Economy, energy and ecology based comparison of heating systems in dwellings

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ABSTRACT: This paper presents the results of a simulation study in which different heat production systems are installed in a TRNSYS16-model of a terraced house. Micro Combined Heat and Power units, regular high efficiency boilers, condensing boilers and water to water heat pumps are considered. High-temperature radiators, low-temperature radiators and floor heating are simulated as heat distribution systems. The evaluation is based on the gross energy consumption, the amount of Greenhouse Gases emitted, the primary energy use and the Net Present Value over the lifetime of the building.

NOMENCLATURE

CHP	Combined Heat and Power
Cond	Condensing gas boiler
COP	Coefficient Of Performance
Fl	Floor heating in day zone combined with low temperature radiators in night zone
GHG	Greenhouse Gases
HE	High-Efficiency gas boiler
HP	Heat Pump
HT	High Temperature radiators
LT	Low Temperature radiators
NPV	Net Present Value
SPF	Seasonal Performance Factor

1 INTRODUCTION

Alternative energy systems for residential use are gaining consideration. Introducing small scale, energy efficient and environmental friendly systems in such a vast market would have a considerable impact on the global energy use and the emission of greenhouse gases. Although these systems perform well in test conditions, the question remains whether they outperform classical boilers once they are installed in the building.

Therefore, TRNSYS16v1.037 is used to model a typical Belgian terraced house with different types of heat production systems, each of them combined with a compatible heat distribution system. These simulations allows us to compare the energy efficiency, as well as the ecological and economic merits of the different heating system set ups in the building, based on primary energy use, CO_2-emissions and Net Present Value, respectively.

The assessed heat production systems include CHP systems, heat pumps, condensing gas boilers and high efficiency gas boilers, while the heat distribution systems considered are high-temperature radiators, low-temperature radiators and a system of floor heating in the day zone combined with low-temperature radiators in the night zone. The CHP units and the heat pumps are, contrary to the boilers, not directly connected to the heat distribution system, but the produced heat is buffered in a stratified storage tank.

To study the performance of the different production and distribution systems installed in the building, the total efficiency of the system at building level is calculated. This means that not only the heat emitted by the radiators or floor heating is regarded as useful, but also heat “losses” from production and distribution systems contributing to intended temperature increase. In other words, the whole building forms the system and only unused heat that flows to the exterior is considered as a loss. To determine the advantages and drawbacks of the heating systems, the total efficiency is then subdivided in production, storage, distribution and control efficiency.

2 MODELS

The building is a compact terraced house with an outer volume of 446 m³ and an exterior surface of 256 m². Together with an average U-value of 0.8 W/m²K and non-forced natural ventilation dimensioned following the Belgian standard (BIN 1992), this leads to a net energy demand of 10181 kWh. 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 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 system is controlled by a four-way valve and a proportional controller. The radiators used are based on Type 72 from IEA annex 17, but numerically optimized by Kummert (2001).

The heat is emitted to the zone, partly as convective energy to the zone air point 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%. 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. hysteresis (Ast 1988). To focus on the behaviour of the system in 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 to and from the radiators.

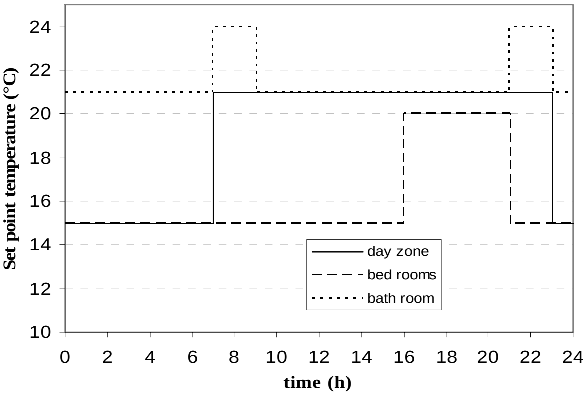

Figure 1 Set point temperatures for the day zone, night zone and bath room.

A condensing and a non-condensing boiler are modelled in TRNSYS as a combination of an ideal heater and two water pipes. The capacity of the water in these pipes is set equal to that of the boiler and with a correct pipe 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 is reached. In the other case, when the heat demand is too low, the boiler cycles to keep a minimal temperature, and boiler heat is slowly added to the distribution system. Finally, without heat demand, the boiler can cool down to temperature of its zone.

