ANALYSIS OF THE EXERGY-CONSUMPTION OF FOUR TYPES OF BUILDINGS

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ABSTRACT

This paper proposes a comparison between the use of exergy analysis and traditional energy analysis for buildings. The principles of exergy analysis are outlined, and a specific method for buildings is proposed. The results of this analysis show that a longterm increase in the sustainability of buildings can be achieved only by sharply reducing the energy demand of electrical appliances and by improving the efficiency of the electricity production process. Improvements in the exergetic efficiency of heating and cooling systems that can be obtained by applying low-temperature heating and high-temperature cooling can also have positive effects on sustainability, but further reductions in the demand for heating and cooling by passive building physics measures will have no long-term effects.

INTRODUCTION

In the past, considerable effort has been put into calculating the flow of energy in buildings, in order to predict and reduce their consumption of energy during their operational lives. According to the first principle of the thermodynamics, however, energy is always conserved and never consumed. It is the quality of the energy, also known as exergy, that is consumed, and not the energy itself. Because exergy is directly related to sustainability, an interesting comparison can be made between the results of energy flow analyses and the results of exergy flow analyses. This paper introduces such a comparison and presents an initial analysis of measures that should be taken to increase the sustainability of buildings. Section 2 explains the exergy principle in more detail. Section 3 applies this principle to buildings in order to calculate their exergy demand, and section 4 addresses the calculation of primary exergy consumption, which is the total amount of exergy needed to satisfy the exergy demand of a building. Examples are given for two dwellings and two office buildings. In both cases, one of the buildings is a pre-war building and the other is modern.

ENERGY, EXERGY AND SUSTAINABILITY

The first principle of thermodynamics is that of energy conservation. It states that the sum of all energy put

into a system is equal to the sum of the increase in internal energy within the system and the energy rejected by the system. Taken literally, this means that saving energy is not possible, as energy is never destroyed. In every real process, however, something is destroyed, and that is the quality of the energy, also called exergy. This is the subject of the second principle of thermodynamics. Energy produced at higher temperatures is of higher quality, meaning that more work can be produced with this energy. Figure 1 provides an illustration of a situation in which the temperatures of several types of energy produced by the combustion of gas are plotted against the quality of the energy. In this example, the combustion of gas delivers 1 MJ of electricity. Electricity is of maximum quality, as it can be fully converted into power. During this conversion, heat at lower temperatures will be rejected. On the other hand, heat at the temperature of the outside air (7°C in Figure 1) is in equilibrium with its surroundings, and can therefore no longer be converted into electricity or power. This is why burning gas in a boiler in order to heat a building is very inefficient; the potential of the gas is not fully used. With the same quantity of gas, it would have been possible to produce electricity and power. The residual high temperature heat could have been used in the process industry. Residual heat from this process could have been used by low-temperature industry (e.g., the pulp industry), and this heat would have eventually reached a temperature suitable for heating a building (about 30°C). A consequence of the direct use of gas to produce heat for a building is that the electricity of power that has not been generated must be generated by other means, and this increases the primary use of fuels and the related emissions. Exergy is therefore a good measure for the sustainability of a system. More information on this subject can be found in Dincer 2000, Wall et al. 2001, Rosen et al. 2001 and Boelman et. al 2003.

ENERGY AND EXERGY DEMANDS OF BUILDINGS.

This section addresses the energy and exergy demands of buildings. These demands are based purely on energy balances between the building maintained at a defined level of comfort and its environment. When defining the energy or exergy demand, it is important to consider both the physical aspects of a building and its uses. This is because the ways in which a building is used influence the internal heat load and the lighting and power demand considerably, and therefore the



Figure 1 The exergy principle, illustrated by means of gradual energy conversion

building's overall energy demand as well. All relevant energy items should be taken into account to avoid focusing on a single aspect of the demand, which could lead to erroneous assumptions about energy savings. For instance, adding insulation decreases heat demand but increases cooling demand, while having fewer windows decreases heat demand but increases lighting demand.

