EXERGY ANALYSIS IN THE BUILT ENVIRONMENT - DYNAMIC REFERENCE TEMPERATURES AND ALLOCATION OF EMBEDDED EXERGY

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Summary

The shortcomings of ordinary energy analysis of a system becomes obvious when energy is used on very different quality levels. The global emphasis on energy saving is partly successful. Considering however more systematically the exergy destroyed in the processes will lead to a better insight into the potentials for the conservation of the global energy resources and radically reduced environmental impact. The present paper tries to outline the practical aspects of combining exergy analysis with a dynamic performance analysis for a building with its systems. Also how the exergy destroyed should be evaluated in context with the investment and resources needed to provide the necessary technical preconditions for a low exergy system. The CONSOLIS tool which is an Excel based tool for dynamic energy analysis in buildings has been modified in order to include heat-pumps and the influence of the temperature levels in the heating/cooling system on the COP and the consumption of bought exergy. For a well insulated one family house in Stockholm the result shows an example with a high potential to save exergy compared to conventional system solutions for heating and cooling. Also it can be concluded from the analysis that measures for saving exergy will in most cases save exergy on a global scale if they prove to give acceptable private economy.

1. Introduction

The shortcomings of ordinary energy analysis of a system become obvious when energy is used on very different quality levels. The global emphasis on energy saving is partly successful. Considering however more systematically the exergy destroyed in the processes will lead to a better insight into the potentials for the conservation of the global energy resources and radically reduced environmental impact.

The use of so called low exergy components and systems in buildings for space heating and cooling is not new. In some cases they have been introduced for different reasons such as floor heating to improve comfort and heat pumps technology in order to save bought energy.

The present paper tries to outline the practical aspects of combining exergy analysis with a dynamic performance analysis for a building with its systems. Also how the exergy destroyed should be evaluated in context with the investment and resources needed to provide the necessary technical preconditions for a low exergy system. The paper is not about detailed exergy analysis on systems in buildings. Such an analysis for a given set of boundaries can be found in existing scientific papers and textbooks. Schmidt (2004) gives a good overview on the analysis of exergy destruction in a heated building and describes the development of a tool for such analysis.

The issues that are treated in this paper are the choice of reference temperature for the exergy analysis, the exergy content of goods and services that are needed for the low exergy design or so called embedded exergy and a methodology for implementing the exergy analysis in a conventional energy analysis.

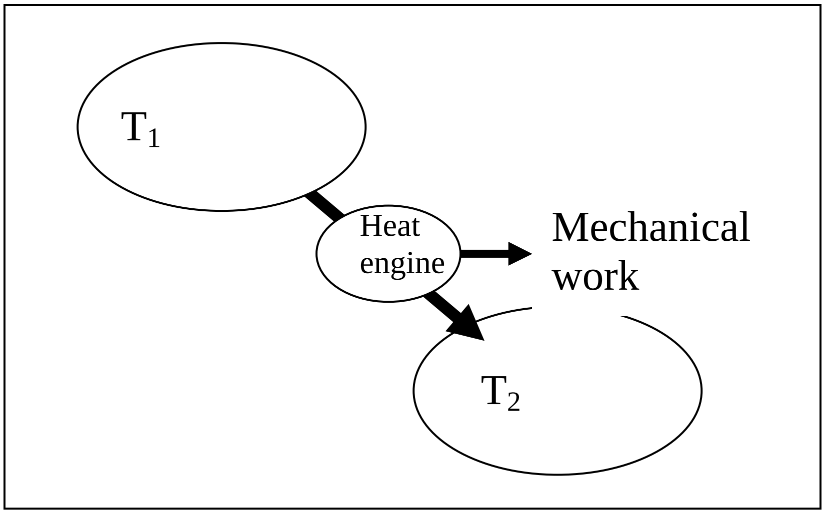


Figure 1. The definition of exergy

2. Exergy analysis and a choice of reference temperature

The quality of energy is related to a certain reference temperature. The classical definition is that exergy is the maximum mechanical energy that can be generated by a process where a given amount of energy is transferred from a heat reservoirs at constant temperatures T_1, K to an ideal heat engine between T_1 and T_2, K, see figure 1. In its simplest form the exergy can be expressed as

$$\mathrm{Exergy} = \mathrm{Energy}_1 \, (1 - \frac{T_2}{T_1}) \tag{1}$$

Obviously the exergy content of the reservoir at T_1 will be depending on the choice of reference reservoir T_2 or what we refer to as the reference temperature.

