AN INTEGRATED APPROACH FOR FINANCIAL AND ENVIRONMENTAL COST OPTIMISATION OF HEATING SERVICES

Recommendations for a Belgian dwelling case

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Abstract

A four-year project has started in 2007 to develop a methodology that can be applied to optimize the Belgian dwelling stock. The aim of the project is to optimise buildings concerning their environmental impact, their financial cost and the quality they offer over the whole life cycle, from the production of primary raw materials to the final demolition and end-of-life treatment. In the first phase of the project the optimisation methodology is developed; i.e. environmental impacts are analysed by means of life cycle assessment (LCA); financial costs are calculated based on life cycle cost analyses (LCC); and the quality evaluation is based on multi-criteria analyses (MCA). The aim of the optimization is to realize the highest marginal quality improvement for the additional financial and environmental cost. In a second phase the developed methodology is translated into a work instrument and applied to different dwelling types. This paper goes more deeply into the role heating services play in the environmental and financial costs. For a typical Belgian dwelling initial and life cycle costs for commonly used as well as advanced heating configurations are compared. Since energy consumption for heating is dependent of the way the building envelope is built, the analysis is performed on two dwelling configurations with a different insulation level.

Keywords

Life Cycle Assessment, Life Cycle Costing, Element method, Pareto optimisation, heating services

1. Introduction/Background

The construction sector typically provides 5 to 10% of employment through construction jobs and generates 5 to 15% of GDP at national level (UNEP 2006; ILO 2010). However, the impact of the built environment – including housing – on nature and society is vast. Not only is energy use in buildings responsible for more than one third of global greenhouse gases; construction, maintenance and renovation activities also account for 40% of world's material flows (UNEP 2007). It is even more alarming that barely 20% of the world's population, i.e. the richest countries, is responsible for the consumption of 86% of world's material resources (Fernandez 2003).

Meanwhile an accelerated trend of urbanisation and expansion of cities is visible. Although in some cities environmental issues, such as commuting, are easier dealt with, in most urban areas they are intensified. A city with a million inhabitants consumes daily 9.500 ton fossil fuel, 625.000 ton water, 32.000 ton oxygen, emits 29.000 ton CO_2 and dumps 500.000 ton used water (Battle 2007). Despite urban development, adequate accommodation is still unaffordable for a large part of the world population. The UN Human Settlements Program (UN-HABITAT) estimates that 600 million urban residents and 1 billion rural dwellers in developing countries live in inadequate housing. The main cause may be attributed to poverty [Brown 2003].

In many European countries affordable and adequate housing are hot topics too. High-density countries such as Belgium and the Netherlands can be considered as an extensive built-on region, where building plots are scarce and expensive.

Despite serious efforts, such as cleaner production techniques for building materials, more severe energy performance regulations for buildings and social loans for renovating dwellings, limited changes are noticeable. This can partly be attributed to the long service life of buildings - causing very slow changes. Nevertheless, more and better orientated actions should be taken. It is however very difficult to identify the impact of measures.

2 Aim of the study

The aim of the study presented in this paper is to formulate a scientific basis for policy formulation for a more sustainable dwelling stock in Belgium. In order to do so the three widely recognised aspects of sustainability have to be addressed in an integrated way.

Indeed, environmental improvements come at a certain cost. Both the investment cost and the operational costs are of interest, in terms of budget restriction and financial efficiency respectively. Furthermore, an environmental and financial sane building lacking quality is a building with a limited service life.

In order to quantify environmental impacts, financial costs and qualities of the current Belgian housing stock in an integrated way and to formulate sane recommendations for a more sustainable one, a new evaluation method has been developed in 2007 during a four-year research project sponsored by the Belgian Science Policy (BELSPO). This methodology is presented in this paper.

This paper focuses on the role **heating (sub) systems** play in the environmental impacts and financial costs of a typical Belgian dwelling. In addition, recommendations will be given to enhance the environmental and financial performances of heating systems, in relation to the entire life cycle of a representative dwelling. In this study the quality of the dwelling is left constant.

3 Methodology

In order to evaluate environmental impacts (EI), financial costs (FC) and qualities of the current Belgian dwelling stock and to provide federal and local governments a scientific basis to optimise it, three existing methods have been integrated in a single evaluation methodology, named “Sustainable, Financial and Quality evaluation of Dwelling types” (SuFiQuaD). For the calculation of FC and EI the whole life cycle of a reference dwelling is considered, by carrying out **Life Cycle Assessment** (LCA) and **Life Cycle Costing** (LCC) respectively. This implies that production of building materials, transportation, construction, use, maintenance, replacements and end-of-life treatments are considered. For the quality evaluation a **Multi-Criteria Analysis** (MCA) is conducted.

In the following sub paragraphs all aspects of the SuFiQuaD methodology are further described.

To focus on the environmental and financial performances of a single building element – or a combination of some elements – without losing the relation to the whole building, the **element method** is integrated in the SuFiQuaD methodology. The element method is a well known technique in the construction sector, used for cost calculation and cost control (Flanagan 1997).

By multiplying the environmental impact or financial cost per unit of element with the ratio of that element (i.e. amount of element per square meter of total floor area of the dwelling), the

environmental impact or financial cost per square meter of floor area for that specific element is determined. The limitation to one (or some) element(s) can be useful when trying to optimise that (those) specific building element(s).

3.1 Life cycle assessment

The environmental impact assessment is done by performing a Life Cycle Assessment (LCA) (ISO 2006a; ISO 2006b; Guinée et al 2002; REGENER 1997; SETAC 2003) of the dwelling. Derived from the function of the dwellings, the functional unit is defined. The functional unit should measure the performance of the different dwelling types and should provide a reference to which all the environmental inputs (use of raw materials and energy) and outputs (emissions to air, water, soil, other) can be normalised. Since dwellings fulfil more than one function, the choice of the functional unit is not simple. Different functional units occurred in studies reviewed within the literature study. In the REGENER project (1997), for example, the whole building, located at a certain point in a given region, is considered as the basic functional unit. Within the SuFiQuaD methodology “one square meter of the net floor area” is considered as basic functional unit. To be able to compare dwellings with a different life expectancies the environmental impact per “square meter of the net floor area per year” is also calculated. In addition, the SuFiQuaD method also calculates the results per inhabitant to correct any appearance that larger buildings are more sustainable than smaller ones. For all dwellings that are assessed an average service life of 60 years is assumed. According to (Ammar et al 1980) this is an acceptable average for the Belgian context. Sensitivity analyses are performed to assess the impact of other service years on the final results.

The collection of the environmental data (i.e. life cycle inventory - LCI-data) is mainly related to the ecoinvent database (2007). For the life cycle impact assessment of the inventoried inputs and outputs; the Eco-indictor 99 method (Goedkoop et al 2001) is used. In addition, a method is developed to translate EI into monetary values (i.e. euros). In order to cover as many environmental aspects as possible a selection of different existing methods for the translation of environmental aspects into monetary terms are combined. This hybrid method is based on a combination of the impact assessment as used within the series of the European ExternE projects (Bickel et al 2005), the Eco-indicator 99 approach (Goedkoop et al 2001) and other research projects on monetisation based on “willingness to pay for environmental damage” (Ott et al 2006).

