.

More general considerations on exergy and ecology can be found in (Susani, Pulselli, Jørgensen, & Bastianoni, 2006), where a convergent use of exergy in different fields of knowledge is met and in (Rosen & Dincer, Exergy as the confluence of energy, environment and sustainable development, 2001) (Connelly & Koshland, 2001) and (Gong & Wall, 2001) whose conclusions are the high suitability of exergy as parameter for sustainability and sustainable development.
5. Exergy analysis tools: SEPE

Within the IEA ECBCS Annex 37 project, a pre-design sheet for exergy-optimized building design has been produced (Schmidt, Design of low exergy buildings - Method and a pre-design tool, 2004). It allows the assessment of the exergy flows in a building through the energy chain, from the primary energy sector to the building envelope. Though it proved to be a very valuable tool, a new program more focused on the HVAC systems was needed to perform exergy analyses. A new modular simulation program named SEPE (Software for Exergy Performance Evaluation) was developed on the core of the previous work of (Karlström & Jóhannesson, 2006) at the Department of Building Technology, KTH (Molinari, 2009). It is an Excel-based tool by which it is possible to model and analyze the most common heating- and cooling-systems. The software performs iterative loops and calculates the outputs on a physical basis thus increasing the model reliability. The various components of the heat transmission and conversion chain are here modeled as intelligent modules, each one with independent internal sets of equations and interfaces that can communicate with other modules. An arbitrary system can be constructed on a ordinary Excel sheet by copying and pasting ready made modules in an interconnected structure. By connecting the input and output variables for different modules it is possible to create a whole space of heating and cooling systems representing duct and pipework connecting different functional components such as fans, heat exchanger etc. Every system component is characterized by its internal equations. Since the dependent variables are calculated by the sole pressure and absolute temperature, this ensures a quick connecting process and control. The highly efficient iterative solver in the Excel program allows us to freely use feedback loops and non-linear algorithms for component performance. The algorithms have to be carefully constructed to avoid division by zero during the iteration process.

Every component with a single flow has the same shape and dimension to allow symmetry in the distribution of the components and in the cascade. It is split in three areas:

- Left side: here all the inlet variables are given and calculated.
- Central area: in this part all the internal parameters (such as the working fluid, mass flow etc.) are considered together with the defining equations.
- Right side: here all the outlet variables are yielded and displayed.
It is therefore a natural consequence, although not necessary, that the system is assembled from left to right to improve the ease in reading.

The only component allowing double flow is the heat exchanger, which is therefore composed by the superposition of two single sub-systems. By means of a heat exchanger it is possible to connect a primary system (typically the generation one) with the secondary one (for instance, the distribution and the emission system).

Available components are classified by destination use. Many systems can be used for multiple purposes: the adiabatic saturator, for instance, can be used for evaporative cooling and for a cooling tower for the condenser of a heat pump (see Table 2).

**Table 2: SEPE components.**

<table>
<thead>
<tr>
<th>Generation</th>
<th>Distribution</th>
<th>Emission</th>
<th>Environment</th>
<th>Multi-purpose components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler</td>
<td>Air ducts</td>
<td>Airborne systems:</td>
<td>Environment</td>
<td>Heat exchanger</td>
</tr>
<tr>
<td>Heat pump Chiller</td>
<td>Water pipes</td>
<td>AHU (Air Handling Unit) for heating and AHU cooling</td>
<td>Borehole</td>
<td></td>
</tr>
<tr>
<td>Solar collector</td>
<td>Fan</td>
<td>Waterborne systems</td>
<td>Room, heating and cooling case</td>
<td></td>
</tr>
<tr>
<td>District heating</td>
<td>Water pump</td>
<td>Floor cooling, floor heating and radiator</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adiabatic saturator</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Program logic**

The Annex 37 Pre-design sheet is a tool which works in cascade. It basically follows a top-down strategy. SEPE instead has been created with a bottom-up approach. The advantage of this strategy is the possibility of more detailed modeling of the systems, modularity, easy updating and customization of the models. Together they constitute complementary tools for exergy analysis either in a broad perspective (Pre-design) or addressing more the HVAC system (SEPE).