The efficiency of the gas-water heat exchanger is derived from information of the boiler producers and two EES-models developed at the thermodynamics laboratory from the ULG (Lebrun, pers. comm.). 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 can only keep their efficiency when modulating (Van der Veken et al. 2005).

The circulation pump installed, consumes 50 Watt during operation, of which 75% is transferred into heat injected into the water circuit and 25% is lost to the zone air. The condensing boilers are equipped with a ventilator of 70 Watt, while for the high-efficiency boilers 40 Watt is sufficient. This mechanical energy is also converted into heat but lost through the chimney, which is taken into account by reducing the boiler efficiency.

The high-efficiency boiler has a fixed outlet temperature of 90°C when combined with high-temperature radiators and 50°C in combination with low-temperature radiators or the combination of floor heating and radiators. In contrast, the outlet temperature of the condensing boiler depends on the outside temperature. The reason to install no weather compensation control on high efficiency boilers is the negligible impact of this control on its efficiency (Van der Veken et al. 2005). Both boilers will be turned off when the daily average outside temperature rises above 12°C, since at that time of the year there is no net heat demand anymore.

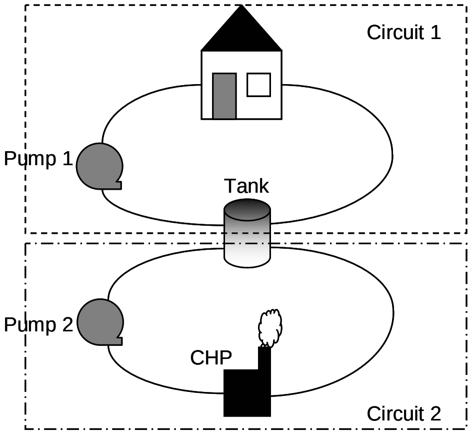

Figure 2: Schematic view of the CHP-configuration

The CHP model is based on the above described model of a modulating condensing boiler, combined with measurements on a Stirling CHP-unit (Mertens & Mertens 2005). The boiler model, however, is slightly adapted, since the storage tank makes a minimal boiler temperature at low demands unnecessary. The thermal power of the CHP-model unit can vary from 5.2 to 8 kW, whereas the electric power ranges between 0.4 and 1.25 kW in stationary regime. The CHP-unit is not directly connected to the water distribution system. In fact, two separated circuits can be observed, as illustrated in Figure 2.

Circuit 1 is the heat distribution loop, with its own pump and its own control system as described above, and this circuit is connected to high- or low-temperature radiators. Circuit 2, on the other hand, is the heat production loop. More precisely, heat is produced by the CHP-unit and stored in the stratified storage tank. This circuit also has its own pump and control system. The pump is running at the same time as the CHP as well as 15 minutes after turning off the CHP-unit, to assure that all heat available in the CHP-unit is transported to the storage tank. The stratified storage tank is modelled by a type 4 TRNSYS-model (SEL 2004), the number of layers is set equal to 8, the tank volume to 1000 litre.

The CHP-unit is turned on when the temperature of a certain layer is too low; the temperature as well as the layer depends 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 supplied with heat. No heat will be produced when the average outside temperature rises above 12°C. A dead band on the desired tank temperature, as well as a minimum fixed on and off time, prevents continuous pump and CHP cycling.

The water-to-water heat pump is modelled by a TRNSYS type 668 (Thornton et al. 2004). It is a non-modulating heat pump which delivers 9.52 kW with a source temperature of 10 °C and a supply water temperature of 35 °C (COP of 4.4). The heat pump configuration can be represented by replacing the CHP-unit in Figure 2 by a heat pump. Analogous to the CHP-model, the pump in circuit 2 will be turned off 15 minutes after the heat pump and also continuous on-off- switching is prevented similarly. More precisely, the model accounts for a fixed time on or off, a dead band on the temperature of the tank, and a variable amount of layers heated. To reduce costs, the use of off-peak electricity is given a light preference, by increasing the desired tank temperature at night. The pump, as well as the stratified storage tank, has the same characteristics as in the CHP-configuration.