3.2 Life cycle costing

To calculate FC over the whole life cycle the sum of the present values is calculated. Both the initial cost as the total cost are analysed in terms of budget restriction and cost efficiency.

$$LF = IF + \sum_{t=0}^{t=LS} PV(PF_t) = IF + \sum_{t=0}^{t=LS} \frac{PF_t \times (1+g_F)^{(t)}}{(1+d_F)^{(t)}} \quad (1)$$

With:

LF = financial life cycle costs

PV = Present Values of costs

IF = initial investment cost

PF_t = periodical (future) financial cost

g_F = growth rate (annual) on periodic financial costs

d_F = discount rate (annual) on periodic financial costs

t = time (in years)

LS = life span of dwelling or element

In analogy to Equation (1), the environmental life cycle costs are defined in the following way:

$$LE = IE + \sum_{t=0}^{t=LS} PV(PE_t) = IE + \sum_{t=0}^{t=LS} \frac{PE_t \times (1+g_E)^{(t)}}{(1+d_E)^{(t)}} \quad (2)$$

With:

LE = environmental life cycle costs

PV = Present Values of costs

IE = initial environmental cost

PE_t = periodical (future) environmental cost

g_E = growth rate (annual) on periodic environmental costs

d_E = discount rate (annual) on periodic environmental costs

t = time (in years)

LS = life span of dwelling or element

The initial costs (IF and IE) include the material cost, production cost and transportation cost of the processed materials, as well as construction costs of the building (labour cost, indirect costs, etc.). The periodical costs (P_t) are costs during the use phase of the dwelling and include cleaning, maintenance and replacement costs. The growth rate of costs differs for processed building products and energy costs. The time value of money is incorporated by

defining a discount rate. The characterisation of growth and discount rates are different for environmental and financial costs.

Finally, the total initial costs (IT) and total life cycle costs (LT) are considered by adding up the corresponding environmental and financial costs: respectively IE and IF; and LE and LF.

3.3. Quality evaluation

The qualities of a building are a complex clew and are user and context specific. In the SuFiQuaD methodology it is evaluated by carrying out a Multi Criteria Analysis (MCA). To make the quality assessment as transparent as possible, a hierarchal structure is adopted.
Within the SuFiQuaD methodology all dwelling qualities are divided in four main aspects: dimensional, functional and technical characteristics and the surroundings of the dwelling. Each aspect is subdivided in different sub-aspects. Each criterion within each sub-aspect is evaluated using a score function and graded on a scale from zero to ten. The different scores are then weighted and aggregated into a final single score for the quality performance of the dwelling. (Spirinckx et al 2009)
Since the dwelling qualities for the research presented in this paper are left unchanged, the MCA within the SuFiQuaD methodology is not further discussed. More information about it can be found in (Allacker et al 2006).

3.4 Pareto optimisation

For the determination of the most preferable measures for one type of dwelling or element, the basic approach is to search for the highest marginal quality improvement for the additional cost. This means that one starts from a reference building or element and compares the alternatives with this reference. The subset of options that is more preferable than the other options is graphically represented by the **Pareto front**. (Allacker et al 2008)
Different optimisation criteria are considered: initial financial cost (IF), initial environmental cost (IE), life cycle financial cost (LF) and life cycle environmental cost (LE), initial total cost (IT) and life cycle total cost (LT), with and without the inclusion of the quality evaluation. It is possible that these different criteria will lead to a different ranking of the optimal options.

4 Case study

4.1 Selection of a representative Belgian dwelling

The Belgian dwelling stock is very heterogeneous. According to national statistics (NIS 2001) a freestanding dwelling is the most common dwelling type in Belgium (29.3%), closely followed by terraced dwelling (25.6%), flat (25.3%) and semi-detached dwelling (19.9%).

While most semi-detached and terraced dwellings are older than 1945 (together 15.5% of the entire dwelling stock), most freestanding dwellings and apartments are built later, respectively in the period 1971-1981 (6.0% of the entire stock) and after 2001 (3.2% of the entire stock). In other words, a single archetypical dwelling for Belgium does not exist.
In the SuFiQuaD methodology this issue is tackled by the selection of 16 different reference dwellings, subdivided according to the dwelling type (freestanding, semi-detached, terraced and apartment) and the construction period (<1945, 1945-1970, 1971-1990 and 1991-2007).

For the analysis detailed in this paper, a compact and south-oriented freestanding dwelling of 123m² floor area for a family of 4 persons from the period 1991-2000 is used as reference. A representation of the architectural plans is shown in Figure 1.



Figure 1: representation of referential detached dwelling (dimensions in cm) (Allacker 2010)

4.2 Technical services

In the framework of the SuFiQuaD project the term '**technical services'** (TS) comprises the following systems: space heating (SH), domestic hot water (DHW), ventilation, provision of electricity, water treatment and evacuation, and elevator system (only for apartment blocks).
Due to the fact that lighting and movable electric devices are not or only in a minor way building dependent, these services have been further excluded from the assessment.
In the framework of the SufiQuaD project, the analysis of TS is somewhat different than the analysis of other dwelling elements. Compared to walls, floors and roofs, the above mentioned sub systems consist of a vast amount of processed materials. Whereas structural or skin elements are principally a combination of a few layers of processed materials – all measured in m² – TS are made of a complex network of linear, surface and volume components – quantified in different units and consisting of a multitude of materials.

Furthermore, the complexity of the analysis is increased because the choice of TS sub systems is often related to other building parameters, such as the insulation level, air tightness and the orientation of the dwelling. Therefore analysis of TS is carried out on building level, through which a distinction is made between two contrasting dwelling cases:

- A **non-insulated** dwelling (K100), i.e. worst case scenario
- A **highly insulated** (and air tight) dwelling (K20), i.e. best practise

The analysis detailed in this paper is carried out for a life span of the dwelling of 60 years. Sensitivity analyses using a life span of 120 years are carried out on element level.

4.2.1 General parameters

Due to technical evolution services are prone to 'frequent' replacement over the lifespan of the building. In this study it is assumed that all technical components are replaced over a period of *30 years*.

Different VAT rates are used over the lifespan of the dwelling: *21%* for the initial production, installation and/or construction, *6%* for the refurbishment or replacement of the technical components. Taking into account the Belgian situation in 2008 the following financial costs for energy carriers are used:

Table 1: Considered energy cost for each energy carrier

Energy carrier	Cost without VAT and taxes [€/MJ]	Overall cost* [€/MJ]
electricity	*0,0426*	*0,0548*
gas	*0,0113*	*0,0139*
oil	*0,0131*	*0,0164*
pellets	*0,0113*	*0,0137*

*a VAT rate of 21% is incorporated in the overall financial energy costs

4.2.1 Description of studied Space Heating systems

The space heating system (SH) is characterised by a set of sub systems: type (A), production (B), distribution (C), emission (D) and control (E). The flowchart below gives an overview of all studied SH configurations.

