Energy Policy 40 (2012) 452–464

Contents lists available at SciVerse ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Environmental and economic performance of heating systems for energy-efficient dwellings: Case of passive and low-energy single-family houses

L. Georges [a,b,*], C. Massart [a], G. Van Moeseke [a], A. De Herde [a]

[a] Architecture et Climat, Université catholique de Louvain (UCL), Place du Levant 1, B-1340 Louvain-la-Neuve, Belgium
[b] Department of Energy and Process Engineering, Norwegian University of Science and Technology (NTNU), Kolbjørn Hejes vei 1B, 7491 Trondheim, Norway

ARTICLE INFO

Article history:
Received 20 April 2010
Accepted 20 October 2011
Available online 9 November 2011

Keywords:
Heating systems
Passive house
Cost-benefit analysis

ABSTRACT

In order to reduce the energy consumption of the building stock, a major trend is to drastically reduce the space-heating (SH) needs by improving the thermal performance of the envelope. In general, this measure is combined with efficient heating systems to minimize the delivered energy and greenhouse gas emissions. Nevertheless, these better systems are often more expensive so that the extra-investment could be hardly recovered for small-scale energy consumption. The main objective of the article is to show how equilibria between cost-effectiveness and environmental performance of heating systems are changed when small SH needs are considered (i.e. for passive and low-energy houses). The scope is limited to new single-family dwellings. Furthermore, the passive house standard provides means of simplifying the SH by using the ventilation air: the idea is that savings should counterbalance the extra-investment in super-insulation. In theory, a new global economic optimum is generated at the passive house level. The second objective of the work is to study which conditions could lead to this new optimum. Only a detached-house typology is investigated to address this last issue. Regarding methodology, all the investigations are done considering the Belgian context. Energy and environmental performance is evaluated using a method that complies with the EN-15603 and EN-15316 standards.

1. Introduction

Considering the global warming issue, the importance of reducing the emissions of greenhouse gases (GHG) from the building stock does not need to be demonstrated any more. A typical measure is reducing our energy needs and subsequently using energy-efficient solutions. The attractiveness for an end user for investing in an energy-savings measure strongly depends on its ability to combine cost-effectiveness with good environmental performance. The present article analyzes this equilibrium for heating systems in low-energy single-family houses. The rationale of the study as well as the two specific objectives addressed in the paper are developed in the remainder of this section.

1.1. Performance of energy supply systems in well-insulated envelopes

In order to reduce the environmental impact from the building stock, the main trend is to drastically reduce the space-heating (SH) needs. Basically, this is done through a large insulation of the building envelope to reduce the transmission losses. Given the level of efficiency that has to be reached, infiltration and ventilation losses are also important. Infiltration has therefore to be minimized by ensuring the air-tightness and ventilation has to be controlled. When these losses are sufficiently reduced, the internal and solar gains can counterbalance a significant part of the remaining losses so that the *net energy need* to be covered by the SH system is relatively low. This approach to reduce the net SH need is well depicted by the passive house concept (Feist et al., 2001). This standard stipulates reaching a maximum of 15 kWh/m^2 year of net SH need, a level that is far below the mean performance of the Belgian building stock (roughly 10 times lower ICEDD, 2008).

Once the net energy need is reduced, it has to be produced using efficient energy supply systems. In general, this is a mandatory condition to minimize delivered energy consumption.

* Corresponding author at: Architecture et Climat, Université catholique de Louvain (UCL), Place du Levant 1, B-1340 Louvain-la-Neuve, Belgium.
Tel.: +32 10 47 21 42.
E-mail addresses: laurent.georges@ntnu.no (L. Georges),
catherine.massart@uclouvain.be (C. Massart),
geoffrey.vanmoeseke@uclouvain.be (G. Van Moeseke),
andre.deherde@uclouvain.be (A. De Herde).

0301-4215/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enpol.2011.10.037

Unfortunately, efficient systems are generally more expensive in terms of investment. For example, let us compare the investment in direct electric SH to the investment in a domestic heat pump. The first solution has a lower purchase price than the second but uses more electricity. This is particularly sensitive for energy efficient envelopes as, by definition, their net energy needs are relatively low and the energy costs during operation are therefore low. In terms of payback time, their energy costs counterbalance more slowly the extra-investment in installing the most efficient systems. This argument holds true for other heating systems than heat pumps, such as for biomass boilers and solar thermal panels. From the end user's point of view who wants to select an energy system in a well-insulated envelope, the better impact on the environment of the best systems could be hampered by their higher investment costs (that reduce their global economic performance).

Furthermore, a misleading approach is to consider that the net SH need of a well-insulated envelope is so low that interest in investing in efficient energy supply systems is no longer relevant from an environmental point of view. In other words, the net SH needs are so small that the difference in delivered energy between the different energy systems would be negligible. According to this argument, the end user should only focus on the economic performance of the energy supply systems if the net SH needs are very low.

Consequently, the first and main objective of this contribution is to answer to the following question: *is the relative performance between energy supply systems modified when the net SH needs are drastically reduced compared to the situation with standard buildings* (*represented by the current building stock*)? The performance of energy supply systems is investigated here using two major dimensions: the first is environmental efficiency, the second is the economic dimension. The environmental impact is only measured here using the total primary energy consumption and the equivalent-CO_2 emissions, while the economic performance is rated using the total discounted costs.

1.2. Performance of the passive house standard

A functional way to define a passive house is also often encountered: the maximum power required to heat a passive house is sufficiently reduced so that SH can be done by the air from the controlled ventilation (Feist et al., 2005). In fact, this corresponds to SH power that is lower than 10 W/m^2 in central Europe. In this case, by keeping the air flow rates compatible with hygienic ventilation standards, the air temperature does not need to exceed 50–55 °C to counterbalance all the thermal losses in design weather conditions: a higher temperature would indeed lead to dust carbonization in the supply air. This air can be warmed at a central location by a heating coil and then be distributed to the different thermal zones of the passive dwelling using its ventilation network. This leads to a major simplification of the SH distribution where no additional distribution system is required (e.g. a hot-water loop equipped with radiators). Finally, passive house proponents claim that the cost reduction induced by air heating can contribute significantly to counterbalance the extra-investment for insulation and a heat recovery unit (see Schnieders and Hermelink, 2006, Fig. 22; Ceera, 2008; Feist et al., 2005). As a consequence, the total costs, the sum of the investment and energy costs during operation, should have a *second economic optimum*. For new single-family houses, it is often shown that the first global optimum is located between a net SH need of 40 and 60 kWh/m^2 year. The new global optimum would be created at the passive house level (i.e. 15 kWh/m^2 year) by the simplification induced by the air heating. This is a strong argument in favor of the passive house concept as it acts against the common reluctance to make heavy investments in insulation. The building would be energy efficient as well as cost optimal which is the best combination from the end user's point of view.

The second objective of this paper is to check the last statement on the basis of the Belgian equipment market, mainly using the current prices in this country. The idea is to use results developed during the investigations of the environmental and economic performance of energy supply systems (i.e. the first objective of the paper) to better understand the conditions that could lead to the emergence of a global economic optimum at the passive house level.

1.3. Outline of the paper

The remainder of the article is organized as follows. After describing the current regulatory context in building performance and giving a short literature review in Section 2, the methodology to evaluate the environmental and economic performance is introduced in Section 3. The first question about the performance of the various energy supply systems is then evaluated in Section 4 for different net SH needs. Finally, in order to investigate the second objective of the present contribution, the global performance that couples architectonic measures to improve the envelope with different heating systems, are compared in Section 5 for one single, but typical, geometry of a detached house.

2. Regulatory context and existing contributions

The energy policy for dwellings is now briefly introduced for the region where this study concentrates on. On 16 December 2002, the first European Directive for the Energy Performance of Buildings (EPBD) (European Parliament, 2002) was adopted. The Member States had to transpose the Directive into their national laws. In Belgium, this translation termed EPB was done at the regional level (i.e. in the Flemish, Brussels-Capital and Walloon regions). For the time being, each regional EPB calculation is based on steady-state methods using monthly energy balances. In particular, Wallonia integrated the Directive into its legislation on 19 April 2007 (Walloon Government, 2007).

The extra-investment and cost-effectiveness of passive houses were analyzed in the EU-funded demonstration project CEPHEUS (Feist et al., 2001). From 1998 to 2001, 221 houses were built at the passive house standard in the five countries participating in this major experimental project. According to Schnieders and Hermelink (2006), the extra-investment for construction and engineering systems ranged from 0% to 17% of the total cost with a mean value of 8% over the different implementations. The payback time was estimated to be around 25 years of service life. According to these authors, a significant part of the additional cost was induced by the immaturity of the equipment sector and it was expected that mass production of passive house elements would lead to more favorable economic performance.