The heat distribution systems, modelled in the heat pump configuration are low-temperature radiators and a combination of floor heating in the day zones and low-temperature radiators in the night zone.

3 METHODS

To determine the yearly average control, distribution, storage, production and total efficiencies at building level, one simulation per heating configuration does not provide sufficient information. Instantaneous production efficiency at system level could be easily defined as the ratio of the heat delivered to the storage circuit to the energy that the system consumes to produce that heat at that moment. At building level, however, part of the production losses into the building are recuperated by useful temperature increases in adjacent zones. Furthermore, by yearly averaging the efficiencies, recuperation of waste heat over time can take place as well. Therefore it is necessary to perform five simulations per heating system. These simulations are described in Figure 3.

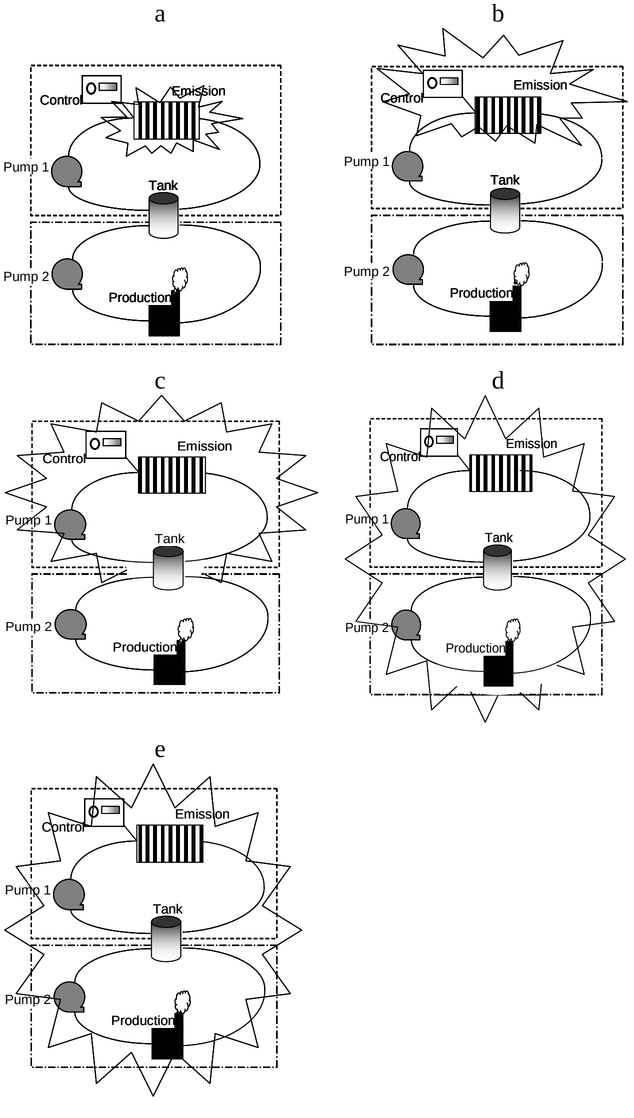

Figure 3: Schematic view of 5 simulations with different heat emitting properties to determine partial and total efficiencies at building level

Figure 3 a represents the net heat demand, which is the minimal energy needed during the heating season to obtain the desired set point temperatures. It is determined as the heat consumption of an ideal heating system with perfect control which is available in TRNSYS. Since the total heat system is perfect, this net energy demand will be the same for all heating system configurations.

Figure 3b represents the simulation with perfect heat distribution, storage and production, so that the only remaining loss factor is the control inefficiency.

Figure 3c represents perfect heat storage and production, but distribution pump and pipes that give off heat to their environment and a control system that is not perfect.

The simulations represented by Figure 3d have only a perfect production system and, finally, Figure 3e shows the real situation in which the production, storage and distribution systems “loose” heat and the control shows an off set.

To determine the total efficiency of the heating system at building level as defined above, the net heat demand (3a) is divided by the annual energy consumption (3e). The energy consumption is the sum of the energy consumed by the production system where the electricity of all auxiliary appliances should not be forgotten.