Energy demand

The system studied is as follows: Heat is added to the building by lighting, people and appliances, and air flows into and out of the building through infiltration and ventilation. Ventilation air can be treated initially in an air-handling unit, where it is chilled or preheated. The total energy demand consists of seven items:

- Demand for heat in the building, Q_{heat}
- Demand for cold in the building, Q_{cold}
- Demand for heat in the air-handling system, $Q_{heat,}^{ahu}$
- Demand for cold in the air handling system, Q_{cold}^{ahu}
- Demand for lighting, Q_{light}
- Demand for ventilators when using mechanical ventilation, Q_{ventil}
- Demand for appliances, such as computers and servers, Q_{appl}.

The model for the heat and cold balances within a building envelope is based on hourly energy balances that take into account transmission, ventilation, infiltration losses and heat accumulation in the construction, as well as heat load through sun, appliances, people and artificial lighting. More details can be found in Itard 2003 and Itard 2005.

The heat and cold balances in air-handling systems are simple enthalpy balances based on the temperature of the outdoor air and the specified temperature of the airsupply into the building. These balances are needed only when a mechanical ventilation system is used. The calculations for appliances and lighting are based on a specified electrical load per square meter of gross floor area.

The energy demand for ventilators is calculated assuming known pressure losses in the ducts.

Exergy demand

The exergy demand for cold and heat in the building is calculated using the method described in Schmidt 2004. If T_{in} refers to the indoor air temperature, and T_o to the temperature of the surroundings (outside air temperature), the exergy demand for heat or cold in the building expressed in J/K is:

$$E_{heat \ cold} = Q_{heat \ cold} (1 - \frac{T_o}{T_{in}})$$
(1)

The exergy demand for cold and heat in the airhandling unit is calculated using the method described in Shukuya 2002. In the following equation, T_{blin} refers to the temperature of the air that is supplied to the building's rooms.

$$E_{heat \ cold}^{ahu} = Q_{heat \ cold}^{ahu} \cdot (1 - \frac{T_o}{T_{blin} - T_o} Ln \frac{T_{blin}}{T_o}) \quad (2)$$

Lighting, appliances and ventilators are electrical equipment. For all electrical equipment, an exergetic efficiency of one is applied, and therefore:

$$E_{light, ventil, appl} = Q_{light, ventil, appl}$$
(3)

Test cases

Definition of the test cases

Two typical Dutch dwellings and two typical office buildings were chosen as test cases. Dwelling and office building A are older buildings, built before WW

Characteristics	Dwelling A	Dwelling B	Office Building A	Office Building B
-Gross floor area (m ²)	80	80	3000	3000
-LxBxH (m)	10x8x2.8	10x8x2.8	30x20x18	30x20x18
-Number of storeys	1	1	5	5
-Location	Middle of an	Middle of	an Detached	Detached
	apartment block	apartment block		
-Rc-value walls, roofs,	0.7	2.5	0.7	2.5
floors (m ² K/W)				
-U-values windows	7	2.1	7	2.1
(W/m^2K)				
-Window %	30	30	40	60
-Sun transmission	0.8	0.6	0.8	0.3
coefficient windows				
-Sunblinds	Indoor blinds	Indoor blinds	no	no
-Light transmission	0.8	0.7	0.8	0.6
coefficient windows				
-Air infiltration rate	1	0.3	1	0.3
(m ³ /hm ³)				
- m ² gross floor area per	40	40	20	20
head				
-Lighting load (W/m ²)	10	10	10	10
-Electrical load appliances	5	5	15	15
(W/m^2)				
- Minimum indoor day-	20-16	20-16	21-16	21-16
night temperature in				
winter (°C)				
- Maximum indoor day-	32-32	32-32	24-28	24-28
night temperature in				
summer (°C)		. -		
-Ventilation rate (m ³ /hm ³)	0.5	0.5	2.5	2.5
-Mechanical ventilation	no	no	yes yes	
-Opening times	-	-	7-18 hour, 5 days a 7-18 hour, 5 days	
			week	a week

Table 1 Main characteristics of the buildings in the test cases

II, and they both have poor insulation. Dwelling and office building B are modern, well-insulated buildings.

The main difference between office buildings and dwellings is the way in which the buildings are used. The internal heat load in a dwelling is much lower than that of an office building, in which there is an average of one computer per person that runs all day. The occupancy rate is also much higher in an office building. In office buildings, the most people are present during the day, whereas in dwellings, the most people are present during the night. Table 1 summarizes the characteristics of both dwellings and office buildings.