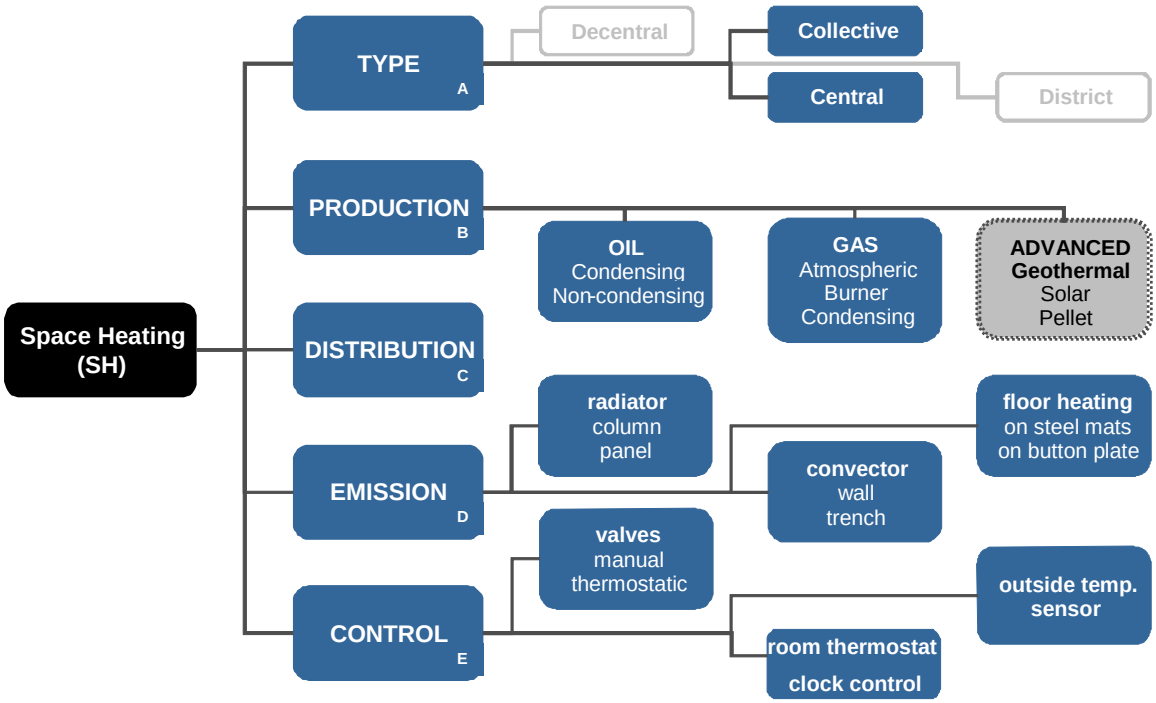

Figure 1 Configuration flowchart of space heating system

In all studied configurations central heating is considered for individual dwellings (A). An important distinction is made between commonly used production systems and advanced ones (see grey dotted box in flowchart), i.e. based on renewable energy sources or biomass. The advanced ones are only considered in the well-insulated dwelling. For all studied configurations the same distribution components (C) are used, i.e. a double-pipe octopus-system. Each emission device is connected with local collectors in a loop via PE ducts. The PE ducts in reality differ in diameter, but are simplified to a fixed outer diameter of 16mm and a thickness of 2mm. The same type of ducts is used for the supply of water. Contribution analyses showed that these distribution components only have a minor influence on both financial and environmental costs. The following group of variations is studied:

Production system (B):

- Oil boiler: non-condensing or condensing (both floor models)
- Gas boiler: non-modulating classic atmospheric (floor model), non-modulating gas burner (floor model) or modulating condensing (wall model)
- Heat pump: ground/water (with vertical or horizontal heat exchange), air/water, air/air (only for passive house)

- Pellet furnace: non-condensing or condensing (both with storage silo and automatic supply)

Emission system (D):

- Column radiator: cast iron or steel plate
- Panel radiator: steel plate
- Wall convector: aluminium
- Trench convector: PET or steel with aluminium or Merbau grid
- Floor heating: PE-RT on steel mats or on button plate

Control system (E):

- Manual valves + room thermostat (MV+RT)
- Manual valves + room thermostat + outside temperature sensor (MV+RT+OS)
- Thermostatic valves + clock control (TV+clock)
- Thermostatic valves + clock control + outside temperature sensor (TV+clock+OS)

It is difficult to separate the overall efficiency of heating systems in efficiencies of the sub systems, since production, distribution, emission and control components influence each other. Van der Veken and Hens (2010) showed that the combination of some control and production systems is better avoided due to a low overall efficiency.

For example, in a well insulated dwelling the constant, but low energy demand by thermostatic valves during milder days causes a non-modulating high efficiency boiler to cycle the whole day – and so producing high boiler losses at times when little or no heat is needed. In order to reduce the boiler working time, it is better to control heating through a central thermostat in combination with manual valves (and outside temperature sensor). On the other hand, the highest overall efficiency using a (modulating) condensing boiler is obtained with thermostatic valves (and outside temperature sensor), since the boiler can operate on partial load during milder days. Combing the thermostatic valves with a clock control switches the boiler on/off in function of the time (e.g. day/night). (Van der Veken et al 2010)

According to the European standard EN 12831 (CEN 2003) on heating systems, the K100 and K20 dwellings have a design load of respectively 14kW and 5kW. The required capacity of the selected heat production system and the sizing of the emission devices are calculated according to (Hens 1996). (Allacker 2010)

4.2.2 Description of studied Domestic Hot Water systems

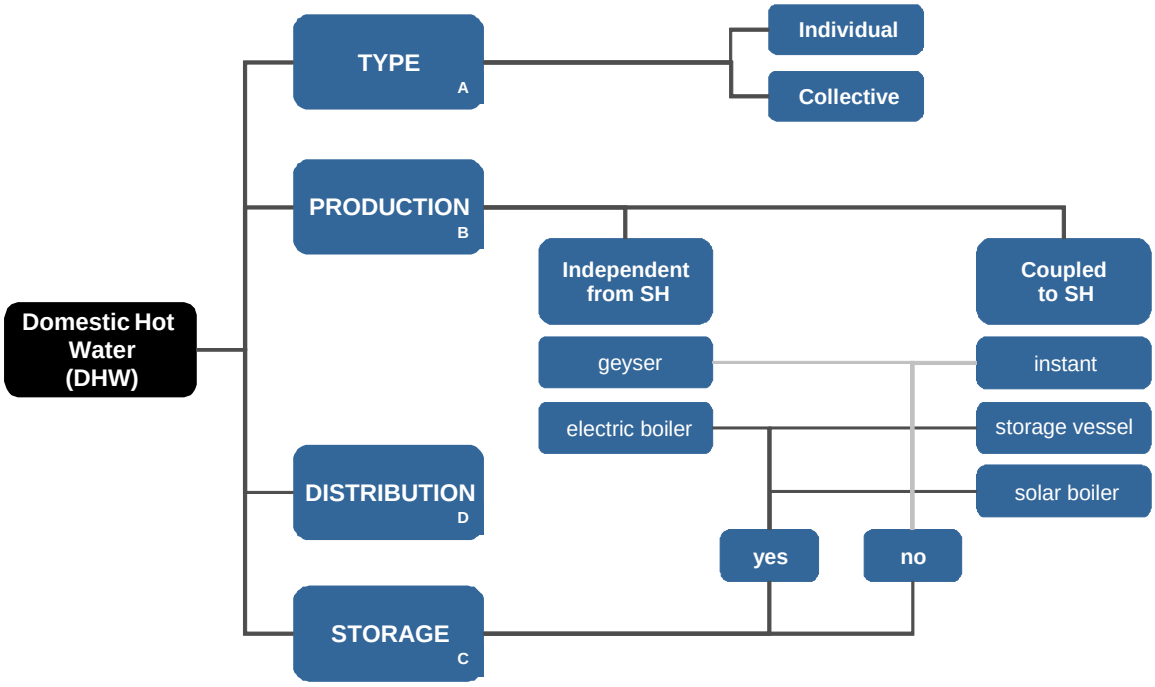

Figure 2 Configuration flowchart of domestic hot water system

Similar to SH, the domestic hot water system is characterised by different sub systems: type (A), production (B), storage (C) and distribution (D). The flowchart in Figure 2 gives an overview of all DHW configurations. Complementary to SH, only individual installations (A) are analysed and the same distribution components are used for all combinations.