A recent contribution from Audenaert et al. (2008) performed an economic analysis of passive and low-energy houses compared to standard houses. This study considered data representative of the Flemish context but only dwellings with gas boilers were analyzed, a solution widespread in Belgium. From this study, it turns out that the payback time strongly depends on selected scenarios for the increase in the energy costs. Compared to a standard house built in accordance with the local EPB legislation, a low-energy house with an energy need of 30 kWh/m^2 year and a passive house using 15 kWh/m^2 year have a break-even time ranging from 9 to 12 years and 23 to 30 years, respectively. Typically, extra-investments were evaluated to be 4% for a low-energy dwelling and 16% for a passive house (mainly for insulation and ventilation). Finally, this led these researchers to conclude that a low-energy house is the current global economic optimum. Their study only considered the economic dimension.

In investigations by Coninck and Verbeeck (2005), Achten et al. (2009) and Renard et al. (2008), the cost-effectiveness of energy-saving measures was investigated in the context of the Brussels, Flemish and Walloon regions, respectively. These multi-criteria studies considered the economic aspects and the environmental dimensions for different building typologies. Furthermore, they integrated the architectonic measures in parallel to different energy supply systems so that global performance was analyzed. According all these studies, the global economic optimum is located at the low-energy insulation level and not at the passive house level. These works are good points of comparison for the present contribution. In fact, our methodology to evaluate the economic performance is quite similar to the work of Achten et al. (2009), an approach that originated from the investigations by Coninck and Verbeeck (2005). Nevertheless, the methodology to evaluate the performance of heating systems is different in the present work, as well as the objectives of the research.

Finally, Badescu (2007) investigated the economic performance of ground thermal energy for passive houses. Unfortunately, the investment costs for the heat pumps were set far too low to be representative of the Belgian market. Furthermore, the methodology to evaluate the system performance differs significantly from the present approach. Finally, the main objective of Badescu's study was the cost and less focused on the environmental impact of systems. Nevertheless, this study showed clearly that systems are worth being investigated in the context of passive houses.

3. Methodology

3.1. Environmental and energy efficiency assessment

The methodology to evaluate the efficiency and the environmental impact of heating systems complies with the EN-15603 standard. Using conversion factors and the delivered energy consumption in a dwelling for each energy carrier (sometimes termed *final* consumption), the method enables the total primary energy consumption and the equivalent-CO_2 emissions to be evaluated. These are the only two indicators used in the present work to characterize the environmental performance of heating systems. For instance, the embedded gray energy in the building and energy systems is not considered here. As far as the delivered energy consumptions are concerned, they are evaluated for each energy carrier using the different parts of EN-15316 standard. In general, these standards give representative model parameters in their annexes. They also give some latitude to the reader concerning the modeling approach. For the sake of the completeness, the choices made here are introduced in the next subsection.

3.1.1. Details of the evaluation method

In the EN-15603 procedure to evaluate the performance of the building, the calculation method starts from the net SH and net domestic hot water (DHW) needs and then subsequently evaluate the efficiency, the thermal losses as well as the auxiliary electricity consumption for the emission, distribution, storage and production *sub-systems*. In fact, the method proceeds upstream compared to the actual direction of the energy flow (i.e. from emission to the production sub-system, from the needs to the source). The EN-15603 standard considers two different ways to take into account the recoverable thermal losses of the sub-systems to get the reduction of the net SH need. In the holistic approach, the recoverable losses are directly added to the internal gains of the building so that the SH need has to be re-evaluated accordingly. In this last approach, the net SH energy needs and energy systems performance have to be evaluated in a coupled way (e.g. using an iterative method). Unfortunately, the analysis of the energy systems performance cannot then be realized alone without considering the architectonic properties of the building. In other words, energy systems cannot be analyzed without considering a specific building project and typology. On the contrary, using the *decoupled* approach, the recoverable losses are not added to the internal gains but only reduce the consumption of the energy sub-system considered. Though it is less accurate, this method enables the consumption of different energy systems to be evaluated using the net SH need as a constant input (during all the evaluations). This is the approach followed in the present work. The interested reader is invited to consult the EN-15603 standard for an extended explanations. It should also be mentioned that the heat production sub-system is always assumed to be placed within the protected volume of the envelope.

In fact, the present method only considers to the parts of the EN-15603 standard that deal with heating. The net SH need is the first input in the analysis fixed by the user. In this way, the investigation is located downstream of the architectural measures. One assumes that the building has given thermal properties, summarized by its net energy SH need, and that one has to choose the best heating system to respond to this demand. This approach enables the performance of different heating strategies to be compared, and can investigate how they modify the global energy footprint of the building. Furthermore, the emission and distribution sub-systems for the DHW are assumed unchanged between all the test cases investigated here, so that their recoverable thermal losses are assumed to be already integrated into the net SH need (i.e. the first input of the method). The second input of the method is then the gross DHW need (i.e. the input energy into the DHW distribution sub-system). In summary, the initial data for the analysis is the total heat demand of the building, being the combination of:

1. Q_{SH}^{net}, the net energy need for the SH,
2. Q_{DHW}^{gross}, the gross energy need for the DHW.

The complete procedure is illustrated by Fig. 1. The electricity consumed by auxiliaries is evaluated for each sub-system, again from emission to the production, and finally summed up. Additional electricity consumption is considered if the dwelling is equipped with controlled mechanical ventilation (CMV): a typical value of 2 kWh/m^2 year is assumed here.

3.1.2. Conversion factors

In terms of conversion factors, the average factors and not the marginal factors are considered here. The factors for the total primary energy and for the equivalent-CO_2 emission are extracted from the Gemis 4.5 database (Oeko Institute, 2009) because it takes the fuel life cycle into account: extraction, conditioning, transport and combustion. This is particularly valuable for energy based on wood. Considering the carbon cycle, it is well known that the impact of wood combustion on GHG is neutral. Nevertheless, it takes energy to extract and transport the wood. This is integrated in the Gemis factors. Furthermore, following the Gemis methodology, the hypothesis behind the evaluation of the conversion factors should be transparent. The selected values are given in Table 1.

Concerning the electricity delivered by the grid, the Gemis database integrates the production of nuclear power plants. In Belgium, they currently represent about 60% of the national electricity production. In fact, this leads to a total primary energy

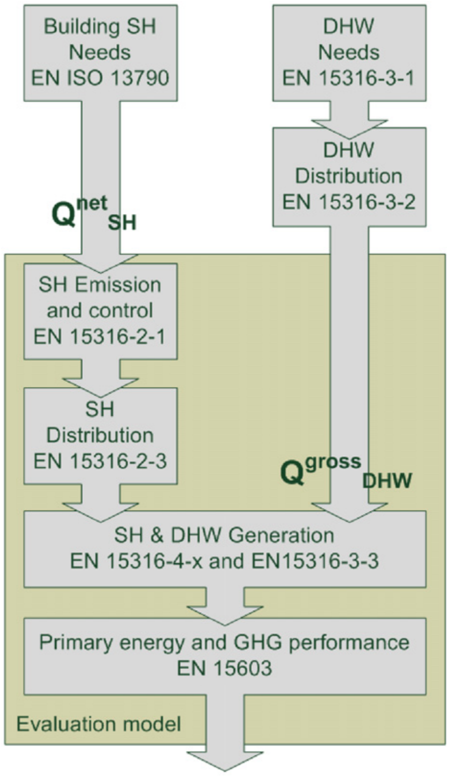

Fig. 1. Sketch of the procedure to evaluate the environmental and energy performance of heating systems based on the EN-15316 and EN-15603 standards. The part covered by the present methodology is pictured by the green box. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Conversion factors for Belgium extracted from the Gemis database (Oeko Institute, 2009).

Energy carrier	Primary energy factor, $kWh_{prim}/kWh^{HHV}_{deliv}$	Equivalent-CO_2 production coef. $g_{eq-CO_2}/kWh^{HHV}_{deliv}$
Selected values		
Natural gas	1.1	232
Wood pellets	1.2	46
Wood logs	1.05	22
Electricity (Belgian mix 2010, European Commission, 2003)	3.096	216
Electricity (Belgian mix 2030, European Commission, 2003)	2.3	534
Informative		
Electricity (Regional EPB, Walloon Government, 2007)	2.5	–
Electricity (EN 15603, European Standard EN 15603, 2008)	3.31	617

factor that is higher and an emission of CO_2 that is lower than using when the regional EPB conversion factors. Nevertheless, the future of nuclear power plants in Belgium is quite uncertain (D'haeseleer et al., 2009). A phase-out has been officially planned even though this decision has been reconsidered in order to achieve post-Kyoto goals in terms of national CO_2 emission levels. Considering a phase-out of the nuclear power plants, energy production will be progressively replaced by gas and coal power plants. As a consequence, the electricity mix will then be characterized by a lower total primary energy factor but much greater emissions of CO_2 than using nuclear power. Two sets of conversion factors are then investigated: the first refers to the current situation (termed mix 2010) while the second considers a nuclear phase-out (termed mix 2030). Both cases were already implemented in the Gemis database using European Commission's (2003) scenario. Although it is specific to the Belgian context, these two sets enable the investigation of two distinct configurations that can be found in many countries, or when considering different geographic boundaries for electricity production: electricity production characterized by low CO_2 emissions with a high level of total primary energy, and the opposite situation with high CO_2 emissions with a low level of total primary energy. The conversion factors for the UCPTE electricity mix given by the Annex E of EN-15603 (European Standard EN 15603, 2008) are also presented in Table 1 as a point of comparison.