The simulation-software tool h.e.n.k (Itard 2003) was used to make the calculations. Calculations made using this software tool are based on semi-dynamic calculations and hourly weather data for one year. The implementation of exergy calculations in this software has been described in Itard 2005. The calculations were conducted for the typical oceanic climate of the Netherlands.

Results

Figures 2 and 3 present the results of the calculations for the dwellings.



Figure2 Average annual energy demand (MJ/year) for a prewar (A) and a modern (B) dwelling.



Figure 3 Average annual exergy demand (MJ/year) for a prewar (A) and a modern (B) dwelling.

As expected, the measures taken to insulate dwelling B had an enormous effect on the energy demand (see figure 2) for heating, which was reduced approximately to 20% of its initial value. The overall energy demand of the dwelling B was reduced to 45% of the energy demand of dwelling A. Because of the higher insulation grade, dwelling B requires more cooling. As suggested by the stack-diagram for B, future policies should be aimed at further reducing the demands for heating, cooling, lighting and appliances equally, as these four items are of approximately the same magnitude. Figure 3, which plots the exergy demands for both dwellings, shows that the overall exergy demand for dwelling B remains at 90% of the exergy demand for dwelling A, even when the exergy demand for heating in dwelling B is reduced by a factor of 5. As stated in section 1, this is because heating and cooling are energies of low intrinsic quality, and the required temperature is not much higher (or lower) than the temperature of the surroundings. In contrast, the exergy demand for lighting and other electrical appliances is relatively high, because electricity is needed. With regard to the long-term sustainability of buildings, therefore, it is more important to focus on reducing the irreversibility of the electricity demand of dwellings than it is to focus on decreasing the already marginal irreversibility of the heating and cooling



Figure 4 Average annual energy demand (MJ/year) for a prewar (A) and a modern (B) office building



Figure 5 Average annual exergy demand (MJ/year) for a prewar (A) and a modern (B) office building.

demands.

The results for the office buildings (see figures 4 and 5), whose internal heat load and occupancy profiles differ greatly from those of dwellings, strengthen this point.

<u>Primary</u> Consumption of Energy and Exergy.

Primary energy consumption

Buildings need equipment in order to meet their energy demands. Boilers or heat pumps can be used to meet the heating demand. Compression cooling machines can be used to meet the cooling demand. The electricity that is needed must be produced by a power plant. Regardless of the type of equipment that is used, it will always be subject to conversion efficiency. This means that the amount of energy needed by the conversion equipment is different from the overall energy demand.

Example for heating: If the heating demand is 1MJ, and a gas boiler with an overall efficiency of 0.85 is used, the primary energy consumption to meet the heating demand is 1/0.85 = 1.18 MJ.

Example for cooling: If the cooling demand is 1 MJ, and a compression cooling machine which has an efficiency of 3 is used (this is possible because a heat pump also uses free energy from the surroundings), the heat pump needs 1/3 = 0.33 MJ of electricity to meet this demand. This electricity, however, is produced in a power plant. If the efficiency of the power plant is 0.4, the primary energy consumption to meet the cooling demand becomes 0.33/0.4 = 0.83 MJ.

For this paper, calculations have been made using an overall efficiency that takes into account both conversion and distribution losses. The primary energy consumption is calculated for all energy items defined in section 2, also taking the efficiency of electricity generation into account when electricity is needed.

$$Q_{\text{primary}} = \eta. \ Q_{\text{demand}} \tag{4}$$

Primary exergy consumption

Equation 5 is used to calculate the primary exergy consumption, where ε_{ex} is the exergetic quality factor of the entire energy conversion process:

Character-	Dwelling A	Dwelling B (boiler)	Dwelling B (heat pump)	Office Building A	Office building B (boiler)	Office building B (heat nump)
15005	a 1 1		(near pump)			D (near pump)
-Heating	Gas boiler	Gas boiler	Elect. Heat	Gas boiler	Gas boiler	Elect. Heat pump
equipment	(η=0.83)	(η=0.83)	pump η=4.3	(η=0.83)	(η=0.83)	η=4.3
-Cooling	No	Elect. compr.	Elect. compr.	Elect. com.	Elect. compr.	Elect. compr.
equipment		Cool. mach.	Cool. mach.	Cool. mach.	Cool. mach.	Cool. mach.
		η=3.6	η=3.6	η=3.6	η=3.6	η=3.6
-Electricity	η=0.38	η=0.38	η=0.38	η=0.38	η=0.38	η=0.38

