THE PERFORMANCE OF DIFFERENT HEATING SYSTEMS IN RESIDENTIAL BUILDINGS WITH VARYING INSULATION QUALITY

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ABSTRACT

Alternative energy systems for residential use are gaining consideration. Although these systems perform well in test conditions, the question remains whether they outperform classical boilers in real conditions. Therefore, simulation results for different combinations of heat production and heat emission systems are given in this paper for three insulation levels of a residential building.

The evaluation of the global systems is based on overall economic performance, amount of emitted CO_2 and primary energy use. The latter provides an indication of the use of natural resources. However, to incorporate the quality of the energy flows in and around the building, an exergetic balance is also presented.

INTRODUCTION

The new European building legislation focuses on energy consumption. Therefore alternatives to fossil fuels for house heating, like heat pumps (HP), gain interest. The recently soaring oil and gas prices increase the economic potential of these alternative energy systems as well. Installing small scale energy efficient and environmentally friendly systems in such a vast market would have a considerable impact on the global energy use and emission of greenhouse gases.

The aim of this research is to compare the economic, ecologic, energetic and exergetic performance of these alternative energy systems with classical production systems on natural gas. Therefore, TRNSYS16v1.037 is used to simulate the different combinations of heat production and heat emission systems, integrated in a building.

The building modelled, is a typical Belgian terraced house with insulation level varying from an average U-value of 0.8 W/m²K to 0.2 W/m²K. Heat production systems considered are high efficiency and condensing gas boilers, air to water and water to water heat pumps. They are combined with convenient heat emitters, which can be conventional high temperature radiators (HT), low temperature radiators (LT) or a combination of floor heating in the living room and kitchen and low temperature radiators in the other rooms (Fl).

These simulations enable to compare the different heating system set ups in houses with varying heat losses. The economic comparison is based on the Net Present Value (NPV), and thus takes into account the investment, installation and maintenance costs, as well as the energy consumption. The ecological comparison is based on CO_2-emissions during operation. A whole Life Cycle Assessment will not be taken into account in this paper, but will be performed in the framework of the ongoing EL²EP-project (see acknowledgements). For the energy consumption, the primary energy use of all systems is compared. The exergetic analysis is based on (Schmidt, 2004), in which a method is presented for a whole building exergetic evaluation. In this paper, the method is used for an exergetic comparison of the different heating systems in houses with varying insulation level.

SIMULATION

The reference building is a compact terraced house with an outer volume of 446 m³ and an exterior surface of 256 m². Non-forced natural ventilation is dimensioned according to the Belgian standard (BIN, 1992). Three insulation qualities are considered: an *average*, a *well* and a *heavily* insulated variant. They have average U-values of 0.8 W/m²K, 0.5 W/m²K and 0.2 W/m²K and with one inhabitant working at home, this results in net heat demands of 10232 kWh/a , 7118 kWh/a and 5180 kWh/a respectively.

The internal gains show a peak in the morning and the evening due to the activity of inhabitants and the normal use of home appliances. The living habits of the people are also reflected in the set point temperatures for the building zones as illustrated in Figure 1.

The floor heating in the day zone is simulated using "active elements" available in TRNBUILD (SEL, 2004) and extra floor insulation is applied to compensate for the extra losses due to a higher floor temperature. The floor heating control is split up in a central control and an individual room control, as in practice (Olesen, 2001). The central control unit

regulates a three-way valve based on a heating curve so that the water supply temperature changes according to the outside temperature. In addition, an on/off-controller opens and closes the water flow to the day zone, according to the measured dry bulb temperature and the set-point selected by the user.

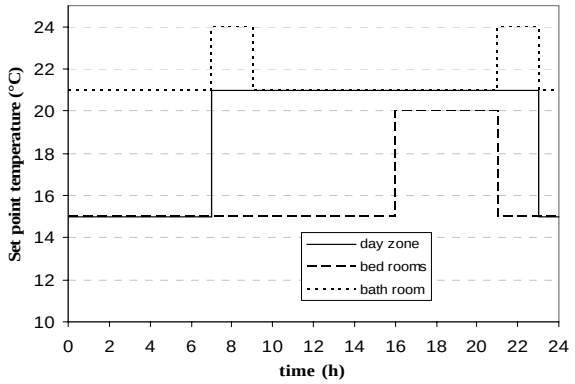

Figure 1 Set point temperatures for the day zone, night zone and bath room.