The control efficiency is then defined as the ratio of the energy consumptions of simulations with (3a) and without perfect control (3b). The distribution efficiency is defined similarly, by dividing the yearly consumption of the simulation without (3b) and with distribution losses (3c). The denominator of the storage efficiency can be calculated by the simulation with storage losses (3d) while the numerator is the energy consumption of simulation (3c) again. Finally, the production efficiency is defined by dividing the energy necessary to heat the building with a perfect production system (3d) by the total energy consumption (3e).

The economic analysis is based on Net Present Value calculations, as explained by Verbeeck & Hens (2005). All prices for the heat distribution system are based on the average of a market study with the help of several Belgian heating contractors. Prices for the heat production systems are available from D’haeseleer et al. (2004) and Lhoëst et al. (2003), Chimneys (not in case of a heat pump), boilers, CHPs, heat pumps and vertical heat exchangers, gas connections, electric auxiliaries, the distribution network, radiators, thermostatic valves, floor heating as well as 21% VAT (current VAT in Belgium for new buildings) and labor costs are taken into account.

4 RESULTS

Table 1 summarizes the resulting efficiencies of all simulated configurations. Table 2 shows the yearly average temperatures of the whole building and the storage room, where the heat production system is installed.

Comparing the control efficiencies of all configurations, it is shown by Table 1 that low-temperature radiators outperform the other distribution systems considered. The better performance is also illustrated by the lower average temperature in the rooms, as can be seen in Table 2.

Table 1. Efficiencies of a high-efficiency boiler, a condensing boiler, a heat pump and a CHP-unit when coupled to a floor heating system, high-temperature or low-temperature radiators.

Heating System	$\eta_{control}$ (%)	$\eta_{distribution}$ (%)	$\eta_{storage}$ (%)	$\eta_{production}$ (%)	η_{tot} (%)
HE HT	93.7	97.7	100	83.0	76.0
HE LT	95.2	97.9	100	84.4	78.7
HE Fl	86.2	97.2	100	83.6	70.1
Cond HT	94.4	97.5	100	86.4	92.1
Cond LT	96.1	98.0	100	91.6	94.2
Cond Fl	87.2	97.4	100	92.4	84.9
HP LT	94.5	98.8	98.9	265	244
HP Fl	89.9	98.9	99.4	285	251
CHP HT	93.9	97.9	98.8	77.7	70.6
with electricity production				90.0	81.8
CHP LT	95.5	97.4	99.3	81.8	75.6
with electricity production				94.1	86.9

Table 2 Yearly average temperatures over all rooms and of the storage room for all configurations

Heating System	Average all rooms (°C)	Average storage room (°C)
HE HT	21.15	24.68
HE LT	20.91	23.19
HE Fl	21.30	24.02
Cond HT	21.02	24.72
Cond LT	20.91	23.19
Cond Fl	21.42	24.81
CHP HT	21.92	25.83
CHP LT	20.91	23.50
HP LT	21.16	21.15
HP Fl	21.50	21.03

Since reaching at least the set point temperature is a precondition, a lower average temperature means less overheating. The large thermal lag of the floor heating systems results in a smaller temperature drop at night. Furthermore, when discontinuous solar heating and free gains enter the zone, floor heating reacts slower and the room temperature rises above the set point (Van der Veken et al. 2005). Finally, the control is measuring dry air temperature in these simulations, which disfavours floor heating systems, since they radiate more energy than radiators. This last remark also applies to the two types of radiators, since the low-temperature radiators have more panels and welded on lamellas and therefore working more convectively than high-temperature radiators.

Comparing the different heat production systems for each heat distribution system, it is shown by Table 1 that the condensing boiler leads to the highest control efficiencies. This is due to the implemented outside temperature sensor, which directly influences the temperature of the distributed water. In case of the CHP and the heat pump, the outside temperature sensor determines the temperature of the layers in the stratified storage tank. The high efficiency boiler is not driven by the outside temperature and therefore has lower control efficiency.

The distribution efficiency is around 98% for all systems, although the piping of high-temperature systems looses more than double the amount of energy lost by low-temperature systems. Since all the piping is in the protected volume, around 87% of the distribution losses can be recuperated.