3.2. Investigated systems

3.2.1. Test cases

The net SH need is a model input. Five specific values are considered throughout the remainder of this work. The *standard* building is assumed to have a net energy requirement, Q^{net}_{SH}, of 120 kWh/m^2 year. This is the order of magnitude for a detached house with the minimal EPBD requirements of Wallonia. Practically, Belgium has a maritime temperate climate, the design external temperature for SH is typically -10 °C. The *low-energy*, the *very low-energy* dwelling are defined here by a Q^{net}_{SH} of 60, 30 kWh/m^2 year, respectively. An *intermediate* level is considered at 45 kWh/m^2 year between the very low and low-energy test cases. By definition, the *passive house* has a Q^{net}_{SH} equal to 15 kWh/m^2 year. The gross energy need for DHW, Q^{gross}_{DHW} that includes the distribution losses, is fixed to 3000 kWh/year although this amount clearly depends on the occupant behavior. This amount is representative of the consumption of four permanent occupants.

3.2.2. SH emission and distribution sub-systems

For the passive house test case (see Table 2), the air is considered to be the default emission and distribution sub-system. Corresponding investments listed in Table 3 are based on a single heating coil placed in the supply air duct, downstream of the heat recovery unit. For the other four test cases, a hot-water

Table 2
Summary of the energy demands of the five test cases: the typical maximal power of the envelope losses in design weather conditions are reported in the last column.

House	Net energy need for SH (Q^{net}_{SH}) (kWh/m^2 year)	Gross energy need for DHW (Q^{gross}_{DHW}) (kWh/year)	CMV with heat recovery	Electricity for CMV (kWh/m^2 year)	Max power of losses (kW)
Passive	15	3000	Yes	2	~1.5
Very low-energy	30	3000	Yes	2	~2.0
Intermediate	45	3000	No	0	~4
Low-energy	60	3000	No	0	~5
Standard	120	3000	No	0	~8

Table 3
Investment costs without value-added tax (VAT) for the distribution and emission systems: the electric heating coil has the same price as a hot-water coil.

Energy	Material (€/piece)	Installation (€/piece)	Total (€/piece)
Radiator	350	250	600
Heating coil	550	450	1000

loop equipped with radiators is required as, by definition of the passive house, their envelopes are not efficient enough to be heated by the ventilation air (see the nominal heating powers in Table 2). For the sake of simplicity, only low-temperature radiators equipped with thermostatic valves (TRV) are considered here. Floor heating is not covered in the present work. In a single-family house, 8 radiators is a typical number of heat emitters to ensure thermal comfort. The energy requirements for the SH emission and distribution is computed using part 2 of the European Standard EN 15316 (2007).

Using these reasonable assumptions, it is possible to evaluate the savings induced by the air-heating simplification compared to a conventional hot-water loop equipped with radiators. From the prices reported in Table 3, the minimal investment cost for the air-heating is about 1 k€ while a low-temperature radiators network is roughly 5 k€. Thus, the saving is thus estimated to be 4 k€ without value-added tax (VAT).

3.2.3. *Heat production sub-systems*

As already mentioned, passive houses are characterized by SH power of less than 10 W/m^2. The design power of a passive single-family dwelling is then typically close to 2 kW. Most existing heat production sub-systems are oversized for this application. The smallest gas, wood boilers or classical heat pumps have a minimum of 8 kW and even using a power modulation of 10–30%, the delivered power is still too high. Domestic fuel boilers are currently oversized for passive house applications and are not considered in the present work, even though small modulating oil boilers are appearing progressively on the market. If no buffer tank is installed, oversizing leads to frequent start and stop cycles of the boiler. A fully physically consistent approach would evaluate this phenomenon using dynamic simulations, as done in Peeters et al. (2008), but this is beyond the scope of the present contribution. For the sake of the simplicity, the following assumptions are made:

- The energy requirements and efficiencies of the heat production sub-systems are evaluated using part 4 of the European Standard EN 15316 (2007). These evaluation methods differ between the types of production sub-systems and their particular technology. The models are essentially based on steady-state approaches. Monthly periods for the energy balances are applied here. An exception is nonetheless made for heat pumps where their efficiencies are not evaluated here using the EN-15316 standard (part 4-2). In fact, heat pump (HP) performance depends on many parameters, such as the equipment performance or the installation quality (e.g. the control). According to HP specialists, simple steady-state approaches fail to reproduce the large range of efficiencies that can be found in real installations. As a consequence, a range of annual seasonal performance factors (SPF) is preferred here in place of the efficiencies computed using the standards (EHPA, 2009; Wemhoener, 2010). Finally, wood stoves are not covered by the EN-15316 standard so that adaptations of the wood boiler standard have been performed in order to cover the stove technology.
- Wood boilers are considered to be systematically coupled to a buffer tank. The volume of this buffer is designed to store a long combustion cycle at nominal power: a minimum of 30 min for wood pellets and about 1 h for wood logs. These long production cycles should minimize the emission of pollutants and enable the best efficiency to be reached. The energy that is stored in the buffer tank will be distributed following the rhythm of the needs in the building. As this buffer tank is not reloaded continually, the boiler remains inactive during relatively long periods where the boiler temperature is not maintained. This assumption leads us to neglect the boiler losses during the stand-by periods, the major part of the thermal losses are emitted by the buffer tank. For other production sub-systems, a buffer tank is also considered when the nominal power is oversized compared to the needs of the envelope. For instance, a buffer tank is assumed to be systematically coupled to the heat pump in order to ensure long production cycles. In fact, it is well-known that too short production cycles for HP leads to significant reduction in performance and accelerated mechanical wear.

Different strategies to perform the heat production are reported in Table 4. The first group is the approaches based on electricity. This method is characterized by the lowest investment that is almost negligible.

The second group is based on the natural gas, a solution that is widespread in Belgium. The first approach here corresponds to instantaneous DHW production which leads to a typical boiler power of 25 kW. As already mentioned, this is oversized for energy efficient houses so that a buffer tank is considered for the SH. The second approach is based on semi-accumulation production of DHW. The boiler power is reduced to 10 kW and the DHW storage tank is integrated with the boiler. Both methods, based on a condensing gas boiler, have investments that can be regarded as intermediate.

The third group takes the wood-based approaches into consideration (i.e. based on pellets or logs). In terms of investment, only the prices for high-performance devices are considered in order to ensure the best environmental performance. Wood boilers here transfer their energy to a buffer tank to ensure long production cycles. Their investment cost is higher than gas boilers. On the opposite, wood stoves radiate their power directly into their thermal zone. They will be termed *standard stoves* in the remainder of this work. The DHW must then be produced by an independent system (that could be an electric or a gas water-heater). In between, intermediate emission strategies can be found. Some stoves directly emit a fraction of their power and the rest is transferred to a hot-water loop using a heat exchanger. They are often termed *hydro-stoves*. From the manufacturer's data, one typically finds 30% of direct radiation for 70% transmitted to the hot water, subsequently stored in a buffer tank. The stored heat can be emitted subsequently into the building, following its instantaneous needs. In hot periods where no SH is required, DHW has to be produced using another sub-system (as an electric backup heater). Wood stove approaches have investments that range from costs of the gas to wood boilers.

Heating strategies based on heat pumps (HP) are then introduced. On the one hand, *standard* HP are considered. HP designed for standard existing dwellings are contrasted with HP especially developed for passive houses. Standard HP are characterized by the highest investments. Fortunately, dedicated products are developed for passive house applications such as *compact* air-water HP that use the ventilation air (sometimes termed *combi* HP). They present a smaller investment than the standard HP but their performance are sometimes lower.

Finally, all these approaches can be complemented using solar thermal techniques. Only solar production of DHW is considered

Table 4
Properties of the different heat production sub-systems investigated, possibly including a buffer tank: HP stands for heat pump, HW for hot water circuit and Rad. is the shortening of direct radiation. The nominal production efficiency η_{prod} is based on the lower heating value (LHV). SPF only corresponds to HP. Finally, the investment without VAT is reported in the last column.