The radiators used are based on Type 72 from IEA annex 17, but numerically optimized (Kummert, 2001). The heat is emitted to the zone, partly as convective energy to the zone air and partly as radiation towards the zone walls. Depending on the power and size of the radiators, the convective part ranges from 50% to 87.5%. Since the heat loads of the three buildings vary with the insulation quality, the radiators have not the same power and dimensions. The layout of the floor heating, on the other hand, is not altered, but the set-point temperature is lowered according to the heat load.

Each radiator is accompanied by a proportional controller that determines the incoming flow. These controllers can be regarded as "perfect" thermostatic valves. In reality, the thermostatic valve measures a temperature that is the weighted average of the temperatures of air, walls, the water in the pipe and the emission system. Furthermore, the flow also depends on the pressure drop of the flowing water over the valve and the history of the valve itself, i.e. on hysteresis (Ast, 1988). To focus on the behaviour of the system in its totality, it is assumed that the valves are adjusted for these deviations. The water flow through the distribution system is determined by adding the flows through the different circuits.

A condensing and a high-efficiency gas boiler are modelled in TRNSYS as a combination of an ideal heater and an insulated water tank. The capacity of the water in this tank is set equal to that of the boiler and with a correct heat loss coefficient it is possible to simulate the boiler envelope losses. When the heat demand of the system is in the modulating range, 3 to 11 kW in this case, the burner is turned on and the water from the distribution system flowing through is heated by the ideal heater until the set temperature (which depends on the outside temperature) is reached. In the other case, when the heat demand is lower than 3 kW, the boiler cycles to keep a minimal temperature and heat is slowly added to the distribution system by the boiler capacity. Finally, without heat demand, the boiler can cool down to the temperature of its zone.

The efficiency of the gas-water heat exchanger is derived from information of boiler producers and two EES-models developed by Lebrun (2004). The efficiency of high-efficiency boilers increases with lower water supply temperature, but by far not as much as for condensing boilers. Furthermore, the latter benefit from operating at part load, while the former are hardly able to maintain their efficiency when modulating (Van der Veken et al., 2005). Together with the envelope losses, this results in the boiler efficiencies of Table 1 ($T_{WSUPPLY}$ is the temperature of the water at the boiler outlet).

Table 1: Boiler efficiency of condensing and High Efficiency boiler (HE) in relation to HHV

BOILER TYPE AND LOAD	$T_{WSUPPLY}$ = 30°C	$T_{WSUPPLY}$ = 60°C
Cond 100%	96.5 %	89.0 %
Cond 30%	97.5 %	87.5 %
HE 100%	86.5 %	85.5 %
HE 30%	86.0 %	85.0 %

The circulation pump of the distribution network consumes between 17 and 77 Watt, depending on the water flow rate. Of this energy, 70% is transferred into heat injected into the water circuit, and 30% is lost to the zone air. The condensing boilers are equipped with a ventilator of 67 Watt, while for the high-efficiency boilers 40 Watt is sufficient. Their electricity consumption is depending on the air flow raised to the third power and therefore also on the boiler load. The heat produced by the ventilator is assumed to only warm up the air going into the burner, but this benefit is already included in the used boiler efficiency. Finally, the electronics of the boiler control consume 15 Watt as long as the boiler is switched on, and this energy is emitted to the air of the room.