Comparing the storage efficiencies, it is clear that storing high temperature water leads to higher losses, which is confirmed by the storage room temperatures shown in Table 2.

Production efficiencies are the highest for the simulated heat pump. The water to water heat pump results in a SPF of 2.73 in case of low-temperature radiators system and 3.01 in case of floor heating, while in test conditions a COP of 4.4 was reached. This difference is due to the fact that heat pumps are highly sensitive to the temperature difference at which they have to work, more precisely the lower the temperature difference, the better the performance. The floor heating system shows the lowest temperature difference, but the higher SPF is compensated a little by lower control efficiency. Nevertheless, the total efficiency is still the highest for the floor heating coupled heat pump.

Comparing the efficiencies of the boilers, it is clear that high-efficiency and condensing boilers result in comparable production efficiency when combined with a high temperature distribution system. However, when condensing boilers are combined with a low temperature distribution system, they perform much better than high-efficiency boilers. This is due to the utilization of the latent heat of the exhaust gases, which can only take place at temperatures below circa 60°C. Under this threshold, the production efficiency rises sharply.

The condensing boiler coupled to the floor heating system performs even better due to the steady energy consumption, which means more time at part load, for which the condensing boiler has higher efficiencies.

The simulated CHP-unit, which is in fact a condensing boiler equipped with a Stirling engine, shows the same tendencies. In Table 1 the thermal and the total efficiencies are given for the CHP-unit. The thermal production efficiency as such, is quite low, but if we take the electric production into account, the total production efficiency looks very promising.

4.1 *Energy*.

The comparison is based on the energy consumed to reach the thermal comfort conditions as determined by the set temperatures. As the CHP unit produces electricity besides heat, the primary energy consumed to produce the same amount of electricity by the electricity generation system needs to be taken into account as well. Therefore an allocation method (Commission Ampere 2001) is used to allocate the energy use proportionally to heat and electricity respectively. The conversion coefficient[1] between primary energy and electricity is assumed to be 2.5; for gas this value is taken equal to 1 (Verbeeck & Hens 2005). The use of electricity for pumps and fan is taken into account.

As indicated by Table 3, heat pumps perform better than gas boilers when focusing on primary energy use. Considering the total efficiencies in terms of primary energy, the results for heat pumps in Table 1 must be divided by 2.5 (conversion factor for electricity). This results in a value of 97.6% for the HP-LT system and 100% for the HP-Floor system. These values confirm the results given in Table 3.

Table 3. Gross and primary energy consumption for all simulated configurations.

Heating System	Gross energy use gas	Gross energy use electricity	Primary energy use
	(MWh)	(MWh)	(MWh)
HE HT	12.1	0.23	12.5
HE LT	11.6	0.26	12.1
HE Fl	13.1	0.35	13.7
Cond HT	11.8	0.32	12.6
Cond LT	10.8	0.33	11.7
Cond Fl	11.8	0.44	12.9
HP LT		4.07	10.2
HP Fl		4.04	10.1
CHP HT	12.4		12.4
CHP LT	11.6		11.6

The simulated CHP-unit has an electric efficiency of 10 to 13%. Decreasing the ratio between thermal and electric power, and thus producing more electricity, would decrease the primary energy allocated to heat. In that case, both alternative heating systems would outperform the traditional boilers.

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[1] No distinction is made for conversion coefficients of different countries, as nuclear and fossil primary energy cannot be compared easily.

The SPF of the heat pump is a factor of major importance, as explained earlier. A small decrease of 1% in the SPF value would result in a 1% rise of the electricity consumption and a 1% increase of the primary energy use.

All other configurations lead to results that could be expected based on the results given by Table 1.

4.2 *Ecology*

The ecological comparison is based on the amount of CO_2 emitted by the different heat production systems; NO_x, CO and other pollutants are not considered. Also for this analysis, allocation is used.

The CO_2-emissions associated with natural gas and electricity are given in Table 4 (Commission AMPERE 2000). The composition of the electricity generation system, and its effect on the emitted CO_2 for France, Germany, and Belgium is evaluated by Commission AMPERE (2000), Luickx et al. (2005) and Peersman et al. (2002).