Table 2 Main characteristics of the energy conversion systems with overall efficiencies

$$E_{primary} = Q_{primary} \cdot (1 - \frac{T_o}{T_{conv}}) = \varepsilon_{ex} \cdot Q_{primary}$$

(5)

For instance, if waste heat at the temperature T_{conv} =323 K is used for heating applications, and if the outside temperature is 275 K, the quality factor will be 0.16. In this paper, it is assumed that the exergetic quality factor of a power plant is 1, as is the exergetic efficiency of a boiler (see also Schmidt 2004). This is because of the high temperature at which gas is burned in the boiler.

Test-cases

Both dwelling A and office building A use highefficiency boilers with a year-average overall efficiency of 0.83. No cooling equipment is used in dwelling A, and a compression-cooling machine with a year- average overall efficiency of 3.6 is used in office building A.

For dwelling B and office building B, which are both well insulated, there are two calculated options for the heating equipment: a boiler with an average overall efficiency 0.83, and a heat pump with an average overall efficiency of 4.3. Both the dwelling and the office building use compression-cooling machines with an average overall efficiency of 3.6.

A power plant generates the needed electricity with an efficiency of 0.38, which is the average efficiency of Dutch power plants, including distribution losses. This electricity is used by all electrical equipment (lighting, appliances and ventilators), as well as by the heat pump and the compression-cooling machine. The electricity use of a gas boiler is assumed to be zero (see Table 2).



Figure 6 Average annual primary energy use (MJ/year) for a prewar (A) and a modern(B) dwelling.







Figure 8 Average annual primary energy use (MJ/year) for a prewar (A) and a modern (B) office building.



Figure 9 Average annual primary exergy use (MJ/year) for a prewar (A) and a modern (B) office building.

There are fewer differences between the uses of primary energy and exergy than there are between the demands for energy and exergy. The stack diagrams for primary exergy use and primary energy use show similar results. This is because all of the energy conversion systems in the test cases have similar exergetic quality factors.

There is an interesting discrepancy between the exergy demand for heating and cooling and the primary exergy use for these items. This discrepancy can be seen by comparing figure 3 with figure 7, and figure 5 with figure 9. While the exergy demand for heating and cooling is almost negligible (less than 7% of the overall exergy demand in the case of dwelling and office building B), the exergy use for heating and cooling accounts for approximately 25% of the overall exergy use when a boiler is used, and approximately 18% when a heat pump is used. This means that much more can be done to improve the exergetic efficiency of heating and cooling generation systems.

The total exergy use for electrical equipment (e.g., appliances, lighting and ventilators), however, remains the largest component of total exergy use. At a constant electricity demand, exergy use can be reduced only by greatly improving the efficiency of power plants or using electricity generation based on wind or sun.

CONCLUSIONS

This paper has proposed a comparison between traditional energy analysis of buildings and exergy analysis. The energy analysis concerns the quantities of energy that are being used, whereas the exergy analysis addresses the quality of this energy, and therefore the rational use of energy.

The results of the exergy analysis suggest that longterm increases in the sustainability of buildings can be achieved only by reducing the energy demand for electrical appliances considerably and by either improving the efficiency of the electricity production process or applying sustainable electricity generation based on sun or wind. The reduction of the lighting demand is possible by designing buildings that make maximal use of day lighting and by developing efficient lighting. The energy demand for appliances, such as computers and televisions, should also be decreased considerably.

The improvement of the exergetic efficiency of heating and cooling systems by applying low-temperature heating and high-temperature cooling will also have positive effects on sustainability, but further reductions in the heating and cooling demand through the application of passive building physics measures will have no long-term effects.

Finally, present fuel prices and tax structures that are not related to the rational use of fuels are obstacles to long-term sustainability (see also Dincer 2000).

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