- Production system (B) – Storage system (C):
  - Independent from SH:
    - *i. gas geyser[1], i.e. without storage*
    - *ii. electric boiler, 120l*
  - Coupled to SH:
    - *iii. Instant (i.e. without storage)*
    - *iv. storage vessel, 120l for an oil and gas generated furnace or 300l for a heat pump or pellet furnace [2]*

[1] The capacity of the geyser is 14l/min for ΔT = 25K or 7l/min for ΔT = 50K
[2] In order to reduce the on/off switching of the heat pump a larger storage vessel is chosen compared to a gas or oil boiler.

v. *solar boiler, using an existing or external storage vessel, 120l for an oil and gas generated furnace or 300l for a heat pump or pellet furnace.*

For a proper comparison of heating systems, SH and DHW are always looked at together. Components for exhaust of gasses (i.e. ducts and chimney) and supply of gas and oil (i.e. pipes and oil storage tank), as well as supplementary parts, such as circulation pumps and expansion vessels are taken into account in the assessment.

5 Analysis Approach

In order to have a better understanding of the impact of heating services on the environmental and financial life cycle cost of the reference dwelling and to formulate clear enhancement measures, the analysis is carried out in four distinct phases:

1. Analysis of the contribution of representative heating services and other building components in the environmental, financial and total life cycle costs for both dwelling cases (i.e. K100 and K20)
2. Definition and interpretation of the Pareto front of all configurations for the entire heating system. Two different configuration groups are made: (a) commonly used and (b) advanced configurations
3. Comparison of the relative life cycle cost profile of all configurations for each heating sub system
4. Formulation of scientifically based recommendations

6 Results

6.1 Overall impact of services on the reference dwelling

To analyse the contribution of energy and technical services to the total dwelling cost, an instant coupled condensing gas boiler with low temperature panel radiators and controlled by thermostatic valves in combination with an outside temperature sensor is selected as reference. As will be shown in §6.2 this selection is justified since it appears on all Pareto fronts – i.e. EC and FC for both insulation levels. Since in the reference case a natural ventilation system is selected and no photo-voltaic panels are used, the energy consumption and supply related to TS is mainly related to the heating services (SH and DHW).

In Figure 3 and Figure 4 the relative importance of heating services and energy in the life cycle cost of respectively the non-insulated (K100) and well-insulated (K20) detached dwelling is shown. Heating costs can be more or less halved by (highly) insulating the dwelling.

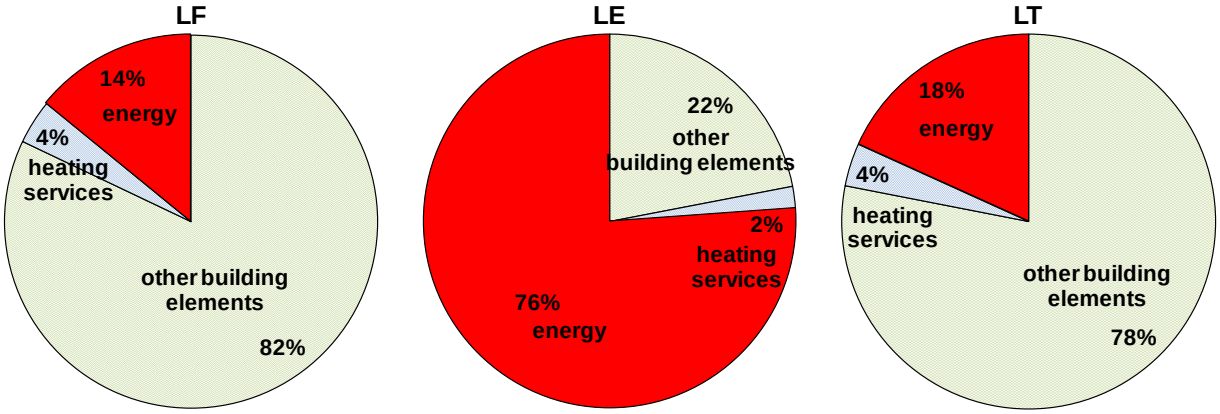

Figure 3 Relative importance of heating services in the (financial – environmental – total) life cycle cost of a representative non-insulated detached dwelling (K100) (Allacker 2010)

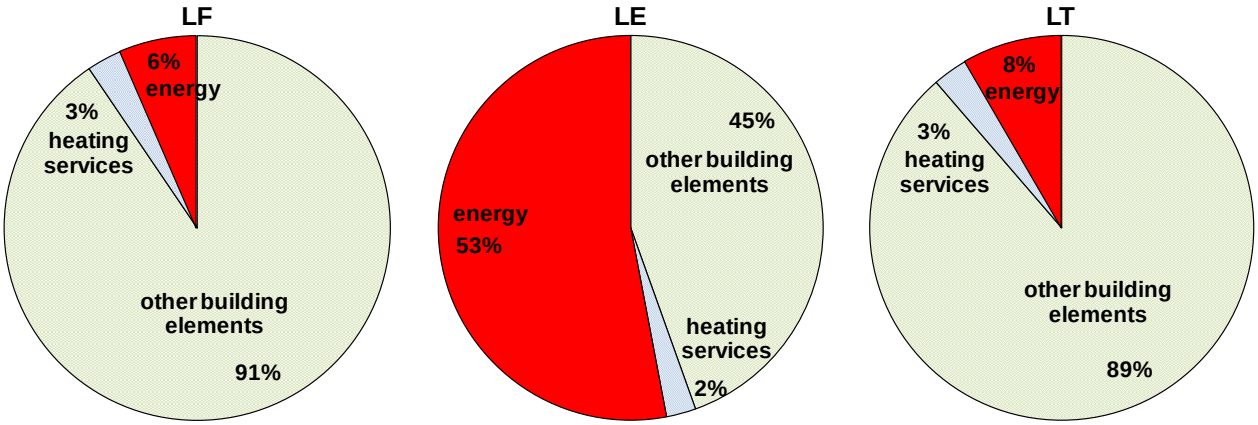

Figure 4 Relative importance of heating services in the (financial – environmental – total) life cycle cost of a representative well-insulated detached dwelling (K20) (Allacker 2010)

Compared to other building elements, heating services represent circa 3% (K100) to 4% (K20) of the financial life cycle costs. Even when the net energy demand is halved by highly insulating the dwelling, energy during use of the dwelling plays a non-negligible role in the life cycle cost profile. Due to the relatively low gas prices (see Table 1) heating costs are responsible for 6% (K20) to 14% (K100) of LF. From an environmental point of view, energy represents the most important part of the life cycle cost, ranging from 53% (K20) to 76% (K100), due to the Belgian energy mix. Heating services are responsible for 2% of LE; while other building elements represent circa 22% (K100) to 45% (K20) of LE. Given that overall environmental costs play only a minor role in the total life cycle costs of dwellings (circa 6%),

the relative importance of energy costs is reduced to 8% (K20) and 18% (K100) of the total life cycle costs.