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

Energy source	Country	CO_2-emission (kg/kWh)
Natural gas	Belgium	0.209
Electricity	France	0.060
Electricity	Germany	0.590
Electricity	Belgium	0.310

Table 5: Total annual CO2-emissions for all heating system configurations.

Heating system	Total annual CO2-emissions France (tons/year)	Germany (tons/year)	Belgium (tons/year)
HE HT	2.53	2.69	2.59
HE LT	2.45	2.59	2.51
HE Fl	2.75	2.94	2.84
Cond HT	2.49	2.66	2.57
Cond LT	2.29	2.46	2.37
Cond Fl	2.50	2.74	2.61
HP LT	0.24	2.40	1.26
HP Fl	0.24	2.39	1.25
CHP HT	2.60	2.60	2.60
CHP LT	2.44	2.44	2.44

Table 5 indicates that heat pump heating leads to the lowest CO2 emissions in France and Belgium. This is due to the high amount of nuclear power plants in their electricity generation system, especially in France. In Germany, however, where fossil fuel plants dominate the electricity production, heat pump heating leads to moderate results. The impact of the electricity produced by the CHP depends on the electricity generation park of the country considered. Due to the low electrical efficiency, this is not pronounced in these results. Increasing the electrical efficiency, however, would lead to the best ranking of these systems in Germany. Condensing boilers combined with a low temperature distribution system lead to low emissions as well. The worst combination for all countries is a high efficiency boiler with floor heating, what could be expected based on the results of Table 1.

4.3 *Economy*

The economic study is based on the principles presented by Verbeeck & Hens (2005). As the building itself does not change with the different heating systems, only the cost of the heat production system and the heat distribution system, are taken into account for the economic study. This includes the cost of extra floor insulation under floor heating systems.

As mentioned before, the investment and replacement costs include the heat production system, the distribution, emission and control system, but also VAT and labour costs. Values for the price of Stirling CHP-units are given by D’haeseleer & Haeseldonckx (2004), 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, 18 and 15 years were taken as the lifetime of boilers (Verbeeck & Hens 2005), CHP-units (Whispertech, pers. comm.) and heat pumps (Lhoëst et al. 2003), respectively. 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 following results:

Table 6: Investment cost I_0, yearly gas cost K_E gas, yearly electricity cost K_E elec and NPV for all system configurations

Heating system	I0 (1000 €)	KE gas (€/year)	KE elec (€/year)	NPV (1000 €)
HE HT	10.5	534	35	25.0
HE LT	12.0	518	41	26.3
HE Fl	12.2	574	53	27.8
Cond HT	11.5	506	51	26.1
Cond LT	13.0	473	54	27.0
Cond Fl	13.2	530	67	28.6
HP LT	20.2	0	602	37.2
HP Fl	20.4	0	595	37.3
CHP HT	13.7	610	-230	27.6
CHP LT	15.2	588	-258	28.1

The investment cost appears to be the most important contribution in this economic study; although the CHP-unit with LT-radiators reduces the total yearly energy cost to 330 €/year, the cheapest solution consists of a high-efficiency boiler with high-temperature radiators. The latter has a yearly energy cost of 569 € but this is still the cheapest option over the building life of 30 years. Also investing in a condensing boiler is not paid back in time, although a condensing boiler with high-temperature radiators is coming 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.

The high SPF of the heat pumps does not compensate for the high investment and electricity cost and therefore this heating system comes out as most expensive option. The investment cost can be lowered by choosing for a cheaper heat exchanger (e.g. air-water), but also a further shift to heat production during night can significantly reduce the electricity cost without influencing the SPF (Peeters et al. 2005).

Reducing the discount rate to 2% or increasing the building life time of the building to 100 years, brings the NPV results closer to each other but does not change the NPV order. The results are more sensitive to the energy costs. Until recently, the natural gas price has been following the oil price quite closely from 0.023 €/kWh in 1999 to 0.045 €/kWh in the beginning of 2006 (GASINFO 2006). If the residential heating oil and natural gas price would rise further to 0.1 €/kWh, which is equivalent to a crude oil price of circa 100 $/barrel, the economic outlook looks much different as demonstrated in Table 7.