Two heat pump types are modelled; an air-to-water and a water-to-water system. As neither model can modulate, they are both combined with a heat storage tank. The tank, a TRNSYS type 4a (SEL, 2004), has a volume of 650 litre and a loss coefficient of 0.1 kJ/h.m².K. The number of layers in this stratified tank is set to 8. The heat pump is connected to the storage tank by a separate hydronic circuit and an extra circulation pump. Both pumps have the same characteristics as the one described above. They are both turned on when the temperature of a certain

layer is too low. Set temperature as well as number of heated layers depend on the outside temperature. More precisely, the colder it is outside, the higher the temperature of the upper layers and the more layers will be heated. A dead band on the desired temperature as well as a minimum on and off time, prevent the heat pumps from continuous cycling. The circulation pump will be turned off fifteen minutes after the heat pumps are shut down. To reduce costs, a light preference is given to off-peak heat production, by increasing the number of layers and the set temperature at night. (Peeters et al., 2005)

The air-to-water heat pump model, based on (Verplaetsen et al., 2001), is slightly adapted using measured data of (Lhoëst et al., 2003). This results in the following equations (1) to (4), where Q_{stat}, Q_{dyn} and Q_{basis} stands for respectively the thermal power in static conditions, in dynamic conditions and at an outside temperature of -10°C with an outlet temperature of 60°C. T_{ext} is the exterior air temperature, while T_{stor} represents the water temperature flowing back from the storage tank to the heat pump.

$$Q_{stat} = Q_{basis}(1 + 0.03(T_{ext} + 10) + 0.02(60 - T_{stor})) \quad (1)$$

$$COP_{stat} = 2.5 + 0.05(T_{ext} + 10) - 0.03(T_{stor} - 35) \quad (2)$$

$$Q_{dyn} = Q_{stat}(1 - \exp(-t/\tau)) \quad (3)$$

$$COP_{dyn} = COP_{stat}(1 - \exp(-t/\tau)) \quad (4)$$

The time-constant τ is equal to 3 minutes. Q_{basis} varies with the insulation degree of the building; namely from 8 kW to 10 kW. An outside temperature of 5°C and T_{stor} at 55°C results in a static COP of 2.65.

The water-to-water heat pump is modelled by a TRNSYS type 668 (Thornton et al., 2004). It is a non-modulating heat pump with a COP of 4.2. Depending on the insulation quality of the house, the installed power varies from 8.7 kW to 11.6 kW with a source temperature of 10°C and an inlet water temperature of 35°C.

All heat production systems are turned off when the daily averaged outside temperature rises above 12°C, since there will be no heat demand above that temperature. They are combined with the three different heat emission systems, except the heat pumps which are not combined with high temperature radiators.

DISCUSSION AND RESULT ANALYSIS

Energy

This comparison is based on the energy consumed to reach the set temperatures. The conversion coefficient between primary energy and electricity is taken equal to 2.5; for gas it is 1 (Verbeeck & Hens, 2005).

The results of this calculation are summarized in Table 2. The difference in COP between both types of heat pumps causes an obvious difference in Seasonal Performance Factor (SPF) and primary energy use. However, the difference between an SPF of 2.8 for the air-to-water heat pump, and 3.4 for the water-to-water variant, has also another reason. The air-to-water system has to fulfil the heat demand with the lowest COP on the coldest days. This results in an oversized installed power during the rest of the entire heating season. As the heat pump is a non-modulating type and the flow rate in its circuit is kept constant, the temperature of the water will rise above the desired value. In all simulations the average room temperature is higher for the air-to-water systems, the fluctuations of the room temperature are larger, and its operation time is much shorter. This over-sizing problem can be solved by a back-up heater or an electrical heating element in the storage tank. This leads to direct electric heating in the coldest parts of winter.

Table 2: Primary energy use associated with gas consumption and auxiliary electricity in MWh/a.

INSULATION	AVERAGE	WELL	HEAVILY
FLOOR HEATING			
HP AW	11.4	8.6	6.2
HP WW	9.2	7.6	5.5
Cond	13.3	10.0	7.2
HE	14.6	10.9	7.8
LOW TEMPERATURE RADIATORS			
HP AW	10.1	8.2	6.1
HP WW	9.1	7.2	5.4
Cond	12.2	9.1	6.9
HE	13.6	10.0	7.4
HIGH TEMPERATURE RADIATORS			
Cond	12.6	9.4	7.1
HE	13.7	10.1	7.4

Floor heating performs poorly in combination with a gas boiler, especially if the HE-boiler is used. This is due to the low control efficiency, when controlled on air temperature and operated at fairly high water temperatures.