The argumentation above justifies a more thorough assessment of the impact of TS on the financial and environmental costs of both reference dwellings. In the following paragraphs the importance of heating services is further detailed and some measures to reduce environmental and financial costs are suggested.

6.2 Overall impact of heating configurations

6.3.1 Overall impact of heating configurations on non-insulated dwelling

Based on the heating system parameters detailed in §4.2, 111 different heating system configurations are defined for the non-insulated dwelling. In order to present legible graphs, these configurations only consider panel radiator as emission component – occasionally combined with floor heating on steel mats. As will be shown in §6.3 no substantial differences in the overall cost profile are discerned between all studied emission alternatives. The following Pareto fronts of the financial and environmental costs (in €/m² net floor area) have been identified.

Table 2: Pareto front of financial costs (IF versus LF) for the non-insulated dwelling (K100) with a life span of 60 years

configuration SH	**configuration DHW**	**IF**	**LF**
		(€/m² fl net)	**(€/m² fl net)**
gas atmospheric; panel radiator; MV+RT+OS	instant coupled	*74,6*	*861,1*
gas condensing; panel radiator; TV+clock	instant coupled	*80,7*	*792,1*
gas condensing; panel radiator; TV+clock+OS	**instant coupled**	***81,1***	***769,4***

* MV = manual valves; TV = thermostatic valves; clock = clock control; RT = room thermostat; OS = outside sensor

Financially seen, an instant coupled atmospheric gas boiler with panel radiators operating with manual valves and a room thermostat combined with an outside temperature sensor offers relatively low energy consumption for the lowest investment. The second Pareto minimum consists of a condensing gas boiler controlled by thermostatic valves. A small investment in a more sophisticated control system, i.e. an outside temperature sensor in combination of thermostatic valves and a clock in the living room, provides the lowest financial life cycle cost. Compared to the atmospheric gas boiler option, a reduction of 8%

and 11% in financial life cycle cost is discerned respectively for the two condensing gas boilers.

Table 3: Pareto front of environmental costs (IE versus LE) for the non-insulated dwelling (K100) with a life span of 60 years

configuration SH	**configuration DHW**	**IE** (€/m² fl net)	**LE** (€/m² fl net)
gas burner; floor heating; MV+RT+OS	instant coupled	*5,6*	*279,8*
gas burner; floor heating; MV+RT+OS	instant coupled + 1 geyser	*7,3*	*278,9*
gas burner; floor heating; MV+RT+OS	2 geysers	*9,1*	*278,1*
gas condensing; floor heating; TV+clock+OS	**instant coupled**	***10,7***	***236,0***
gas condensing; floor heating; TV+clock+OS	instant coupled + 1 geyser	*12,4*	*235,1*
gas condensing; floor heating; TV+clock+OS	2 geysers	*14,2*	*234,3*

* MV = manual valves; TV = thermostatic valves; clock = clock control; RT = room thermostat; OS = outside sensor

Environmentally seen, a (high performance) instant coupled gas burner working with floor heating and a sophisticated control system (i.e. MV+RT+OS) offers the lowest IE. On the level of emission system, floor heating and panel radiator alternatives have a similar cost profile. The biggest reduction in LE is generated by a condensing gas boiler controlled by an outside temperature sensor combined with thermostatic valves and a clock in the living.

Only a slight reduction in LE is noticed by using gas geysers (with or without instant coupled DHW), i.e. less than 1%. This means that environmentally seen, an instant coupled gas condensing boiler is preferred.

In Figure 5 and Figure 6 initial and life cycle costs for the non-insulated dwelling (K100) are depicted according to the type of SH production system. These graphs illustrate the wide spread of the related costs of all configurations. The Pareto front of the total costs (IT vs. LT) is similar to the one of the financial costs.

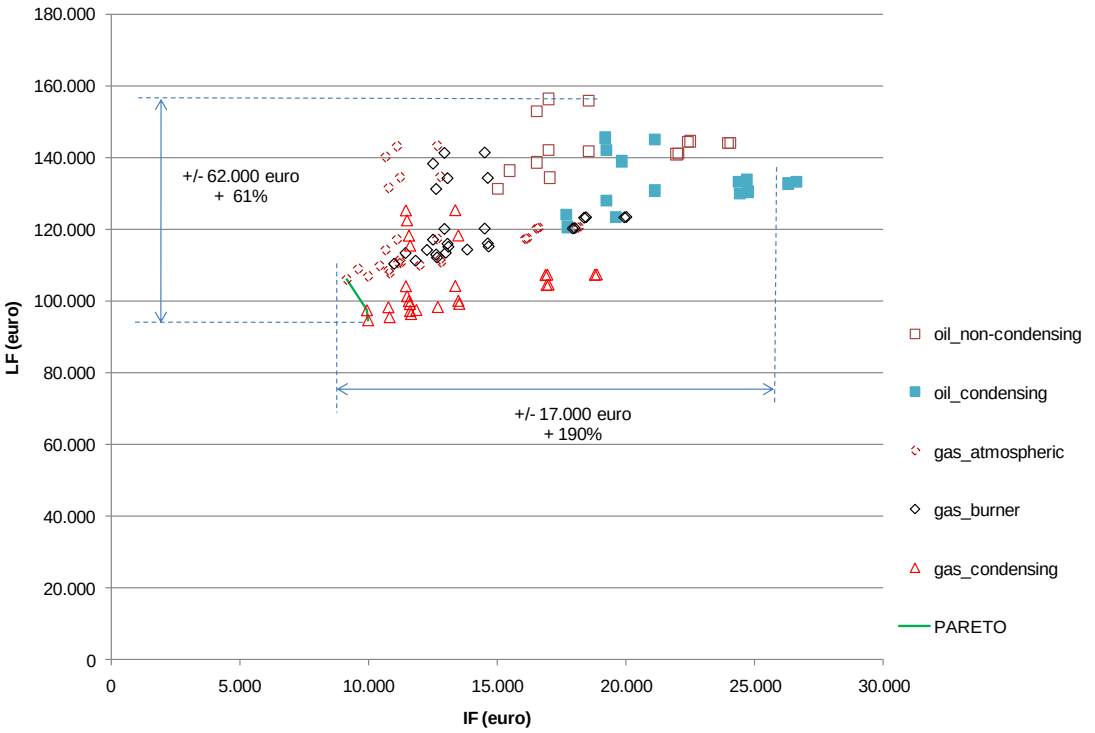

Figure 5 Initial financial cost (in €) versus life cycle financial cost (in €) of all commonly used heating system configurations (SH+DHW) for the non-insulated dwelling (K100)