The result of an exergy analysis for a system where substantial parts of the energy conversion is taking place at a low quality level will be depending on the choice of reference temperature. The choice of reference temperature should reflect a rational use of available energy sources in such a way that the efficiency of the system should be highest when the use of high quality energy is at its possible minimum.

The minimum exergy consumption is achieved if we can deliver energy at the temperature levels required for the process with theoretical Carnot efficiency from the heat source with the temperature closest to the target. The best available heat source can be stated to be for heating the maximum of the air temperature and the ideal ground temperature below the house, i.e. the annual average ground surface temperature which for higher latitudes is close to the annual average temperature for the outdoor air and, for cooling the minimum of the air temperature and the ground temperature.

The choice of heat sources according to above does not in any way guarantee that any system solution could not theoretically have an exergy efficiency larger than one. By storing exergy for heating and cooling between seasons, exergy could theoretically be produced from nothing according to the above definition. The introduction of the exergy destroyed in relation to the investment necessary for harvesting and storing exergy will however hopefully bring us on to the right track again.

The purpose of an exergy analysis can be of different nature. An exergy analysis can be carried out simply to get a better understanding of a system and the potential for saving of bought energy and investment, i.e. to improve the private economy of the owner or user of a building. An exergy analysis could also be a part of a national or global strategy to divert energy use from high quality energy sources such as fossil fuels towards renewable or low quality energy sources. Future building regulation could state a maximum limit for exergy consumption per heated floor area in a similar manner as energy use is restricted today. In this case it would be necessary to go deeper into the analysis of embedded exergy. As an example we could have two components with the same performance but where one of the components is produced with lower exergy than the other but still has a higher price since this has demanded more expensive materials and technology. A simpler approach would however be to account for this by limitations and taxation in the production phase so that the product price would better reflect the exergy efficiency and other parameters of importance for the environment.

3. Treatment of renewable energy sources.

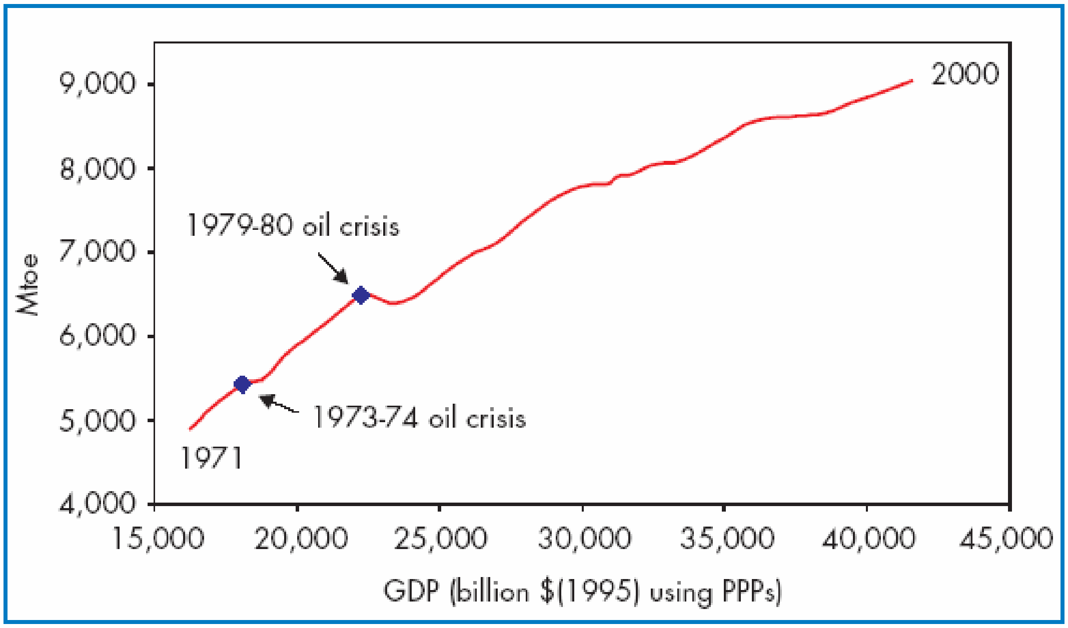
The analysis should divide between local renewables that are harvested on the building site by the building owner such as wind- or hydropower, bio-fuels and solar energy and energy form renewable from commercial sources. The total available solar and wind energy at the site is of limited interest for our analysis. If the investment for the harvesting and distributing the energy is within the economical frame of the property the sources should be accounted for as zero exergy while the investment and operational cost should be accounted for as described below. For renewables that are bought from an external part on a commercial basis the exergy should be accounted for as the real exergy content but limited by a price comparison with common readily available exergy sources such as electricity or petrol since we can assume that the commercial price would reflect the availability of energy carrier.