Ecology

The ecological comparison (results presented in Table 3) is based on the amount of CO_2 emitted by the different heat production systems. SO_2, NO_x, CO, VOC's and dust are not considered. In Table 4, the CO_2-emissions associated with the combustion of natural gas and production of electricity are given for Belgium, France and Germany (Commission Ampere, 2000). Belgium has a fair amount of nuclear power, far more than in Germany, where coal is still widely

used, but less than in France, where hydropower is used in addition.

Table 3: CO_2-emissions associated with gas consumption and auxiliary electricity in tons per year for Belgium.

INSULA-TION	AVERAGE	WELL	HEAVILY
FLOOR HEATING			
HP AW	1.4	1.1	0.8
HP WW	1.1	0.9	0.7
Cond	2.7	2.0	1.5
HE	3.0	2.2	1.6
LOW TEMPERATURE RADIATORS			
HP AW	1.3	1.0	0.7
HP WW	1.1	0.9	0.7
Cond	2.5	1.8	1.4
HE	2.8	2.0	1.5
HIGH TEMPERATURE RADIATORS			
Cond	2.6	1.9	1.8
HE	2.8	2.1	1.8

Table 4: CO_2-emissions associated with gas and electricity production.

ENERGY SOURCE	COUNTRY	CO_2-EMISSION (kg/kWh)
Natural gas		0.209
Electricity	Belgium	0.310
Electricity	France	0.060
Electricity	Germany	0.590

Again the effect of the oversized air-to-water HP as well as the difference in SPF result in a lower CO_2-emissions for all water-to-water heat pump systems compared to the air-to-water HP. The HE boiler is the most polluting solution for all scenarios, due to its lower production efficiency.

Considering the average emissions for the electricity production in different countries (Table 4), it is clear that there is a large influence of the composition of the electricity generation park. In France, heat pumps will outperform the other options even more strikingly, while in Germany they will no longer be the most environmentally friendly option.

Exergy

Exergy expresses the quality of an energy source. An exergy analysis can be performed to evaluate the efficiency of energy use. This allows evaluating which system makes the best use of high quality energy.

For the exergetic analysis, the methodology used is based on (Schmidt, 2004). The analysis takes into account the steps from input of energy into the heating system, till loss of heat through the building envelope. Internal and solar gains, as well as heat produced by artificial lighting are considered.

Figure 2 shows an overview of the different processes in the exergy calculation. For each process the exergetic value of the input is calculated. Equation 5 shows the calculation method for the exergetic input of process i (Ex_i).

$$Ex_i = F_{q,i} \cdot Q_i \tag{5}$$

$$F_{q,i} = 1 - \frac{T_0}{T_i} \tag{6}$$

Q_i indicates the energy input for the step considered. $F_{q,i}$ is the quality factor of the process considered, estimated by means of the Carnot efficiency. T_0 is the temperature of the reference, which is, in these calculations, the outside temperature. The temperature T_i is an estimate of the temperature at which the considered heat exchange takes place. In the generation process, the energy input is not heat, but natural gas and auxiliary electricity, the exergetic factor for electricity (F_{elec}) is 1 kWh/kWh. 1 kWh gas (HHV) has an exergetic value (F_{gas}) of 0.96 kWh (Schmidt, 2004). For the Generation process, this results in equation 7 below. Use_{gas} and Use_{elec} stand for gas and auxiliary electricity consumption.

$$Ex_i = F_{elec}Use_{elec} + F_{gas}Use_{gas} \tag{7}$$

The exergetic output of one process is obviously equal to the input of the next process, as all processes in the heating of a house are considered. Therefore, by comparing the exergetic input of two successive processes, the relative exergetic efficiency of the first process can be calculated.

For all systems with a heat storage tank, the electricity used for the pump in this circuit is incorporated in the storage exergy. The electricity for the main circulation pump is for all heat production systems incorporated in the emission, control and distribution exergetic value (Emcdis).