ID	Sub-system type and nominal power	SH			DHW		Invest. (k€)
		Type	Buffer tank	η^{SH}_{prod} or SPF	Type	η^{DHW}_{prod} or SPF	
(1)	Full electric	Electric	No	1.00	Electric water-heater	1.00	1.0
(2)	Gas boiler (25 kW)	Gas	Yes	1.08	Gas instantaneous	1.08	6.2
(3)	Gas boiler (10 kW)	Gas	No	1.08	Gas semi-accumulation	1.08	5.4
(4)	Pellets boiler (10 kW)	Wood	Yes	0.94	Wood	0.94	12.0
(5)	Logs boiler (10 kW)	Wood	Yes	0.94	Wood	0.94	10.5
(6)	Pellets stove (10 kW)	Wood	No	0.85	Electric water-heater	1.00	5.8
(7)	Logs stove (10 kW)	Wood	No	0.75	Electric water-heater	1.00	4.8
(8)	Pellets stove (10 kW)	Wood	No	0.85	Gas water-heater	1.08	7.9
(9)	Logs stove (10 kW)	Wood	No	0.75	Gas water-heater	1.08	6.9
(10)	Pellets stove (10 kW):	Wood (Rad.)	Yes	0.85	Pellets	0.85	8.0
	30% Rad. and 70% HW	Wood (HW)	Yes	0.85	Electric water-heater	1.00	
(11)	Logs stove (10 kW):	Wood (Rad.)	Yes	0.82	Logs	0.75	8.0
	30% Rad. and 70% HW	Wood (HW)	Yes	0.89	Electric water-heater	1.00	
(12)	Air–water HP (8 kW)	HP	Yes	2.5–3.5	HP	1.5–3	13.2
(13)	Air–water HP (compact)	HP	Yes	2.0–3.0	HP	1.5–2.5	10.5
(14)	Water–water HP (8 kW)	HP	Yes	3–4.5	HP	1.5–3	14.2
(15)	Brine–water HP (8 kW)	HP	Yes	3–4	HP	1.5–3	15.0
(16)	Ground–water HP (8 kW)	HP	Yes	3–4	HP	1.5–3	13.5

Table 5
Extra-investment without VAT for the improvement of the thermal performance of the envelope compared to the standard case (see Table 2). In order to evaluate the relative extra-cost, the standard reference house is assumed to have a base price ranging from 175 k€ to 225 k€. U_m stands for the mean transfer coefficient of the envelope excluding windows.

House	Net energy need for SH (kWh/m^2 year)	U_m envelope (W/m^2 year)	Air tightness (k€)	Insulation (k€)	Triple-glazing (k€)	Ground-work (k€)	Ventilation (k€)	Total extra-cost (k€)	Relative extra-cost (%)
Passive	15	0.11	5	11	8	1	6	31	14–18
Very low-e	30	0.17	3.5	5.5	–	1	6	16	7.1–9.1
Intermediate	45	0.17	3.5	5.5	–	1	–	10	4.4–5.7
Low-energy	60	0.25	3.5	2.2	–	–	–	5.7	2.5–3.2
Standard	120	0.45	–	–	–	–	–	–	–

here. In this context, a solar installation equipped with 4 m^2 is representative of single-family applications. The additional cost for these 4 m^2 is typically 6.0 k€ without VAT assuming upmarket flat-plate collectors.

Micro-CHP as well as district heating are not investigated in this article.

3.2.4. Insulation strategies for the detached house typology

In order to evaluate the global economic performance of energy saving measures on the heating system and the building envelope, the extra-investment to have an envelope with thermal performance that is superior to the minimal EPB requirements should also be considered. As extra-investments depend on the dwelling typology, a specific case must be chosen: in our case, a two-storey detached typology with a net heated surface of 150 m^2. Its envelope has a protected volume of 420 m^3, a 360 m^2 transmission surface and 35 m^2 of windows. Orders of magnitude for extra-investment are reported in Table 5 for the four test cases introduced in Table 2, while SH needs were evaluated using the PHPP software (Feist et al., 2007) and the Brussels climate. These prices are close to values of other authors reported in Section 2.

3.3. Economic performance assessment

The economic dimension is analyzed using the same methodology as in Achten et al. (2009), Coninck and Verbeeck (2005) and Renard et al. (2008). The *investment* as well as the *total discounted cost* (TDC) are the selected indicators to characterize the economic performance. The investment includes the material, the connection to an energy network and the installation costs. It must also be mentioned that no financial incentives are considered here (e.g. reduced taxes) as well as no maintenance costs. The space occupied by the heating systems in the envelope is also not integrated here.

The TDC evaluation is complying with the *global cost* method of the European Standard EN 15459 (2007). The selected discount rates are 2%, 3.5% and 5% (here termed t_a^l, t_a^m and t_a^h, respectively). Furthermore, the value-added tax (VAT) is taken to be 21%, which is representative of new buildings, and the inflation rate 2%. It is assumed that the lifespan for the heating systems is 20 years. Two assumptions for the lifespan of building envelope measures is here considered: 40 and 60 years for the envelope itself, coupled with 20 and 30 years for the mechanical ventilation system. These periods can be shorter than the actual lifespan of the building (i.e. typically more than 60 years). When considering both heating systems and architectonic measures together, their operating times are very different making the economic assessment complex. In fact, three calculation periods are here considered for the TDC evaluations: 20, 40 and 60 years. If the calculation period is longer than the lifespan of a given energy savings measure, a new investment is then done after each corresponding lifespan. If the calculation is shorter than the lifespan of a given energy savings measure, a residual value is considered: it is assumed that the value decreases linearly with time to be zero at the end of the

Table 6
Belgian energy costs in June 2009 including VAT: the prices are split into a part that increases with time and the other part that is assumed constant.

Energy	Production (c€/kWh)	Constant (c€/kWh)	Total (c€/kWh)
Elec. off-peak	3.8	6.8	10.5
Elec. peak	9.5	9.7	19.2
Natural gas	3.5	3.5	7.0
Wood-pellets	5.4	0	5.4
Wood-logs	3.8	0	3.8

Table 7
Three scenarios for the increase of the energy cost (Coninck and Verbeeck, 2005; European Commission, 2004): annual rate of linear increase for the production part of the energy cost.

Energy	Low [S^l]	Medium [S^m]	High [S^h]
Electricity	0.0	2.1	4.3
Natural gas	0.0	2.1	4.3
Domestic fuel	0.0	1.9	3.2
Wood	0.0	1.9	3.2

lifespan. The reader is invited to consult the European Standard EN 15459 (2007) for more details.

The investment costs have been already introduced in the last subsection. It is worth mentioning that it is difficult to establish accurate and fixed values although these costs are vital to properly evaluate the economic performance. Prices strongly vary between manufacturers and installations so that the conclusions extracted from the present work must always be regarded with these cost assumptions in mind. Investments, for the different heating systems or to improve the thermal performance of the envelope, are based on other studies (Audenaert et al., 2008; Renard et al., 2008), on typical values communicated by manufacturers, as well as on the estimations made by installers and by an engineering office, MATRIciel. By definition of the TDC, a difference in investment can be reflected directly in the graphs, or results can be adapted using the economic parameters (i.e. t_a, inflation rate and lifespan).

In line with Coninck and Verbeeck (2005), the increase in gas and oil prices is integrated through three different scenarios termed *low*, *medium* and *high*, these are extracted from a European Commission (2004) report. They will be referred using the shortenings, S^l, S^m, S^h, respectively. In the near future, natural gas will play an increasing role in the production of electricity (at least if the nuclear power plants phase-out takes place as assumed in European Commission, 2004). As a consequence, the rate of increase in the electricity price is here taken equivalent to the gas price. The domestic fuel is directly linked to the oil prices and as wood is a direct competitor of the fuel, its growth rate is expected to follow the same evolution (Renard et al., 2008). The current energy costs are listed in Table 6 while the aforementioned scenarios are reported in Table 7.

4. Results for constant net energy needs

First, only the performance of the heating systems is investigated here: the additional measures to improve the envelope performance are not integrated in the total discounted costs (TDC). As the only variable input in the analysis is the net heat demand for the SH, the following results do not depend on the dwelling typology. Only the SH emission sub-systems can change as a function of net SH need. The air heating is applied for the passive house test case while the hot water loop equipped with radiators is considered for the other test cases, as reported in Section 3. The heating strategies reported in Table 4 are analyzed using the *high* scenario for energy prices, S^h (Table 6) and the *medium* discount rate, t_a^m. By default, the Belgian electricity mix of 2010 is assumed (Table 1). The electricity mix of 2030 will only be considered if it leads to different or refined conclusions.

4.1. Comparison of heating systems for the standard house

The standard test case is first analyzed. The performance of the different heating strategies is depicted in Fig. 2 and the results are summarized qualitatively in Table 8.