4. The exergy of money.

For an exergy analysis to be meaningful in a life cycle perspective we also need to include the exergy of the flow of products and services necessary for the processes. The approach to decide the exergy content of these imports to the system can be carried out on many levels. The first level would be to make an assessment of embedded exergy, i.e. all exergy needed to provide the goods and services needed. Generally this is a rather impossible task because due to the complexity of the processes behind and that the exergy content would be highly depending on the choice of boundaries for the analysis. The case where such an approach is of value is when comparing products with similar functionality but with a different design. The simplest approach would be to simply state that there is a relation between money spent and the exergy destroyed in the community to provide what is paid for. By dividing the BNP for a larger community by the total amount of exergy destroyed from commercial energy carriers that are available from national statistics. A more comprehensive discussion on Thermo-Economics and Extended Exergy Accounting can be found in Sciubba et al (2005).

A more private economical approach would be to simply use the price of exergy from a readily available commercial source such as electricity from the grid or gas. The last approach would lead to synchronization between low exergy design and good economy. An important part that is left out in such an analysis are the externalities, that is the cost of the society in terms of money or exergy to take care of the downstream consequences of the use of energy and resources in terms of waste disposal, pollution etc. Somehow this would be reflected in taxes.

By looking at the Global GDP, and the use of high quality energy worldwise see figure 2. we see that the total GDP year 2000 was 42 billion USD and the consumption of high exergy fuels was about 9000 Mtoe. The energy use, which for the time being on a global scale is fairly equivalent to exergy use, would be 3.6 kWh/€ and looking at Sweden it would be a little less or about 2.5 kWh/€. If we compare with the price of high quality energy such as grid electricity in Sweden we would get about 10 kWh/€. It can be concluded that even if the exergy per GDP is in the same region as the amount of exergy we can as private persons buy on the market it is not to be expected that a private economical design can fully coincide with a design form minimum exergy use. The investment related exergy is however a necessary component in the analysis to avoid sub optimal solutions.



Figur 2. Global use of primary energy vs Global GDP, IEA (2000).

In order to include cost on an annual basis it is of advantage to include investment cost as an annuity demanded for the initial investment. The annuity will be based on the interest rate and the expected technical lifetime of the investment. The interest rate will vary from country to country and the technical lifetime will be longer for investment in the built structure than for the HVAC installations. In this paper the annuity for Sweden will be assumed to be 4 % for the built structure and 7 % for installations such as heating systems and heat pumps. Expectations concerning the future ratio between rising energy prices and inflation may also influence on the chosen annuity.