Figure 3 shows the exergetic comparison between the different heat production systems for the terraced house with an average insulation quality and low temperature radiators. Each bar in the graph represents the exergy input of the indicated process. Striking is the difference in exergy input (represented by the first bar, 'Generation' in Figure 3) for heat pumps versus the other systems. Heat pumps loose substantially less exergy in the heat generation process: small amounts of high quality energy (electricity) are used to transform low quality energy (heat at the low temperature of the source) into a higher quality of

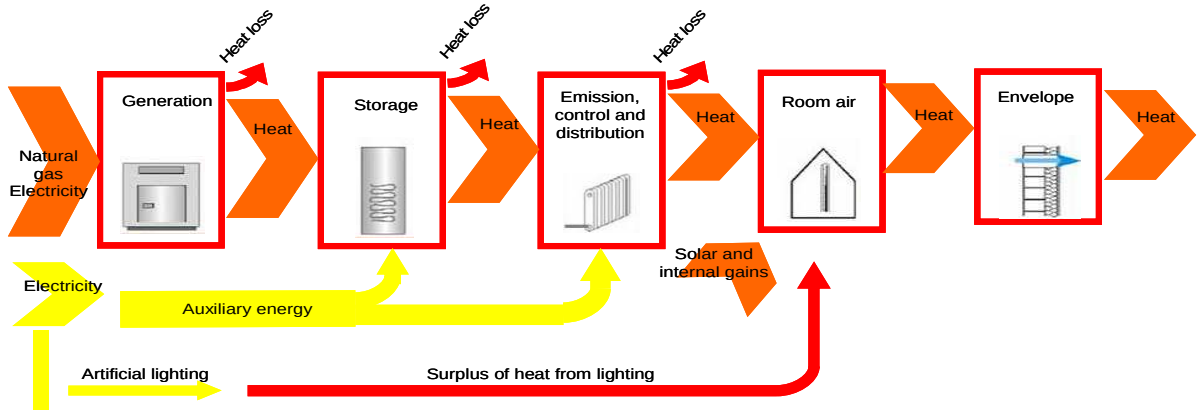

Figure 2. Overview of the different steps in the exergy analyses of domestic heating (in accordance to Schmidt, 2004, modified).

energy (heat at the temperature necessary for heating). This way, high quality energy, and thus energy with a high exergetic value, is used in an efficient way.

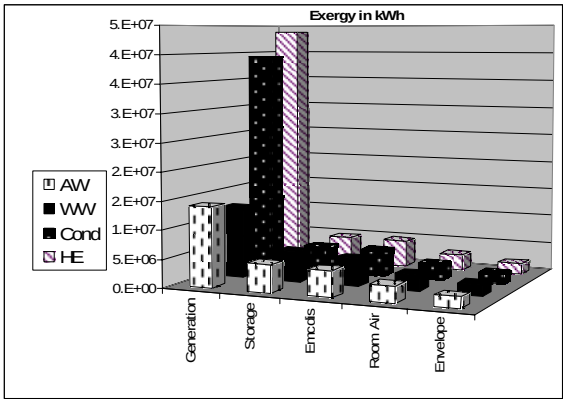

Figure 3. Exergetic comparison between different heat production systems in the averagely insulated house with low temperature radiators.

This is also visible in Table 5, where the relative efficiency for all processes is shown. This table also gives the overall efficiency of the whole heating process: $Ex_{Envelope}/Ex_{Generation}$.. The exergetic loss in the heat production step (Ex_{Emcdis} versus $Ex_{Generation}$) is substantially larger for the gas boilers and the CHP. The storage step does not lead to high exergetic losses. The emission is responsible for an important exergetic decrease, even more than the losses through the building envelope.

In Figure 4 the results for a condensing boiler with different heat emitters are shown. It is clear that the floor heating performs worse than the radiators. The reason is its lower control efficiency, due to the large thermal lag of the heavy emitter, which leads to higher average temperatures (Van der Veken et al., 2005) and therefore larger exergetic losses compared to radiators. This effect is more important than the lower water temperatures in floor heating systems.

Table 5: Exergetic efficiency (%) for different heat production systems in the averagely insulated house with low temperature radiators.