Table 7: Investment cost I_0, yearly gas cost K_E gas, yearly electricity cost K_E elec and NPV when the gas price would double but the electricity price would remain constant.

Heating System	I_0 (1000 €)	K_E gas (€/year)	K_E elec (€/year)	NPV (1000 €)
HE HT	10.5	1220	34	38.5
HE LT	12.0	1180	39	39.3
HE Fl	12.2	1317	51	42.5
Cond HT	11.5	1151	48	38.8
Cond LT	13.0	1071	51	38.8
Cond Fl	13.2	1209	64	42.0
HP LT	20.2	0	576	37.9
HP Fl	20.4	0	571	38.0
CHP HT	13.7	1407	-219	41.7
CHP LT	15.2	1353	-246	41.6

In the case of these high gas prices, the most expensive option of Table 6, the heat pump, becomes economically the most interesting option and the high-efficiency boiler with HT-radiators is almost as expensive as the condensing boilers with radiators.

With increasing fossil energy prices, the electricity cost would probably increase as well. However, this correlation is hard to estimate and largely depends on the existing electricity generation system mix. The electricity price in Belgium, for example, has not followed the fossil fuel price during the last years, thanks to the liberalisation of its energy market and its large share of nuclear power. However, when a perfect correlation would occur and the electricity price would double as well, results are given in Table 8.

Table 8: Investment cost I_0, yearly gas cost K_E gas, yearly electricity cost K_E elec and NPV when the gas and electricity price would double.

Heating System	I0 (1000€)	KE gas (€/year)	KE elec (€/year)	NPV (1000€)
HE HT	10.5	1220	66	39.2
HE LT	12.0	1180	76	40.1
HE Fl	12.2	1317	100	43.4
Cond HT	11.5	1151	95	39.8
Cond LT	13.0	1071	100	39.8
Cond Fl	13.2	1209	126	43.2
HP LT	20.2	0	1141	49.1
HP Fl	20.4	0	1133	49.1
CHP HT	13.7	1407	-430	37.5
CHP LT	15.2	1353	-481	37.0

In this case, CHP is economically the most viable option and the heat pump falls back to the end of the ranking, due to their high sensitivity towards electricity pricing. The cheapest boiler option, the high-efficiency boiler with HT-radiators, is on the long run performing better than the condensing boilers, due to the lower electricity consumption of its ventilator and circulation pump.

Finally, the investment cost can also be correlated with the energy price, due to higher manufacturing and transport costs. Table 9 shows the results when the initial cost increases with 25%. The cheaper options, like boilers and HT-radiators will perform a little better, but the NPV of the CHPs will still be the lowest. Furthermore, these alternative heating systems have more potential to become relatively cheaper once they are mass produced.

Table 9: Investment cost I_0, yearly gas cost K_E gas, yearly electricity cost K_E elec and NPV when the gas and electricity price would double and the investment cost would rise with 25%.

Heating System	I0 (1000 €)	KE gas (€/year)	KE elec (€/year)	NPV (1000 €)
HE HT	13.1	1220	66	42.0
HE LT	14.9	1180	76	43.2
HE Fl	15.2	1317	100	46.7
Cond HT	14.4	1151	95	42.9
Cond LT	16.3	1071	100	43.3
Cond Fl	16.5	1209	126	46.8
HP LT	25.3	0	1141	54.7
HP Fl	25.5	0	1133	54.8
CHP HT	17.1	1407	-430	41.5
CHP LT	19.0	1353	-481	41.3

5 CONCLUSIONS

Regarding the primary energy use and CO_2-emissions, heat pumps outperform the classical gas boiler solutions. In countries with primarily nuclear or renewable electricity production, heat pumps are clearly less CO_2-emitting. On the other hand, in countries that use primarily fossil fuels to produce electricity, residential electricity production by CHP systems can significantly reduce the CO_2-emissions.

However, with today's energy prices the classical high-efficiency boiler is still economically the most feasible option. In spite of the higher yearly energy cost, the low investment cost of these boilers leads to the lowest net present value. Governmental support for alternative energy systems could make them economically more interesting, but also the volatile energy market is a driving force in this direction. Higher electricity prices will favour CHP-units, while heat pump systems benefit from higher gas prices.

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