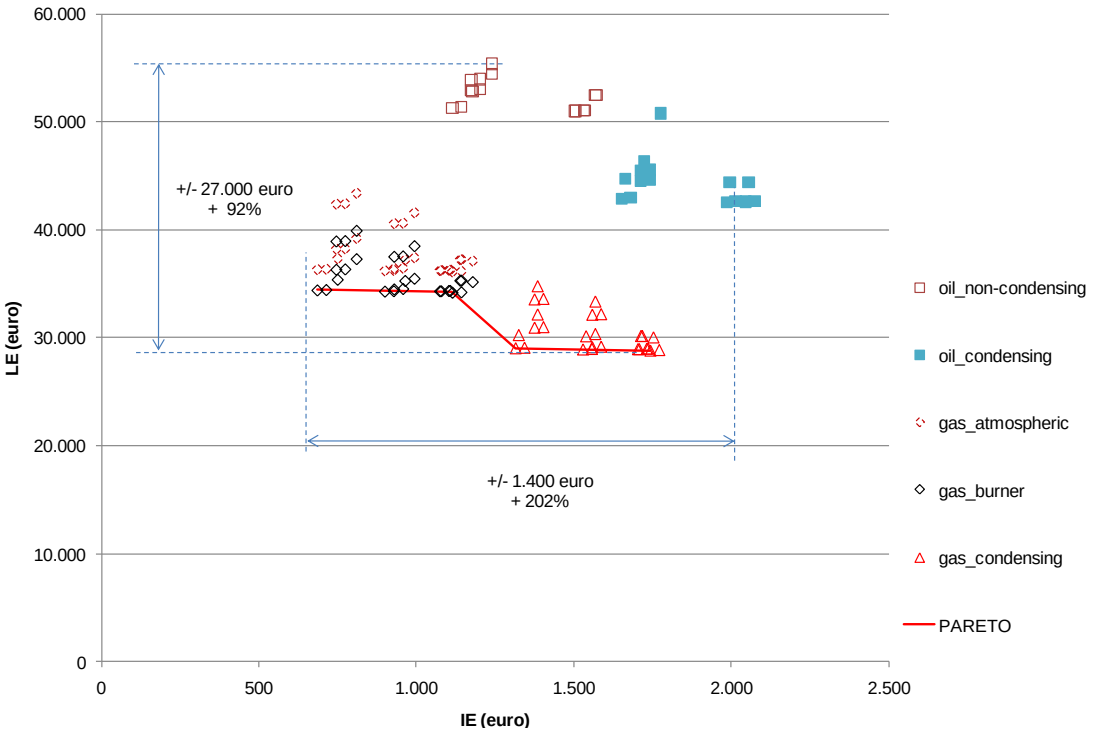

Figure 6 Initial environmental cost (in €) versus life cycle environmental cost (in €) of all commonly used heating system configurations (SH+DHW) for the non-insulated dwelling (K100)

6.3.2. Overall impact of heating configurations on well-insulated dwelling

For the assessment of the highly insulated dwelling not only conventional, but also advanced heating systems are looked at. Once a dwelling is well insulated a heat pump is an interesting solution to minimise energy production. Furthermore, due to the improvement of heating techniques, pellet furnaces become more popular. These relatively new heating solutions are compared with the commonly used ones. In total 117 heating configurations are studied.

As mentioned in §4.2, the design heat load for space heating for the well-insulated dwelling (K20) is low, i.e. 5kW. The capacity of the boiler for space heating is therefore about 8-10 kW. However, for the options where the domestic hot water production is coupled to the space heating installation, the dimensioning of the capacity of the boiler also depends on the need for domestic hot water production. For an instant boiler, a capacity of 24.4kW is assumed (equal as for the stand-alone geysers); while for the system with storage vessel the capacity of 8-10 kW of the boiler is assumed sufficient. For some of the boiler types, no such small devices are available on the current Belgian market. For these, the smallest available is selected.

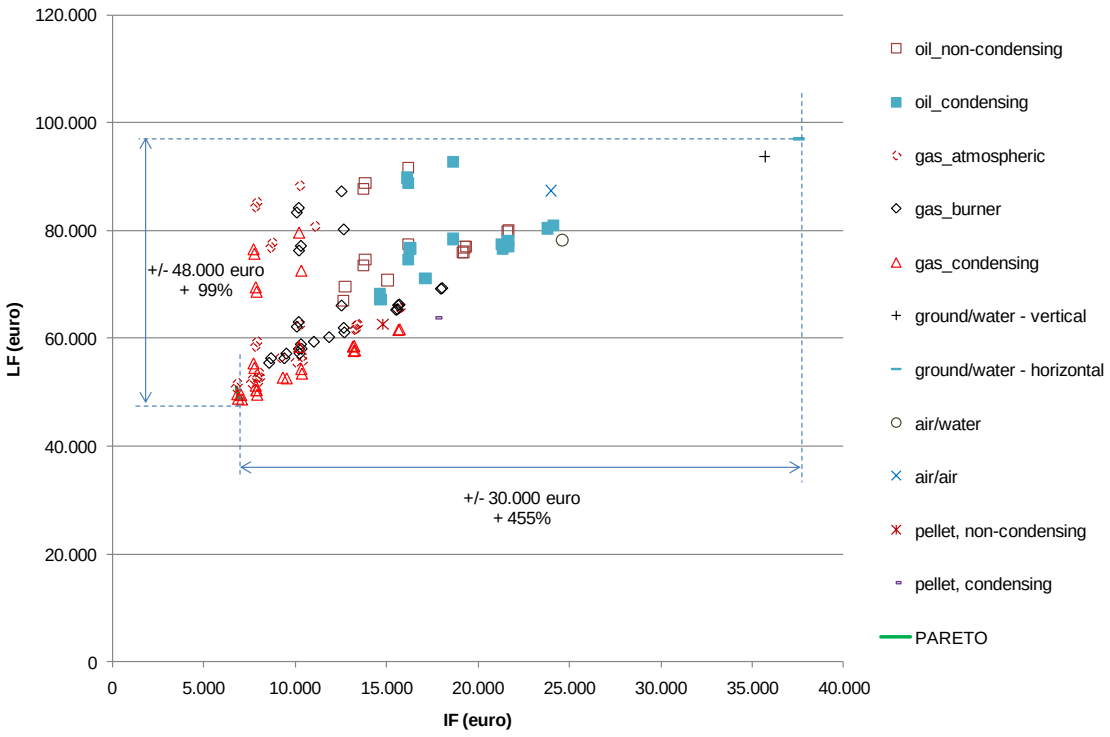

Figure 7 Initial financial cost (in €) versus life cycle financial cost (in €) of all commonly used heating system configurations (SH+DHW) for the well-insulated dwelling (K20)