5. The CONSOLIS energy tool modified for low exergy systems

The Consolis Energy tool, Jóhannesson 2005, is a spreadsheet based model under development and the goal is to meet the new demands of the European Building directive. The earlier standard for calculation of energy use for heating, ISO 13790:2004 Thermal performance of buildings - Calculation of energy use for space heating, will now be extended to also include cooling. In order to get a reasonable modeling accuracy we therefore probably will have to develop models based on hourly calculations instead of monthly balances according to the present standard. The simplifications made for the building dynamics have been treated in Jóhannesson (1981). The approach chosen here is to calculate three typical days per month, clear sky, partly cloudy and cloudy and then project the results for each month with statistical means. The building can be divided into two different temperature zones and surface temperatures and air temperatures are for each zone modeled separately in order to have a better representation of thermal comfort than what a single node temperature would give. An advantage of this procedure is that the climate data needed are basically the mean temperatures and the number of clear and cloudy days for each month. From this information the program generates outdoor temperature profiles and solar radiation on different surfaces for the typical days. The simplified dynamic model is based on one lumped mass node on the inner surface of the constructions, Jóhannesson 1981, and the program has a module to directly calculate the thermal capacity of the node for an arbitrary multilayer construction. The program is entirely written in an Excel spreadsheet which gives a relatively easy access for implementing new processes but at the same time gives the transparency necessary for control of the calculation and results. Dynamic modeling with backward differences and a direct use of the iterative solver within Excel gives very fast and stable solution so that the calculation of annual energy use for heating and cooling is more or less immediate.

The new European directive also demands that the model should include other aspects of the energy balance of a building such as the systems for generation and distribution of heating and cooling, daylighting and artificial lighting together with many other things.

6. Modeling low exergy systems

The Consolis tool has been modified in order to include heat-pumps and the influence of the temperature levels in the heating system on their COP and other system properties on the use of bought exergy. For a well insulated one family house in Stockholm we have the following properties. We have identical building shells with U-values of 0,18 W/m^{2}K for the walls, 0,13 W/m^{2}K for the roof, 0,18 W/m^{2}K towards the ground and 1,2 W/m^{2}K for the windows which have an average g factor of 0,5 and frame factor of 0,8 in the calculations. The buildings are air tight with balanced ventilation and an air to air heat exchanger with efficiency of 65 %. In one of the building we have a low exergy system with heating and cooling integrated in the constructions like a floor heating system and in the other building we have conventional high temperature radiators and cooling convectors. P_{hc} is the power needed for space heating or cooling. These systems will have different temperature levels in inlet temperatures for the heating and cooling systems as shown in table 1.

Table 1. System parameters for a system that heats and cools with small and high temperature differences between the inlet of the heating/cooling system and the room.

	Low temperature heating and cooling	High temperature heating and cooling
Temperature difference for heating and cooling, K	$P_{hc}{\cdot}0{\cdot}031$	$P_{hc}{\cdot}0,833$
Operational power, W	200	150
COP factor -	0.5	0.5
Temperature difference at source, K	4	5

The system efficiency for the heat pump will be based on the Carnot efficiency multiplied by 0.5 and a constant operational power. In this case the source is supposed to be a borehole and outdoor air which means that the source temperature will be the maximum value of these two for heating and the minimum value for cooling, which also is the reference temperature for the exergy analysis. The results of the simulations are given in table 2.

Table 2. Monthly results for energy use for space heating and cooling and bought energy/exergy in Stockholm.

kWh	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	The year
Outdoor temp. K	-0,5	-0,7	1,4	6	11	15	17,2	16,7	13,5	8,9	4,9	2	6,6
Low temperature system													
Space heating	1626	1257	846	335	54	0	0	0	7	312	979	1419	6835
Bought energy/exergy	343	271	203	96	20	0	0	0	5	103	246	319	1606
Cooling	0	0	88	225	624	1017	1278	1053	471	52	0	0	4808
Bought energy exergy	0	0	9	23	44	75	93	76	35	5	0	0	360
High temperature system													
Space heating	1626	1257	846	335	54	0	0	0	7	312	979	1419	6835
Bought energy/exergy	429	335	233	100	19	0	0	0	4	100	269	376	1865
Cooling	0	0	88	225	624	1017	1278	1053	471	52	0	0	4808
Bought energy/exergy	0	0	7	24	57	106	141	115	41	4	0	0	494

The apparently extremely high COP for the cooling is due to the fact that the ground source is for longer periods able to cool without the aid of any compressor work. Annual cost for the a system with a conventional system without heat pump and with split systems for cooling is estimated as the energy needed for space heating plus half the energy needed for space cooling.