An innovative idea of the program is the way exergy is calculated. If no chemical transformations take place, specific exergy, i.e. exergy per unit mass, is a function of pressure and temperature (Bejan, 1997), which means that by determining them in a node it is possible to calculate the exergy content.

Every heating or cooling system is split into sub-systems such as a boiler, a heat exchanger, distribution devices like fans and ducts, an emission tool and a room. Each sub-system has an input and output area that we name node, as previously seen. In each of this area pressure and temperature are known and the same is for specific exergy.

**Figure 9:** Partial layout of the program. Blue arrows represent cells connections.

By multiplying the specific exergy by the mass flowing in the node, the overall exergy flow is known. By subtracting output from input exergy flows, the exergy consumption that actually takes place in the subsystem is determined. This is the most problematic information to obtain. The status of reversible processes, which is also the condition for the minimum entropy generation and exergy destruction, can be instead easily calculated. As both the theoretical process and the actual one are gathered, information on the irreversibility of the process is yielded.
The introduction of a simple exergy efficiency (Kanoglu, Dincer, & Rosen, 2007) shows the potential for improving the process. In formulas it is:

\[
\eta_{th} = \frac{\text{Exergy}_{\text{output,th}}}{\text{Exergy}_{\text{input,th}}} = \frac{\text{Exergy}_{\text{need,system}}}{\text{Exergy}_{\text{destr,system}}}
\]

(10)

Models description

For exergy calculations, a reference state has to be chosen. In the central area of every subsystem cells for the definition of the reference temperature and pressure are present. By default they are connected to the respective environment cells, so that the reference conditions are the environment ones. However, by changing those values, other choices are possible.

In the following Figure 10 an example of a system is displayed. The first rows for all the models are the same both in the right area for the input parameters and in the left area for the output parameters. Temperatures in °C and K and pressure in Pa are displayed. Calculations are performed by using absolute temperature and pressure, while temperature in °C is used for sake of readability.

Figure 10: System overview.

Exergy flowing through the different subsystems is divided into the thermal and pressure component, to display effectively the relative contribution to the overall exergy flow.

Specific exergy content is calculated in a slightly different way according to the medium considered: in case of water it is:

\[
Ex_{tot} = c_p \left[ (T - T_0) - T_0 \ln \frac{T}{T_0} \right] + v_m (P - P_0)
\]

(11)
\[ E_{x_{th}} = c_p \left[ (T - T_0) - T_0 \ln \frac{T}{T_0} \right] \]  
\[ E_{x_{pr}} = v_m (P - P_0) \]  

\( E_{x_{tot}} \) is the total amount of specific exergy (J/kg), \( E_{x_{th}} \) is the thermal contribution (J/kg) and \( E_{x_{pr}} \) is the pressure contribution (J/kg), calculated as the minimum amount of exergy needed to raise the pressure from the reference value \( P_0 \) to a given value \( P \).

The exergy content of the air is calculated, assuming ideal gas behavior, as:

\[ E_{x_{tot}} = c_p (T - T_0) - T_0 \left[ c_p ln \frac{T}{T_0} - Rln \frac{P}{P_0} \right] \]  
\[ E_{x_{th}} = c_p \left[ (T - T_0) - T_0 \ln \frac{T}{T_0} \right] \]  
\[ E_{x_{pr}} = T_0 Rln \frac{P}{P_0} \]

Multiplying the specific exergy by the mass flow in the sub-systems the exergy flows are then obtained for each system node.
6. Papers

The research on exergy based on the previous work has been articulated into the different aspects of the building energy use. The different types of energy flows have been considered together to show the overall exergy use within a test building in “Energy Management in Buildings: Matching Supply and Demand by Means of Exergy”.

Different possible sources of energy supply for space heating, which covers most of the overall energy use in the built environment, have been investigated by means of SEPE in the second paper, “Exergy efficient space heating systems: analysis of different solutions”. Exergy efficiencies proved to be very low for all the traditional solutions.

Household and appliances performances have been investigated in the paper “An exergetic analysis and potential for improving the rational energy use in dwellings”. Different examples of energy match between exergy supply and demand are shown along with optimization.