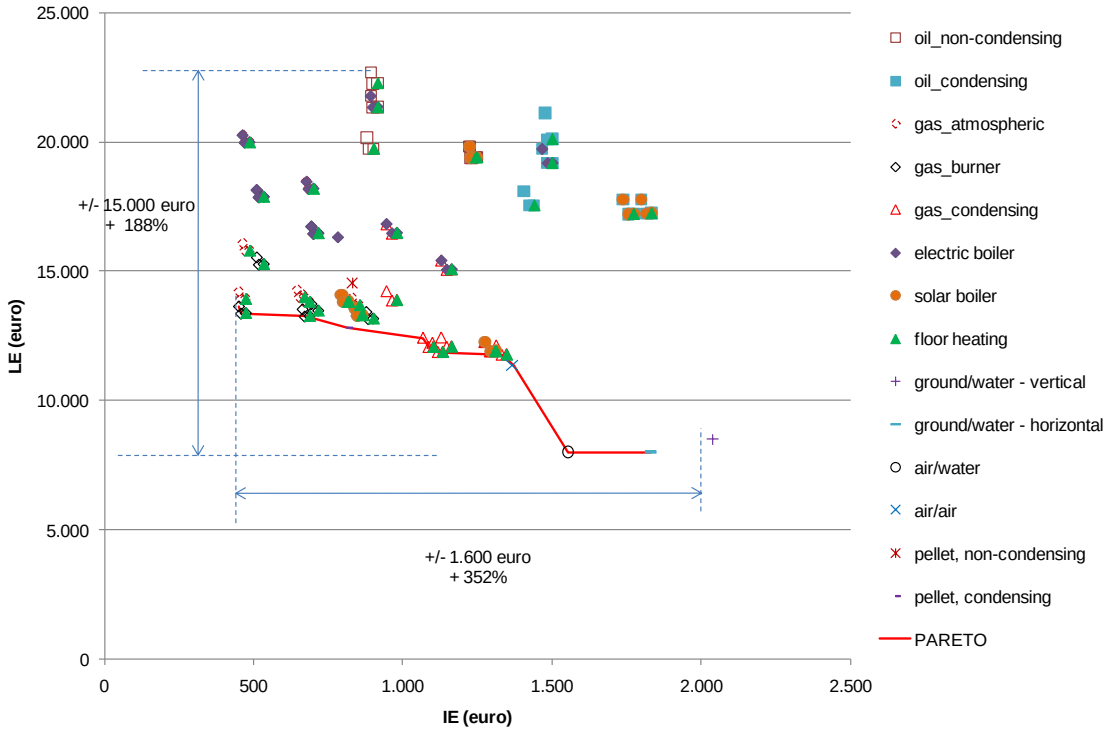

Figure 8 Initial environmental cost (in €) versus life cycle environmental cost (in €) of all commonly used heating system configurations (SH+DHW) for the well-insulated dwelling (K20)

From a financial point of view similar conclusions can be drawn as for the non-insulated dwelling. Although an instant coupled condensing gas boiler with a separate geyser in the kitchen is added as an extra Pareto minimum, the gain in financial life cycle cost is too small (i.e. less than 1%) compared to the former Pareto sub optimum.

Table 4: Pareto front of financial costs (IF versus LF) for the well-insulated dwelling (K20) with a life span of 60 years

configuration SH	**configuration DHW**	**IF** (€/m² fl net)	**LF** (€/m² fl net)
gas atmospheric; panel radiator; MV+RT+OS	instant coupled	*55,0*	*413,2*
gas condensing; panel radiator; TV+clock	instant coupled	*55,9*	*403,4*
gas condensing; panel radiator; TV+clock+OS	**instant coupled**	***56,2***	***396,7***
gas condensing; panel radiator; TV+clock+OS	instant coupled + 1geyser	*57,9*	*395,6*

* MV = manual valves; TV = thermostatic valves; clock = clock control; RT = room thermostat; OS = outside sensor

Heat pumps and pellet furnaces have respectively 61-99% and 29-31% bigger financial life cycle costs, compared to the condensing gas boiler with the lowest LF. Both types of advanced solutions are characterised by a substantially bigger investment and thus also replacement costs. Furthermore, the high energy prices related to electricity (see Table 1) for heat pumps cancel out the benefit of consuming less energy during the use span of the dwelling (see §6.3). For this reason no alternative heating solutions appears on the Pareto front of the financial costs.

Table 5: Pareto front of environmental costs (IE versus LE) for the well-insulated dwelling (K100) with a life span of 60 years

configuration SH	**configuration DHW**	**IE** (€/m² fl net)	**LE** (€/m² fl net)
gas burner; panel radiator; MV+RT	instant coupled	*3,7*	*111,0*
gas burner; panel radiator; MV+RT+OS	instant coupled	*3,7*	*108,7*
gas burner; panel radiator; MV+RT+OS	instant coupled + 1 geyser	*5,5*	*107,8*
pellet condensing; panel radiator; TV+RT+OS	coupled storage vessel	*6,6*	*104,2*
gas condensing; panel radiator; TV+clock	instant coupled	*8,7*	*101,0*
gas condensing; panel radiator; TV+clock +OS	instant coupled	*8,8*	*98,1*
gas condensing; panel radiator; TV+clock +OS	instant coupled + 1 geyser	*9,1*	*96,5*
gas condensing; panel radiator; TV+clock +OS	2 geysers	*10,8*	*95,7*
air/air heat pump; RT+OS	coupled storage vessel	*11,2*	*92,3*
air/water heat pump; panel radiator; TV+clock +OS	**coupled storage vessel**	***12,6***	***65,1***
ground/water horiz. HP; panel radiator; TV+clock +OS	coupled storage vessel	*14,9*	*65,0*

* MV = manual valves; TV = thermostatic valves; clock = clock control; RT = room thermostat; OS = outside sensor

From an environmental perspective the Pareto optima somewhat differ from the ones for the K100 dwelling. For the well-insulated dwelling heat pumps and pellet furnaces do compete with commonly used boilers. Environmental costs (IE and LE) of the condensing pellet furnace are between those of the gas burner and condensing gas burner situated on the Pareto front. Further upgrading to an air/air heat pump is characterised with a reduction of 4% in LE for an equal increase in IE, compared to the condensing gas boiler with the lowest LE. At the end of the Pareto front only advanced solutions are found, i.e. the air/air heat pump, the air/water heat pump and the ground/water heat pump with horizontal exchange – all coupled with a storage vessel for DHW. Only a slight reduction (i.e. less than 1%) of LE is

discerned between the last two named Pareto optima for an increase of 18% of IE. For this reason the air/water heat pump is environmentally speaking preferred.

6.3 Impact of heating sub systems

In order to understand the results shown in the previous paragraphs, the heating sub systems are assessed separately. A condensing gas boiler with panel radiators controlled by an outside temperature sensor in combination with thermostatic valves and a clock in the living is taken as a reference. For the commonly used configurations no heat storage is taken as reference for DHW. For the advanced configurations a coupled storage vessel is the reference DHW system.

Results are only shown for the highly insulated dwelling and a life span of the dwelling of 60 years. Similar conclusions can be drawn for the non-insulated dwelling. Based on the description of SH and DHW (see §4.2), a distinction is made between the following sub-systems: production type and fuel of SH; production type and storage of DHW; emission of SH and control of SH.