	$\frac{Ex_{Envelope}}{Ex_{RoomAir}}$	$\frac{Ex_{RoomAir}}{Ex_{Emcdis}}$	$\frac{Ex_{Emcdis}}{Ex_{Storage}}$	$\frac{Ex_{Storage}}{Ex_{Generation}}$	$\frac{Ex_{Envelop}}{Ex_{Generation}}$
HP AW	67.3	62.2	95.9	33.8	13.6
HP WW	67.2	58.4	91.8	42.0	15.1
			$\frac{Ex_{Emcdis}}{Ex_{Generation}}$		
Cond	68.3	61.8	11.5		4.9
HE	67.1	60.6	10.7		4.4

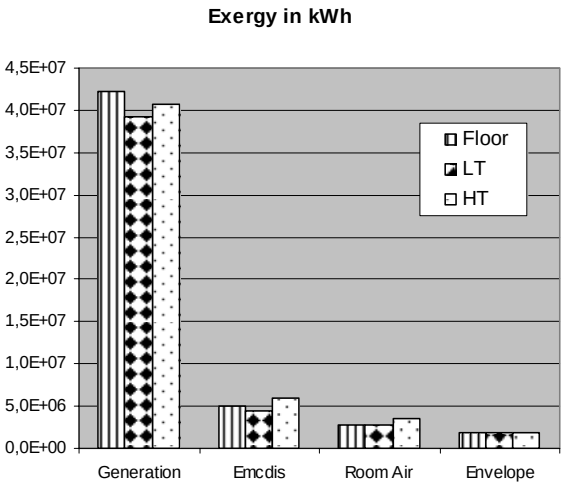

Figure 4. Exergetic comparison between different emission systems in the averagely insulated house heated by a condensing boiler.

The high temperature of the water used in HT radiators leads to higher exergy values at the level of room air, emission and distribution (Emcdis). At heat

generator level, the difference between the emission systems is relatively smaller since the combustion temperature remains the same. The only difference there, is due to the difference in heat demand of the next steps in the house heating process. The combination of these two facts leads to a lower exergy decrease (thus higher exergy efficiency), in the case of HT radiators, when comparing the output of the generation process to its input (Ex_{Emcdis} versus $Ex_{Generation}$), as also shown in Table 6, where the exergetic efficiencies are given.

Table 6: Exergetic efficiency (in %) for a condensing boiler combined *with different heat emitters in houses with different insulation quality.*

	$\frac{Ex_{Emcdis}}{Ex_{Generation}}$	$\frac{Ex_{RoomAir}}{Ex_{Emcdis}}$	$\frac{Ex_{Envelope}}{Ex_{RoomAir}}$	$\frac{Ex_{Envelope}}{Ex_{Generation}}$
AVERAGE INSULATED HOUSE				
Floor	12.0	55.5	67.9	4.5
LT	11.5	61.8	68.3	4.9
HT	14.7	58.3	54.9	4.7
WELL INSULATED HOUSE				
Floor	12.1	53.0	68.9	4.4
LT	11.8	59.1	69.1	4.8
HT	14.6	56.1	56.6	4.6
HEAVILY INSULATED HOUSE				
Floor	11.9	54.0	71.0	4.6
LT	11.6	57.9	71.3	4.8
HT	13.8	55.7	59.4	4.6

A lower insulation quality implies a higher heat demand and more losses to the environment, as shown in Figure 5, but the ratio of envelope exergy versus generation exergy, does not depend on the insulation quality of the house. This is difficult to check on Figure 5, but the last column of Table 6 leaves no doubts.

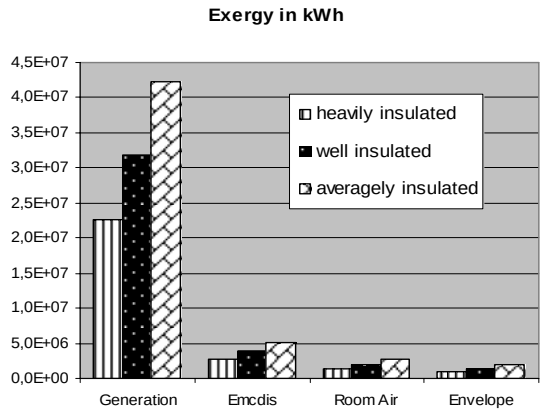

Figure 5. Exergetic comparison between houses with different insulation levels heated by a condensing boiler and floor heating.