The full-electric approach has total primary energy consumption and CO_2 production that are so high that the corresponding markers are beyond the bounds of Fig. 2. Fortunately, this approach is naturally excluded as its TDC of 66 k€ is far higher than other techniques. This is the best situation where the economic performance works for the environment conservation by disqualifying the worst systems from an environmental point of view.

The condensing gas boilers present rather neutral performance in terms investment, TDC or total primary energy. Nevertheless, it is well-known that this technology, which is based on fossil fuels, emits a larger amount of CO_2. Given the current global warming issue, this solution cannot be regarded as optimal. In the following comparisons, this solution is taken as point of reference as gas is widespread in the Belgian heating market.

The economic as well as the environmental performance of the standard heat pumps strongly depends on the SPF considered. The best SPF give interesting primary energy consumptions ranging from 110 to 140 kWh/m^2 year, see Fig. 2(a). Using the lowest SPF values, the primary energy consumption is close to a condensing gas boiler. In terms of CO_2 production, see Fig. 2(b), HP have a positive impact as they significantly reduce the emissions compared to a condensing gas boiler, and this, whatever the SPF range employed. This is a major argument for HP technology. Nevertheless, this is due to the structure of the electricity production in Belgium in 2010 which is mainly driven by nuclear power plants: electricity is characterized by relatively low CO_2 emissions. This situation must be regarded with caution, the questions of nuclear wastes and the safety of nuclear power are still open. Primary energy consumption is a good indicator to monitor this waste production and, as already mentioned, the HP performance concerning primary energy depends on the SPF quality. Furthermore, if the electricity mix of 2030 is considered (the graph is not reported here), the situation is the opposite. Compared to gas, the HP are favorable in terms of total primary energy whatever the SPF considered, while they perform significantly better in terms of CO_2 emissions only if the best SPF are assumed. In both cases, the environmental performance is only fully satisfying if high-performance HP and installations are considered. From an economic point of view, the trend is equivalent: only best SPF give attractive TDC. Using the lowest SPF, the higher investment cost in HP is never fully recovered compared to gas. As a conclusion, efficient HP, with SPF comparable to the highest values of Table 4, are attractive solutions as they combine cost-effectiveness for end users along with good environmental performance. This conclusion holds true for both electricity mixes that are considered. Working with high-performance HP is thus important otherwise the gain from this technology remains questionable. This can be done using efficient equipment but also by ensuring the quality of installations (e.g. a proper control). In this context, the role of a government to enforce quality can be helpful.

The last group is the approaches based on wood. The economic performance is commented on first. The wood-logs boiler is better than the condensing gas boiler as the lower energy cost for wood logs enables the recovery of the extra-investment to install the log boiler. Given the present economic assumptions, the energy

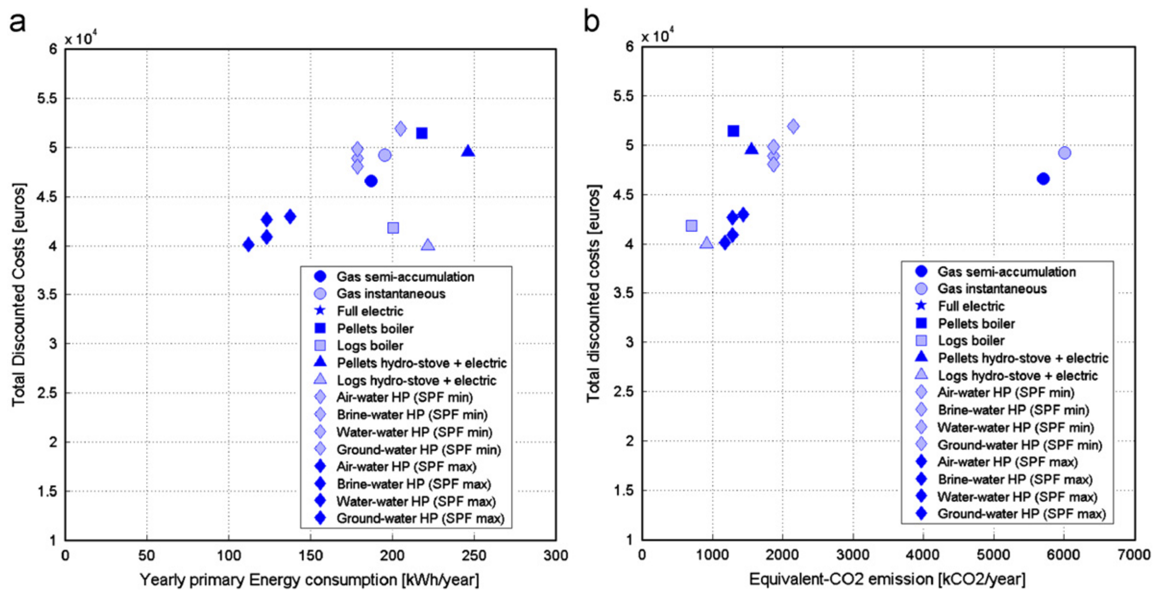

Fig. 2. Case of the reference house with a Q_{SH}^{net} of 120 kWh/m^2 year: total discounted cost (TDC) for 20 years as a function of the total primary energy consumption (a) and equivalent-CO_2 emissions (b) for the different heating strategies without solar thermal panels.

Table 8
Summary of the performance of heating systems for the standard house test case with a Q_{SH}^{net} of 120 kWh/m^2 year. Good performance is pictured by a ⊕, worse performance by ⊖ and performance that is intermediate or prone to interpretation is shown using a ⊙. Strong trends are highlighted by doubling the symbol.

Case	Standard HP				Elec	Gas	Wood-boiler		Wood-stove	
	El-Mix 2010		El-Mix 2030						Hydro+El	
	SPF Min	SPF Max	SPF Min	SPF Max			Log	Pel	Log	Pel
TDC	⊙	⊕	⊙	⊕	⊖⊖	⊙	⊕	⊙	⊕	⊙
Eprim	⊙	⊕	⊕	⊕⊕	⊖⊖	⊙	⊙	⊙	⊖	⊖
CO_2	⊕⊕	⊕⊕	⊖	⊕	⊖⊖	⊖	⊕⊕	⊕⊕	⊕⊕	⊕⊕

cost for wood-pellets remains close to the gas price so that the extra-investment in a pellets boiler is never completely recovered during the 20-years operating time. As far as the wood stoves are concerned, only the technology using a heat-recovery unit is investigated here as it is the only wood stove approach (proposed here) that can ensure thermal comfort in the standard dwelling (i.e. the approaches 10 and 11 in Table 4). As the investment is lower than for wood boilers, the conclusions for stoves remain the same as for the wood boilers, but slightly better. Regarding the environmental performance, the CO_2 emissions of wood approaches are significantly lower than using other heating systems. Nevertheless, the impact of the wood approaches is positive if forests are managed in a sustainable way. In this context, the energy fluxes that will be extracted from the forests are translated by the total primary energy consumption. This consumption ranges from 200 to 250 kWh/m^2 year. The hydro-stove is less efficient than boilers. In conclusion, heat production using wood technologies is not particularly energy efficient but the impact in terms of CO_2 emission is highly favorable (as long as the conversion factors used here for wood are representative and the best combustion devices are employed).

4.2. Comparison of heating systems for the passive house

With regard to the reference standard test case already analyzed, the specificities of heating systems at the passive house level can now be highlighted, see Fig. 3. The performance of the heating systems is summarized qualitatively in Table 9.

The gas boiler is again taken as a reference. Its economic as well as energy efficiencies are still intermediate, as in the standard test case (see Section 4.1). Regarding the level of the CO_2 emissions, this approach cannot be regarded as optimal.

The full electric approach is here problematic. This approach is an economic optimum: its TDC and investment costs are low so that it is an attractive solution from a consumer point of view. Unfortunately, the primary energy consumption as well as the CO_2 emissions are unfavorable. These trends will be more or less important depending on the electricity mix considered. Using the Belgian mix of 2010, the primary energy consumption is close to 110 kWh/m^2 year. In fact, it is an energy footprint comparable to the low-energy house equipped with a condensing gas boiler. The full electric solution must be discarded as the effort to improve the envelope insulation is clearly lost by the inefficiency of the heating system. The passive standard includes a criterion on non-renewable primary energy consumption (Feist et al., 2005). Even though this consumption should be established using the PHPP software, the full electric approach would be prohibited by this limit. Nevertheless, the primary energy criterion is not always applied in local variants of the passive house concept (as it is the case in Wallonia).