The problem of the transportation exergy, i.e. the exergy consumed for circulation auxiliaries, is discussed in the fourth paper: ”A pressure and thermal exergy analysis of a waterborne and an airborne system”. The comparison between a gas boiler with radiators and a heat pump is carried out and remarkable losses are shown in a Sankey diagram.

Finally, a brief presentation of SEPE, published in the IEA ECBCS Annex 49 newsletter 6, is given in the paper “SEPE: an excel calculation tool for exergy-based optimizations”.

In the following, the relative abstracts are given:

**Energy management in buildings: matching supply and demand by means of exergy**

Buildings energy use accounts for a relevant part of the final energy use. In the built environment many processes are present and a relevant part of the total energy use is heat at relatively low temperatures, which is a degraded form of energy. Sources in buildings instead are often thermodynamically valuable sources, such as electricity, fuel oil and natural gas. A mere energy analysis is not capable of illustrating this mismatch between the quality of the energy demand and supply. Exergy analysis clearly shows this as a thermodynamic mismatch. In this paper, an explanation of the exergy analysis approach in buildings is given. The different building energy demands are classified with regard to their exergy content and the potential for using energy better is shown. Two parameters for the evaluation of the energy match are given.
Three different mixes of energy supply to buildings are simulated. The results show that combining different energy supplies can significantly improve the overall exergy efficiency in a building.

**Exergy efficient space heating systems: analysis of different solutions**

The building sector has a high energy demand with low-quality. In spite of this, energy supplies for buildings are almost exclusively high-quality, such as electricity or natural gas. Therefore a high potential for so-called energy savings exists in building sector by means of a more rational use of the energy. Exergy analyses performed thoroughly, i.e. all along the energy conversion chain, clearly show this potential. An Excel-based software has been developed to illustrate the performances of some common solutions for the space heating and to analyze where the most relevant losses are take place.

Exergy efficiencies have been introduced to evaluate the degree of irreversibility in the considered process. In all the solutions the efficiency was below 20%. Direct electricity and fossil fuels heating resulted in much lower exergy performance, around 0.07%.

The results highlight how high-exergy sources like natural gas, direct electricity and fuel oil are not suitable from an exergetic point of view for space heating and should be replaced by low-exergy ones. Waste heat, energy from heat pumps and solar power fit better this scope.

**An exergetic analysis and potential for improving the rational energy use in dwellings.** (Proceedings of the 8th Symposium on Building Physics in the Nordic Countries, Copenhagen, 2008)

The quality of a certain amount of energy is defined as the relative exergy content of this energy. Most of our buildings with their heating and cooling systems today are built for conversion of high quality energy sources to low quality use with destruction of the available exergy as a result. Globally we have a huge potential for transforming our processes to more efficient use of the exergy and also for feeding our processes directly from renewable energy sources without the use of high quality energy sources. Exergy analysis is also important as an innovation driver in buildings and building systems. This work is carried out within the frame of IEA Annex 49 Low Exergy Systems for High-Performance Buildings and Communities. The scope of the annex is to improve, on a community and building level, the design of energy use strategies,
taking into account the different qualities of energy sources, from generation and
distribution to consumption within in the built environment. In particular, this is
carried out by the method of exergy analyses to provide assessment of the
thermodynamic features of any process and to achieve a clear, quantitative indication
of both the irreversibilities and potential for matchmaking between the resources used
and the end-use energy flows. The paper contains a systematic survey of the exergy
consuming processes for building and building appliances, their role in exergy balance,
the level of energy quality needed in primary process and the potential for developing
processes towards improved exergy efficiency. The work presented here gives a listing
of the important processes in buildings with a discussion of their nature from an
exergy point of view. The methodology for analysis is exemplified for a limited
number of processes, dealing with the energy use and exergy destruction in processes,
the potential for exergy saving and the discussion on the technical and economical feasability

A pressure and thermal exergy analysis of a waterborne
and an airborne system. (Proceedings of the 15th „Building Services,
Mechanical and Building Industry Days” International Conference, Debrecen 2009)

The exergetic performances of two different heating systems, a full air system with a
gas boiler and a floor heating with a heat pump, have been analyzed from the
generation to the emission system. Exergy thermal and pressure losses have been
evaluated to illustrate which potential exists for improving the energy use.
Simulations have been performed by means of SEPE, a steady state tool that makes
use of the iterative cycles in Excel.