This last conclusion, the independency of the relative exergy degradation process by process, towards the insulation level, can be generalised as can be seen in Table 6 and this allows us to make a pie-chart of these degradations in Figure 6 that can represent the three differently insulated houses. The relative exergy loss of the input of each process in the heating chain versus its output, is the same for all houses with an equal heating system (production, storage, distribution, control and emission) and does not depend on the insulation quality of the house.

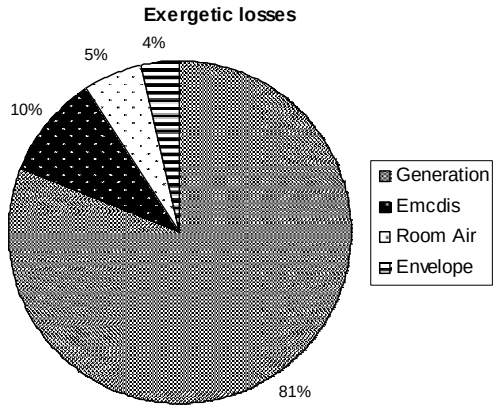

Figure 6. Exergy degradation per step from generation to envelope losses for a condensing boiler combined with floor heating.

Economy

The economic study is based on the principles presented by Verbeeck & Hens (2005). The insulation quality of the building is considered as a boundary condition in the search for an optimal heating system. Therefore, only the costs of the heating system are taken into account for the economic study. The investment and replacement costs include the costs of the heat production system, the distribution, emission and control system, but also Value Added Tax (VAT) and labour costs. Values for heat pump prices can be found in Lhoëst et al. (2003).

A building usage period of 30 years was assumed, which is the average ownership time of a building in Belgium. 20 and 15 years were taken as the lifetime of boilers and heat pumps, respectively (Verbeeck & Hens, 2005), and (Lhoëst et al., 2003). Together with recent Belgian energy prices, a net discount rate of 5%, a yearly net increase of the energy prices with 2%, and no yearly net increase of the investment and maintenance costs have been assumed. This leads to the results for varying envelope insulation qualities presented in Table 7, Table 8 and Table 9.

The investment cost appears to be the most important contribution to the total cost. The cheapest solution for an average insulated building consists of a high-efficiency boiler with high-temperature radiators. The latter has a annual energy cost of 543 € but this is still

the cheapest option over the building life of 30 years. Also investing in a condensing boiler does not pay back over time, although a condensing boiler with high-temperature radiators is coming very close. A modern modulating room thermostat that can lower the boiler temperature when the room temperature is near the set point can further improve this option.

Table 7: Investment cost I0, yearly gas cost KE_{gas}, yearly electricity cost KE_{elec} and NPV for all system configurations in the averagely insulated building.

	I0	**KE_{GAS}**	**KE_{ELEC}**	**NPV**
	(1000 €)	**(€/year)**	**(€/year)**	**(1000 €)**
FLOOR HEATING				
HP AW	13.4	0	477	24.9
HP WW	20.5	0	421	31.9
Cond	13.2	498	35	27.4
HE	12.2	543	30	26.8
LOW TEMPERATURE RADIATORS				
HP AW	13.2	0	507	25.2
HP WW	20.3	0	436	31.9
Cond	13.0	469	30	26.5
HE	12.0	515	27	26.0
HIGH TEMPERATURE RADIATORS				
Cond	11.5	483	27	25.2
HE	10.5	519	24	24.5

The excellent SPF of the water-to-water heat pump is counteracted by the high investment cost. The air-to-water heat pump has still a fairly good SPF and has a competitive price at the same time. The ideal heat emitter for this type of heat pump is floor heating and this combination ends second in the NPV ranking of well insulated building, as can be seen in Table 8.

When the insulation quality is increased further, the radiators sizes can be decreased, which leads to a sharper price for the low temperature systems. As described above, the floor heating is not resized and therefore, this heat emitter becomes relatively more expensive when the heat load decreases. The combination of low temperature radiators and an air-to-water heat pump installed in the best insulated building gets the lowest NPV, together with the cheap HE boiler and HT radiator combination.