Even if such well insulated houses are rare in Japan it is of interest to see its function in a Japanese climate, see table 3. Since the house is well insulated and air tight with a good heat exchanger the heating load is minimum and the cooling load is also kept low. The ground temperature is higher but still a valuable source for cooling.

Table 3. Monthly results for energy use for space heating and cooling and bought energy/exergy for a location in Japan at latitude 35 and longitude 138 for the same building as in Table 2. The climate parameters are from Nasa 2005.

kWh	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	The year
Outdoor temp. K	2,71	3,11	6,6	11,8	16,1	20,4	23,6	24,8	22	15,7	10,2	5,12	
Low temperature system													
Space heating	565	453	236	21	0	0	0	0	0	0	53	365	1693
Bought energy/exergy	130	102	71	11	0	0	0	0	0	0	30	95	438
Cooling	38	63	163	316	554	966	1267	1432	1182	711	254	63	7010
Bought energy exergy	7	12	18	26	61	99	139	148	127	59	23	10	730
High temperature system													
Space heating	565	453	236	21	0	0	0	0	0	0	53	365	1693
Bought energy/exergy	138	109	67	9	0	0	0	0	0	0	24	95	443
Cooling	38	63	163	316	554	966	1267	1432	1182	711	254	63	7010
Bought energy/exergy	6	10	17	38	77	131	188	215	187	99	30	9	1006

7 Economic analysis

The important parts of the economic analysis are given in table 4. The investment in borehole and heat-pump for a one family house is about 11000 €. Extra cost for a low temperature system

Table 4. A simplified economic evaluation for the Stockholm house.

	Conv heating system	Heat pump w high temperature system	Heat pump w low temp system
Cost for heat pump	Base	3000 €	3000 €
Cost for borehole	Base	7000 €	7000 €
Extra plumbing	Base	1000 €	1300 €
Boiler	Base	-2000 €	-2000 €
Split system cooling	Base	-2000 €	-2000 €
Annual extra capital cost w. 7% annuity	Base	490 €	630 €
Maintenance	Base	100 €	100 €
Annual saving kWh/€		6880/430	7993/500

compared to conventional heating and cooling is about 1500 €. For both cases the annuity of the investment will be somewhat lower than 7 %. The economy is a little bit worse for the low temperature system, but on the other hand the low temperature system has the potential to provide better thermal comfort.

It is also interesting to note that the exergy consumption generated by the investment according to above is 3.6 €/kWh which gives an annual exergy generated by the investment as 2100 kWh and 2600 kWh respectively which is less than 1/3 of the saving if the system is run on electricity or fossil fuels. If the system is run on district heating and cooling systems the picture becomes somewhat more complicated since the central plant can involve low exergy technologies. Anyhow it can be concluded from the above analysis that measures for saving exergy will in most cases save exergy on a global scale if they prove to give acceptable private economy.

8. Discussion

The use of the combination of the temperature in the ground and the outdoor air temperature as a reference temperature for an exergy analysis since it relates to generally available sources in the built environment and also to the best practical technology we have today to provide low exergy heating and cooling with fairly good economy. The use of a global or a national factor for the embedded energy in investment is a rather rough approach but looking at the embedded direct production energy in most products compared to their market price it is clear that it is generally a small part of the total exergy generated. From figure 1. it could be argued that the gradient in used exergy per spent dollar has been decreasing since the oil crisis and some marginal relation could be used instead the average. The implementation of exergy analysis in ordinary dynamic simulation programs for buildings is easy when we have a practical approach for the reference temperatures. The potential for saving the global resources becomes more visible in an exergy analysis compared with a pure energy analysis. It is interesting that a house with systems designed for northern latitudes also gives low exergy consumption located in Japan but the economic and cultural preconditions may be quite different.

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