SEPE: an excel calculation tool for exergy-based optimizations. (ECBCS Annex 49 newsletter 6, September 2009)
7. Results

In the present paragraph, the main results of the previous papers are presented. The potential in space heating is shown in Figure 11. In all traditional heating systems considered the overall exergy efficiency was below 20%. Fossil fuels and direct electricity driven heating systems were below 7%.

Exergy flows comparison

Figure 11: Exergy flows comparison in the different case studies. (HP=Heat pump, FH=Floor heating, B=boiler, AHU=Air Handling System, Rs=radiators, DH=District Heating, SC=Solar collector, EFH=Electric floor heating).

Exergy content for many household appliances is displayed by means of the exergy factor in Figure 12. Most of the processes have low-exergy factors but still are supplied with electricity. This results in poor exergy efficiencies and large exergy losses.

Figure 12: Dwelling processes: exergy level and temperatures.
In particular, the lowest exergy efficiencies are found for high-energy demanding processes, like space heating and domestic hot water production. To show the magnitude of those losses the results of a combined analysis of both space heating processes and household appliances are displayed in Figure 13. Exergy demand in a building was split into four different exergy categories: low-, mid- and high- exergy content, meant as ratio between exergy and energy, and electricity. They correspond to space heating, domestic hot water, cooking and electric appliances demand. The demand is displayed in the first column of every category. Supplies like electricity (all el.), with high exergy content, result in extremely high exergy losses, especially where the exergy demand is low compared to the energy. This is shown in the different height between the first and the second dotted black column in of each category. Much better results are reached by combining district heating for the categories with low exergy content (low and mid) and electricity for higher exergy content purposes (high and el).

Figure 13: Exergy and energy needs and supplies comparison. For every exergy class demand is shown together with the different supplies. Energy flows are split into their exergy and anergy components. All el. is the whole electricity supply mix, El & DH is the electricity and district heating supply mix and EL & SC is the electricity and solar collector heating mix.
8. Discussion and conclusions

The energy mix approach shows the potential to save exergy, i.e. to exploit all the energy that is used. A sole energy analysis in buildings hides the real potential for so-called energy savings, as it neglects the quality of the energy. Rational energy managing should be addressed instead. Exergy provides an effective tool to unveil the hidden potential for improving the energy use in buildings.

Systems are poorly performing because little consideration is explicitly given to energy quality. Policies to lower the energy demand, though mandatory as first step towards an improved use of energy, should not neglect the exergy content. The way the energy is supplied should be addressed in a larger extent. Energy with poor exergy content has to be supplied with energy with similar exergy content. A mandatory problem is then the differentiation of the energy demand according to the exergy content.

To increase the exergy efficiency and, equivalently, to use energy in a more rational way, other sources have to be addressed, either with lower exergy sources or with renewable ones, such as solar thermal power or geothermal.

The problem is then shifted to find suitable supplies. Fossil fuels and electricity are high exergy. Electricity can be exploited with low exergy losses with high-COP heat pumps. Use of fossil fuels for thermal purposes shall be avoided.

Solar exergy is high exergy but its exploitation with low exergy efficiencies has not the same relevance as in the case of fossil fuels. Solar energy is abundant and its destruction takes place anyway, regardless of human caption. The main problem with renewable sources is their availability. Geothermal can be exploited only where it is present and solar power cannot be used for space heating unless a proper seasonal storage system is coupled with. Seasonal storage systems are so far limited to experimental projects or particular realizations. Storage systems have also low efficiencies (Koca, Oztop, Koyun, & Varol, 2009) and are rather uncommon for seasonal application.

District heating from cogeneration and geothermal proved to be an appealing at the building level (Figure 11). The issues connected to their exploitation forces to shift the boundary layers of the analysis from the building level to the community level. A rational use of energy should address the community level. This is a cost-effective way to avoid the waste of the exergy potential of high-exergy sources with the exergy cascade and make it possible their integration with renewable sources. Exergy efficiency of the buildings is a prerequisite for a better of energy in this field. The system boundaries have to be enlarged to a dimension where both the energy conversion and use take place with reduced energy transportation losses.
9. Bibliography