Earlier studies like Verbeeck & Hens (2005) pointed out that a high level of insulation, corresponding to the average U-value of 0.2 W/(m².K) used in this study, is not the most economically viable option. However, a further increase in energy prices could change this optimum easily

Table 8: Investment cost I0, yearly gas cost KE_{gas}, yearly electricity cost KE_{elec} and NPV for all system configurations in the well insulated building.

	I0	**KE_{GAS}**	**KE_{ELEC}**	**NPV**
	(1000 €)	**(€/year)**	**(€/year)**	**(1000 €)**
FLOOR HEATING				
HP AW	12.9	0	386	22.5
HP WW	20.0	0	253	28.0
Cond	12.7	396	31	24.7
HE	11.6	428	27	23.9
LOW TEMPERATURE RADIATORS				
HP AW	12.4	0	395	22.2
HP WW	19.5	0	342	29.2
Cond	12.2	367	27	23.6
HE	11.1	399	25	22.8
HIGH TEMPERATURE RADIATORS				
Cond	11.0	381	24	22.7
HE	9.9	404	21	21.7

Table 9: Investment cost I0, yearly gas cost KE_{gas}, yearly electricity cost KE_{elec} and NPV for all system configurations in the heavily insulated building.

	I0	**KE_{GAS}**	**KE_{ELEC}**	**NPV**
	(1000 €)	**(€/year)**	**(€/year)**	**(1000 €)**
FLOOR HEATING				
HP AW	12.4	0	272	19.7
HP WW	19.4	0	238	27.2
Cond	12.1	306	29	22.4
HE	11.1	329	25	21.4
LOW TEMPERATURE RADIATORS				
HP AW	11.6	0	297	19.4
HP WW	18.6	0	258	26.7
Cond	11.3	297	25	21.3
HE	10.3	317	23	20.3
HIGH TEMPERATURE RADIATORS				
Cond	10.5	306	22	20.7
HE	9.5	317	20	19.4

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CONCLUSION

Looking at the primary energy use and CO_2emissions, the heat pumps outperform the classical gas boiler systems. In countries with primarily nuclear electricity generation, like Belgium, or renewable electricity production, heat pumps are clearly less CO_2emitting.

A cheaper air-to-water heat pump can even be one of the best economic decisions in a highly insulated building. If the building is poorly insulated, the classical boiler with high temperature radiators has still the lowest Net Present Value in spite of the high energy costs today.

Reducing the loads on the heating system by passive measures is the best solution to keep the final exergy need of the heat generation low, but this conclusion

could also be derived by assessing the (primary) energy use. Avoiding high temperatures during generation, distribution and emission is another conclusion, which leads to the choice of heat pumps, combined with a low temperature emission system.

NOMENCLATURE

τ	Time constant for heat pump
Cond	Condensing gas boiler
COP	Coefficient Of Performance
COP_{stat}	Coefficient Of Performance for static behaviour
COP_{dyn}	Coefficient Of Performance taken into account dynamic behaviour
Envelope	Building Envelope
Emcdis	Emission, Control and distribution
Ex_i	Exergetic input of process i
Fl	Floor heating in the day zone and low Temperature radiators in the night zone
$F_{q,i}$	Quality factor for process i
GWP	Global Warming Potential
HE	High Efficiency gas boiler
HHV	Higher Heating Value
HP AW	Air-to-water heat pump
HP WW	Water-to-water heat pump
HT	High Temperature radiators
KE_{elec}	Yearly electricity cost
KE_{gas}	Yearly gas cost
LT	Low Temperature radiators
Q_{basis}	Thermal power at -10°C outside temp. and 60°C water outlet temperature
Q_{dyn}	Thermal power taken into account dynamic behaviour
Q_i	Energy input of process i
Q_{stat}	Thermal power in static conditions
T_0	Reference temperature
T_{ext}	Outside temperature
T_i	Temperature at which process I takes place
T_{stor}	Temperature of water from storage tank to heat pump
NPV	Net Present Value
SPF	Seasonal Performance Factor

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