SH using electricity can however be more acceptable. In fact, the efficiency could be improved by adding 4 m^2 of solar thermal panels. The primary energy consumption would be reduced by

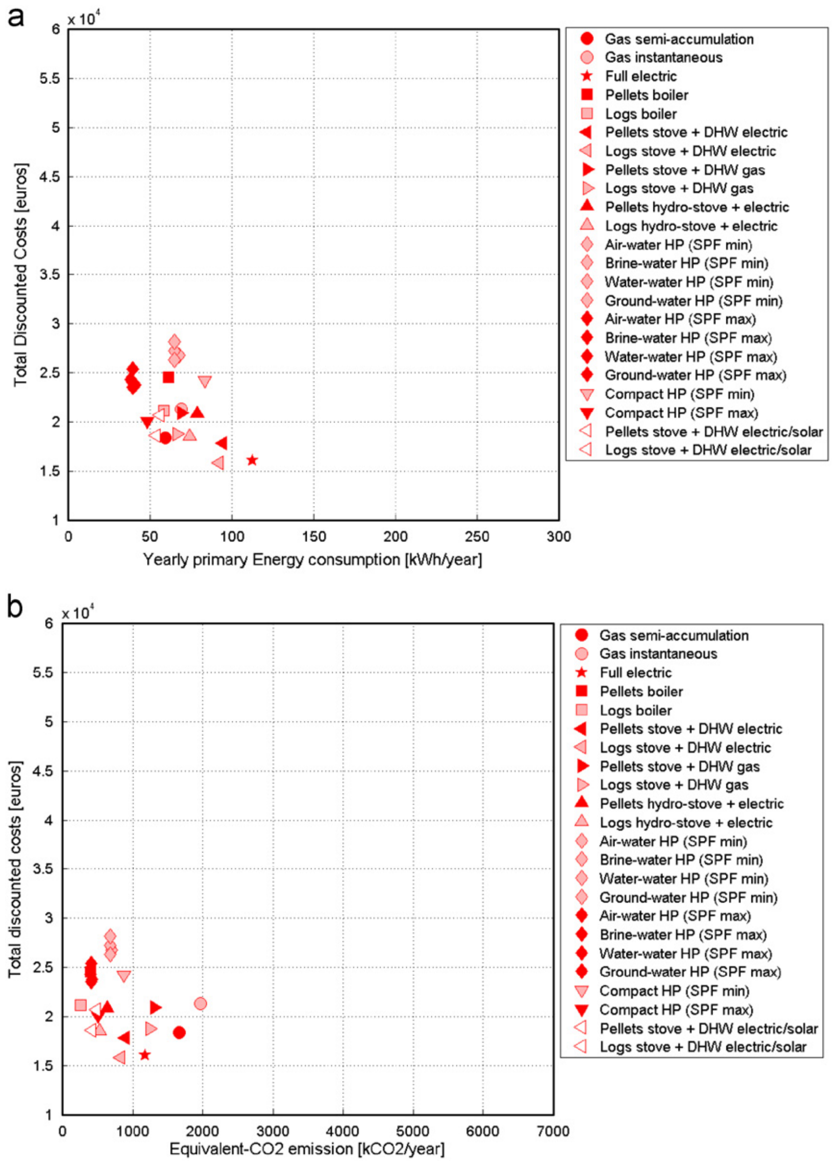

Fig. 3. Case of the passive house with a Q_{SH}^{net} of 15 kWh/m^2 year: total discounted cost (TDC) for 20 years as a function of the total primary energy consumption (a) and equivalent-CO_2 emissions (b) for the different heating strategies without solar thermal panels (unless specified).

Table 9
Summary of the performance of heating systems for the passive house test case with a Q_{SH}^{net} of 15 kWh/m^2 year. Good performance is pictured by a ⊕, worse performance by ⊖ and performance that is intermediate or prone to interpretation is shown using a ⊙. Strong trends are highlighted by doubling the symbol.

Case	Standard HP				Compact HP				Elec	Gas	Wood-Boiler		Wood-Stove					
	El-Mix 2010		El-Mix 2030		El-Mix 2010		El-Mix 2030						DHW Elec		DHW gas		Hydro+El	
	SPF Min	SPF Max	SPF Min	SPF Max	SPF Min	SPF Max	SPF Min	SPF Max			Log	Pel	Log	Pel	Log	Pel	Log	Pel
TDC	⊖⊖	⊖	⊖⊖	⊖	⊖	⊙	⊖	⊙	⊕	⊙	⊙	⊖	⊕	⊕	⊙	⊙	⊙	⊙
Eprim	⊙	⊕	⊕	⊕	⊖	⊙	⊙	⊕	⊖	⊙	⊙	⊙	⊖	⊖	⊙	⊙	⊙	⊙
CO_2	⊕	⊕⊕	⊙	⊕	⊙	⊕	⊖	⊕	⊖	⊖	⊕⊕	⊕⊕	⊖	⊖	⊖	⊖	⊕	⊕

about 40 kWh/m^2 year to reach 70 kWh/m^2 year, for a total investment and TDC comparable to a condensing gas boiler (without solar panels). Of course, a gas boiler could always be equipped with solar panels to give better environmental performance. Nevertheless, this would lead to higher investment costs. In places where the gas network is not present, an electricity-based approach coupled to solar thermal panels can give global performance comparable to that of gas (without panels) for an equivalent investment, total primary energy consumption and TDC. If the electricity mix of 2010 is assumed, electricity plus solar thermal gives better performance in CO_2 than gas, while the performance is equivalent if the electricity-mix of 2030 is considered.

Summarizing the performance of heat pumps becomes even more complex than in the standard case. At the passive house level, their investments are relatively high compared to the energy consumption. Furthermore, the DHW needs are dominant here and HP coefficients of performance (COP) are lower for these levels of temperature. As a consequence, the performance of standard HP for the passive house is reduced compared to the standard test case, both from an environmental as well as an economic point of view. In fact, the extra-investment for a standard HP is not recovered (whatever the SPF range considered). If the best SPF are considered, the high investments for standard HP enable only to give a slight reduction of 10 kWh/m^2 year compared to the gas approach. Using the lowest SPF values, the primary energy consumption is again equivalent to gas. The CO_2 emissions level is still favorable due to nature of the electricity production, mainly realized using nuclear power plants. If the electricity mix of 2030 is now assumed (the graph is not reported here), standard HP have then good environmental performance, in terms of primary energy and CO_2, if the best SPF are applied. The lowest SPF give performance that is comparable to gas for a higher TDC and investment. In conclusion, the trends are complex. As long as the best SPF are assumed, standard HP have good environmental performance at the passive house level but significant extra-costs must be accepted to reach it (i.e. investment and TDC).

The compact HP can enhance the performance of HP at the passive house level (approach 13 in Table 4). If the best SPF are considered, this solution combines an intermediate investment and TDC with good environmental performance (CO_2 and primary energy). Nonetheless, the investment cost for compact HP varies strongly between manufacturers so that this conclusion must be regarded with caution and always reconsidered as a function of a particular project. Furthermore, the lowest SPF factor for the DHW production has been intentionally set low as some compact HP present poor performance for DHW production (i.e. sometimes dominated by a direct electric heater). Using the lowest SPF leads then to poor environmental performance, or at least questionable. As a conclusion, compact HP are attractive solutions for a passive house as long as the manufacturers manage to supply equipment with a moderate investment cost along with the best SPF.

Some wood-based approaches are well suited for energy-efficient dwellings. Wood boilers present good environmental performance: a primary energy consumption that is comparable to gas with the lowest levels of CO_2 emissions. The primary energy consumption, the image of the energy flux extracted from the forest, is more favorable than for the standard house: the quantity of wood required to realize the heating is almost reduced by a factor four. As a conclusion, the wood approaches have a positive impact on the GHG emissions and, compared to the standard house, the low consumption leads to smaller quantities of wood being extracted from forests. Given their high investment costs, wood boilers have lower cost-effectiveness at the passive house level, even though using wood logs reduces this trend. As for the standard HP, the better environmental performance of wood boilers represents extra-costs at the passive house level.

Wood stoves with their intermediate investments are better sized for a passive house. The TDC ranges from values that are slightly lower and higher than gas according to the technology considered. Nevertheless, the environmental performance using standard wood stoves is lower than wood boilers. In fact, the DHW needs are dominant and should be produced by another heating system. If the DHW production is simply performed using an electric boiler, the environmental performance are intermediate between the full-electric approach and the wood boilers. The drawback will be more or less pronounced in terms of CO_2 or primary energy following the electricity mix considered. Whatever the mix used, a fully satisfying solution cannot be found. If the DHW production is performed using a gas water-heater, the performance is then, by nature, between the wood and gas boilers. There is a general comprise between cost-effectiveness and rather intermediate environmental performance. It is maybe better to use this investment (for a gas water-heater) to improve the standard stove to a hydro-stove. Both approaches have comparable investment costs and TDC but the hydro-stove always has better environmental performance. The improvement in terms of CO_2 emissions is more pronounced if the electricity mix of 2010 is applied. Finally, solar thermal panels are an attractive solution to complement the wood stoves, especially when solar energy substitutes electricity or gas. By combining solar panels to wood stoves, investments then shift from intermediate values to higher investments that are representative of wood boilers.

In conclusion, for the passive house test case, heating systems that can be fully satisfying for an end user (by combining economic and environmental performance) are the compact HP with the best SPF, the wood-log boiler (although characterized by a slightly higher TDC), the hydro-stove (with or without solar thermal panels), and the standard stove with solar thermal panels that use an electric backup. Other techniques can be used but at least one constraint on the economic, primary energy or CO_2 dimensions has to be relaxed.

4.3. *Comparison of heating systems for the very low and low-energy houses*

As expected, the cases of the very low and low-energy houses have performance between the passive and the standard houses. As a consequence, conclusions are an intermediate between these two cases.

For the very low-energy house, the full-electric approach is still competitive from an economic point of view (the corresponding graphs are not reproduced here). This is due to its low investment cost compared to other approaches. From the passive house to the very low-energy level, hot water-based approaches should indeed go from an air SH to a hot-water loop equipped with radiators (i.e. an extra-cost estimated at 4 k€). This contrasts with the electric SH where inexpensive electric heaters can be added to increase the heating power of the installation without noticeably increasing the global investment cost (compared to the investment at the passive house level). Again, regulations should be established in order to prevent the full-electric approach being implemented in a very low-energy house.

4.4. *Solar thermal panels*

As solar panels are only considered for the DHW production, their environmental performance is by definition independent of the net energy requirement for SH and thus, from the test cases considered. The best environmental performance is obtained when solar energy substitutes electricity, then the primary energy is reduced by about 40 kWh/m^2 year. If solar panels substitute a condensing gas boiler, the gain is about 19 kWh/m^2 year and 18 kWh/m^2 year to complement wood-based approaches. The economic performance is not significantly lowered when the net SH need is reduced. Best TDC are also obtained when solar panels substitute electricity.

4.5. *Influence of the increase in energy prices*

The three different scenarios, termed *low*, *medium* and *high* and reported in Table 7, are investigated along with the influence of the discount rate. The higher the rate of increase in energy prices, the higher the total discounted costs (TDC). The lower the discount rate the higher the TDC. Nevertheless, the relative positions of the different strategies remain almost unchanged so that conclusions derived from the *high* scenario for the energy

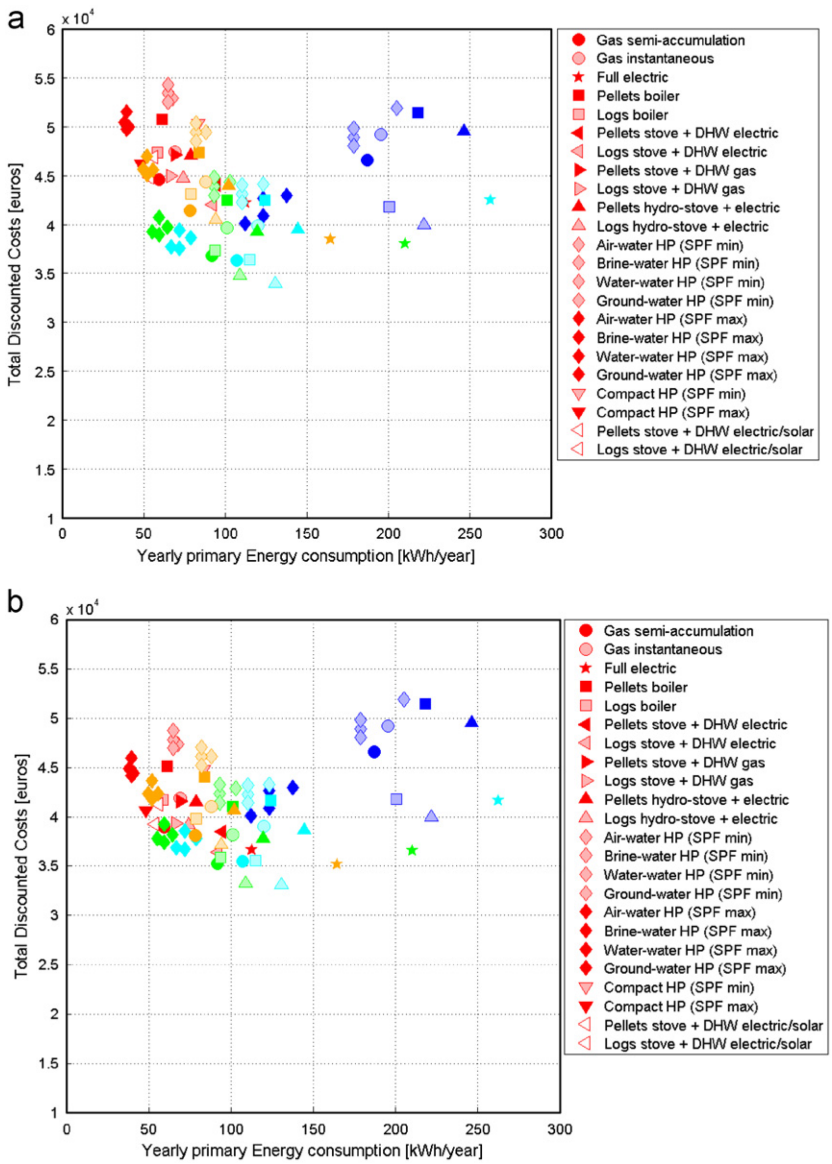

Fig. 4. Total discounted cost (TDC) for 20 years as a function of the total primary energy consumption. Each alternative is depicted by a tag with a color representative of the net SH need and a shape to specify the heating system technology (see graphs legend): *red* is for the passive house, *orange* is for the very-low energy house, *green* is for the intermediate case, *cyan* for the low-energy house and *blue* for the standard test case. (a) Lifespan: envelope 40 years, ventilation 20 years. (b) Lifespan: envelope 60 years, ventilation 30 years. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

prices and the *medium* discount rate, can be considered representative.

5. Global results for different net energy needs

In this section, the performance is evaluated at a global level combining heating systems with energy-savings measures on the building envelope. As a consequence, extra-investments listed in Table 5 are added in the TDC (based on a period of 20, 40 or 60 years). TDC for 20 years are presented in Fig. 4: approaches are distinguished following their net SH needs and the heating system. Again, results are established using the *high* scenario for the increase in the energy prices (S^h) and the *medium* discount rate (t_a^m).

In the following analysis, the full-electric approach will not be considered as it could lead to cost-optimal solutions but characterized by poor environmental performance. Furthermore, results for wood-logs approaches give cost-optimal solutions at high net SH needs: this is due to the price of this energy carrier that is here significantly lower. This characteristic of wood logs could overshadow the economic behavior that one wants to highlight at the passive house standard. The reader is therefore invited to consider this solution apart in the remainder of the section.

Following the passive house definition, the curves should present two global economic optima, the first being located between 30 and 60 kWh/m^2 year and the second generated near 15 kWh/m^2 year when one simplifies the SH system. From Fig. 4(a), the first global optimum can easily be identified by the curve. It corresponds to the very low to the low-energy test cases. To reach best envelope performance, the installation of a CMV using a heat recovery unit becomes necessary so that the global investment is prone to a significant jump. For the passive standard, the triple-glazing generates a second jump. These extra-investments lead to the TDC increase for the very low and

Table 10
Qualitative summary of the passive house TDC as a function of different economic scenarios: $\oplus$ if the passive house is the *global* optimum, $\oslash$ if the passive house is not far from the *global* optimum and results to be discussed, $\odot$ if the passive house test case performs better than the standard house (when both cases are equipped with a gas boiler), and $\ominus$ in other cases.

Economical indicator	TDC 20 years									TDC 40 years						TDC 60 years		
Lifespan (envelope/ventil.)	20/20 years			40/20 years			60/30 years			40/20 years			60/30 years			60/30 years		
Discount rate t_a	t_a^h	t_a^m	t_a^l	t_a^h	t_a^m	t_a^l	t_a^h	t_a^m	t_a^l	t_a^h	t_a^m	t_a^l	t_a^h	t_a^m	t_a^l	t_a^h	t_a^m	t_a^l
Eco. scenario S^l	$\ominus$	$\ominus$	$\ominus$	$\ominus$	$\ominus$	$\odot$	$\ominus$	$\odot$	$\oplus$	$\ominus$	$\ominus$	$\odot$	$\ominus$	$\odot$	$\oplus$	$\odot$	$\odot$	$\oplus$
Eco. scenario S^m	$\ominus$	$\ominus$	$\ominus$	$\ominus$	$\odot$	$\odot$	$\ominus$	$\odot$	$\oplus$	$\ominus$	$\odot$	$\odot$	$\odot$	$\odot$	$\oplus$	$\odot$	$\odot$	$\oplus$
Eco. scenario S^h	$\ominus$	$\ominus$	$\ominus$	$\ominus$	$\odot$	$\odot$	$\odot$	$\oslash$	$\oplus$	$\odot$	$\odot$	$\odot$	$\odot$	$\oslash$	$\oplus$	$\odot$	$\oplus$	$\oplus$

passive houses. As already mentioned, this last conclusion is not new and was already stated in Renard et al. (2008) and Achten et al. (2009) for comparable economic scenarios.

At the passive house standard, two distinct phenomena should give rise to a significant reduction of the investment (and TDC) of SH system: (1) the simplification of the SH distribution sub-system to the air heating and (2) the completed switch in technology where both SH distribution and production sub-systems are changed (i.e. using the compact HP, the standard wood stoves with solar thermal panels). To analyze the first phenomenon, one clearly notices that the curve is continuous for a given heating system when one reduces the net SH need progressively towards the passive house level: the curve only presents one global optimum. On the contrary, the introduction of new heating concept at the passive house level improves the economic performance significantly, generating a clear discontinuity: the compact HP compared to the general trend of standard HP, the standard stoves with solar thermal panels compared to the wood boilers.

The robustness of these conclusions must be tested using different other economic assumptions. Results are summarized in Table 10. Given the level of extra-investment considered in the article, the passive house test case can hardly become a global economic optimum without incentive. Some conditions can nonetheless reduce significantly the impact of the extra-investment by increasing the residual value of the architectonic measures, or by increasing the energy costs: a longer lifespan for architectonic measures (see Fig. 4(b)), a low discount rate and a high increase in the energy prices. With severe conditions, the passive house test case can become a global economic optimum. In this case, the simplification of the heating system contributes significantly to reach this optimum. Again, the complete shift in heating technology (2) is more effective than the air-heating simplification (1) to generate the new global optimum. The air heating only generates a new global optimum for heating systems with relatively low investments (e.g. the gas boiler) and when the economic scenario has already flattened the Pareto front around the very low SH needs.

Let us recall that the present study is a snapshot of the Belgian market using typical current prices. In the future, it could be expected that these prices will be reduced significantly with increasing number of passive house being built.

6. Conclusions

The objective of the article was to investigate the environmental as well as the economic performance of heating systems applied to new efficient single-family dwellings. The evaluation method is based on the European Standard EN 15316 (2007), European Standard EN 15459 (2007) and European Standard EN 15603 (2008) standards using parameter values representative of the current Belgian market (in terms of prices and energy carriers) and do not take any incentive or maintenance costs into account. The total primary energy consumption and the equivalent-CO_2 emissions are the only two indicators used here to rate the environmental impact, while the total discounted costs are used to evaluate the economic performance.

The first objective was to analyze the performance of heating systems without taking the architectural measures into account: the net SH need was the main input for the calculations. It turned out that the heating systems that are efficient for very low net SH needs are those characterized by a moderate investment cost along with good environmental performance. Among systems investigated here, the compact HP with the best SPF, the wood-log boilers, the wood hydro-stoves and the standard stoves supplemented by solar thermal panels for the DHW production (using electric backup) are intrinsically the most appropriate solutions from an end user's point of view. They combine cost-effectiveness with good environmental performance. Furthermore, some solutions that are optimal at higher net energy needs (e.g. for 120 kWh/m^2 year), like the standard HP and the wood-pellet boilers, will involve too high investments to be cost-optimal for very low net SH needs. On the contrary, one solution that is not optimal at higher net SH needs, the full-electricity approach, becomes cost-optimal at very low SH needs while it still presents poor environmental performance. This last solution must be prohibited as it clearly destroys the effort made to improve the thermal performance of the envelope. For example, it can be done through the national or regional regulation.

The second objective was to investigate the global performance, combining the heating system and energy-savings measures for the envelope, for one typical detached house typology. Only economic performance was commented upon. Given the current high level of extra-investment needed to reach the passive house level (i.e. essentially for the triple-glazing and mechanical ventilation), this test case can hardly be a *global* economic optimum. Nonetheless, the passive house can become a global optimum if severe assumptions are considered: a longer lifespan of architectonic measures combined with a low discount rate or a high increase in energy prices. In this case, the simplification of the SH system contributes significantly to create this new optimum. The research found that the complete shift of the heating system is more effective than only limiting the simplification to the air heating (i.e without changing the production sub-system). This effect is clearly depicted by the *compact* heat pump. Nevertheless, the air heating can also lead to the global optimum for heating systems with relatively low investment (e.g. gas) when severe economic scenarios have already placed the passive house close to the global optimum. As cost-effectiveness is a major argument to facilitate the market penetration of passive houses, it is important to make a more precise definition of the conditions leading to the emergence of this new economic optimum. Finally, the present study should be regarded as a snapshot. In the future, it is indeed possible that the mass production of passive houses could significantly reduce the extra-investment.

Acknowledgments

The authors from the UCL want to thank the Walloon public services (SPW) for their support. The corresponding author wants to thank the Norwegian Research Council for their support, as this work was also performed in the framework of the Research Centre for Zero Emission Buildings (ZEB).

References

Achten, K., Coninck, R.D., Verbeeck, G., Van der Veken, J., 2009. Analyzing the economic feasibility of permutations of energy-saving measures with batch simulations and Pareto optimization. In: Eleventh International IBPSA Conference. Glasgow, Scotland.

Audenaert, A., Cleyn, S.D., Vankerckhove, B., 2008. Economic analysis of passive houses and low-energy houses compared with standard houses. Energy Policy 36, 47–55.

Badescu, V., 2007. Economic aspects of using ground thermal energy for passive house heating. Renewable Energy 32, 895–903.

Ceera, 2008. Application des principes de la maison passive en Région de Bruxelles-Capitale. Technical Report, Centre d'Etude, de Recherche et d'Action en Architecture, Rapport Final.

Coninck, R.D., Verbeeck, G., 2005. Technical–Economic Analysis of the cost-effectiveness of Energy Saving Investments. Technical Report, Brussels Institute for the Management of the Environment, Final Report, August.

D'haeseleer, W., et al., 2009. PRIMES scenario analysis towards 2030 for Belgium. European Review of Energy Markets 3 (1).

EHPA, 2009. European Heat Pump Statistics, Outlook 2009. Technical Report.

European Standard EN 15316, 2007. Heating Systems in Buildings, Method for Calculation of System Energy Requirements and System Efficiency. European Committee for Standardization.

European Standard EN 15459, 2007. Energy Performance of Buildings, Economic Evaluation Procedure for Energy Systems in Buildings. European Committee for Standardization.

European Standard EN 15603, 2008. Energy Performance of Buildings, Overall Energy Use and Definition of Energy Ratings. European Committee for Standardization.

European Commission, 2003. Energy and Transport Trends to 2030 (PRIMES). Technical Report, Directorate-General for Energy and Transport.

European Commission, 2004. European Energy and Transport Scenarios on Key Drivers. Technical Report, Directorate-General for Energy and Transport.

European Parliament, Council, 2002. Energy Performance of Buildings Directive (2002/91/EC), December.

Feist, W., Peper, S., Görg, M., 2001. CEPHEUS, Cost Efficient Passive Houses as European Standards supported by the EU. Technical Report, Passivhaus Institut, Final Report, Project information no. 36, July.

Feist, W., Schnieders, J., Dorer, V., Haas, A., 2005. Re-inventing air heating: convenient and comfortable within the frame of the passive house concept. Energy and Buildings 37, 1186–1203.

Feist, W., Puger, R., Kaufmann, B., Schnieders, J., Kah, O., 2007. Passive House Planning Package 2007, Darmstadt, June.

ICEDD, 2008. Energy Consumption Counts of the Walloon Region. Technical Report, Walloon Public Services (SPW), September.

Oeko Institute, 2009. Global Emission Model for Integrated Systems (Gemis), version 4.5, January.

Peeters, L., Van der Veken, J., Hens, H., Helsen, L., D'haeseleer, W., 2008. Control of heating systems in residential buildings: current practice. Energy and Buildings 40, 1446–1455.

Renard, F., Nourricier, S., Pietrantonio, M.D., Feldheim, V., 2008. Technical–Economic Analysis of the Cost-Effectiveness of Energy Saving Investments for Residential Buildings. Technical Report, Service Public de Wallonie, DG04, Final Report, March.

Schnieders, J., Hermelink, A., 2006. CEPHEUS results: measurements and occupants satisfactory provide evidence for passive house being an option for sustainable building. Energy Policy 34, 151–171.

Walloon Government, 2007. Arrêté du 17 avril 2007 du gouvernement wallon déterminant la méthode de calcul et les exigences, les agréments et les sanctions applicables en matière de performance énergétique et de climat intérieur des bâtiments, April.

Wemhoener, G., 2010. Field Monitoring: Results of Field Tests of Heat Pump Systems in Low Energy Houses. IEA HPP Annex 32, Final Report, March.