6.3.1 Production type and fuel of space heating

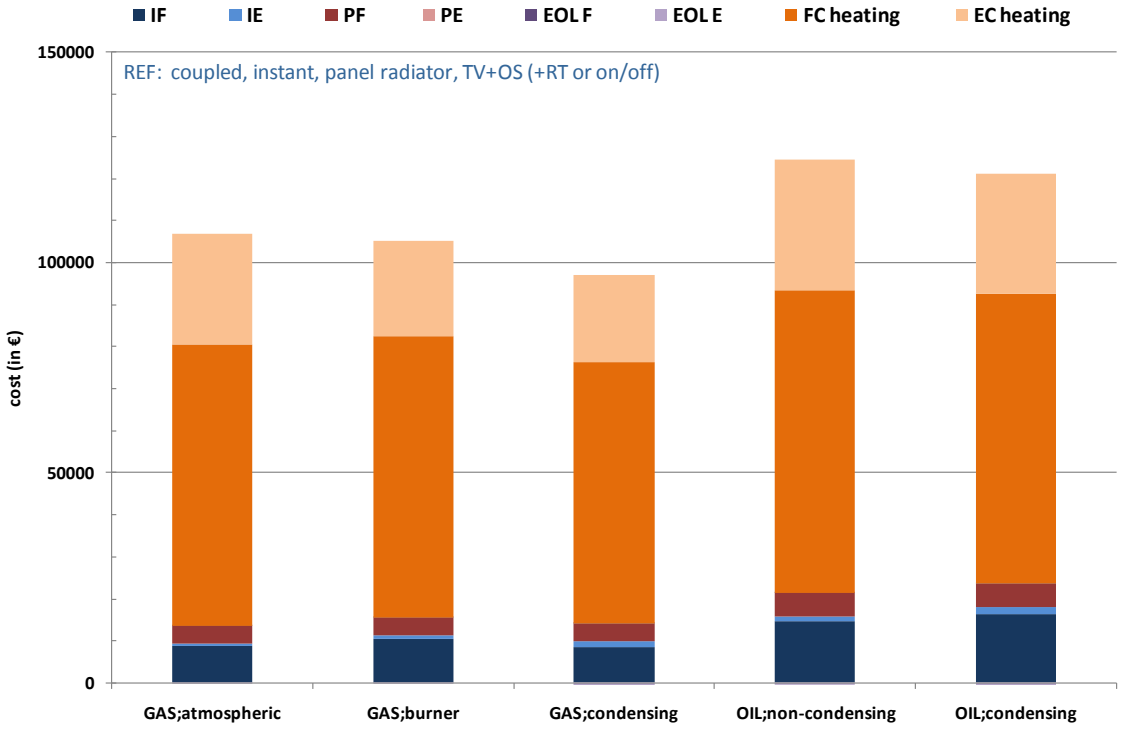

Figure 9 Comparison of production type and fuel sub systems of commonly used space heating systems (in €) for the well-insulated dwelling (K20) with a life span of 60 years

Looking at the graphical representation of the total life cycle cost, two major conclusions can be drawn regarding the selection of production and fuel type of a traditional SH.

First of all, the figures show clearly that oil furnaces have a substantially bigger overall cost than gas furnaces. Not only is the financial investment of an oil heating system bigger than a comparable gas heating system, financial and environmental costs for oil as an energy carrier are respectively 11% and 38% more expensive than for gas.

Beside the fuel choice, condensing boilers consume less energy for a small or negligible increase in initial costs, compared to non-condensing boilers. The environmental cost of production and replacement of condensing boilers is 1.5 times bigger than non-condensing ones, due to the use of stainless steel in these high performance furnaces. In the other furnaces cast iron and steel is used.

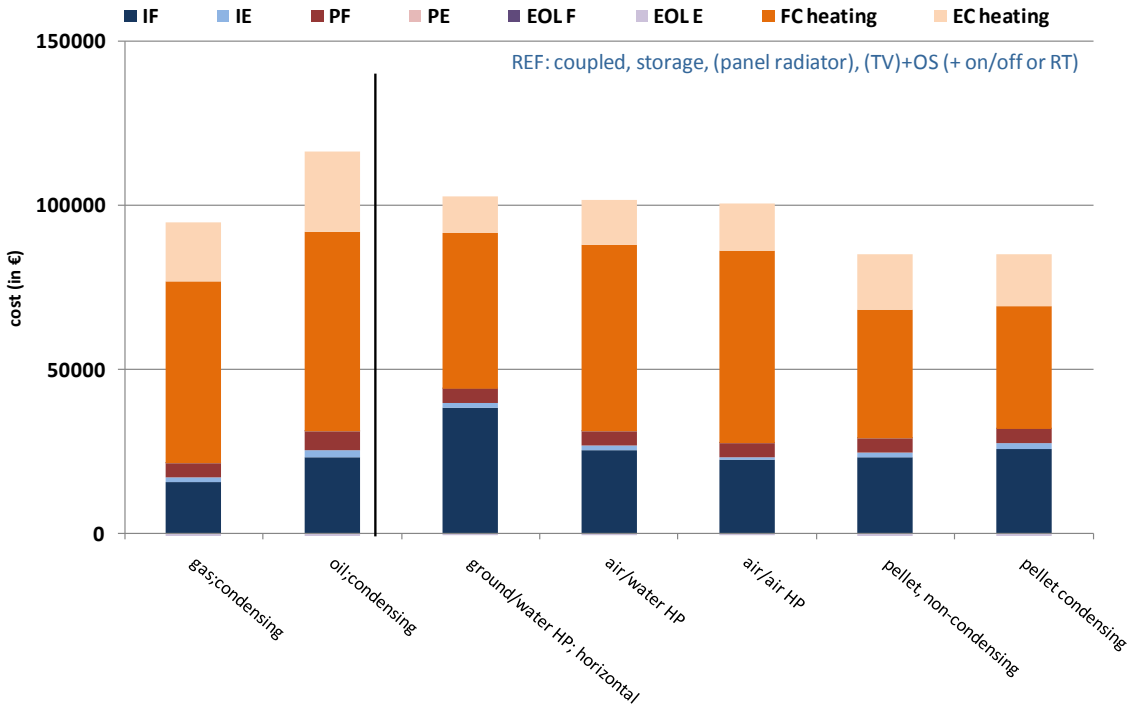

Figure 10 Comparison of production type and fuel sub systems of advanced space heating systems (in €) for the well-insulated dwelling (K20) with a life span of 60 years

The studied heat pumps consume 2.5 – 3.7 times less energy (for SH) than a condensing gas/oil boiler (see Table 6). However, over a life span of the dwelling of 60years, this benefit is more or less cancelled out due to the use of the Belgian electricity production mix, needed to activate the devices – and the combined effect of the discount and growth rate. Belgium's electricity production is characterised by a dominant share of nuclear, gas and hard coal. According to the *ecoinvent* data library, less than 10% of Belgium's electricity supply in 2007

comes from renewable energy sources. Compared to gas and oil as a heating source, electricity has an environmental cost that is respectively 2.4 and 1.6 times bigger.
Furthermore, Belgian electricity is substantially more expensive than gas and oil; financial energy costs are respectively 3.9 and 3.3 times bigger (see Table 1).

Table 6: Energy consumption (in MJ/m² net floor area) of alternative heating configurations with the reference for the highly insulated dwelling (K20) with a life span of 120 years

configuration SH	**Energy SH**	**Energy DHW**
REF: (coupled), solar boiler, (panel radiator), (TV)+RT+OS	**(MJ/m² fl net)**	**(MJ/m² fl net)**
gas condensing	*86,3*	*37,6*
oil, condensing	*85,9*	*36,1*
ground/water heat pump, vertical heat exchange	*23,4*	*20,4*
ground/water heat pump, horizontal heat exchange	*23,4*	*20,4*
air/water heat pump	*33,9*	*20,4*
air/air heat pump (separate, without radiators)	*34,7*	*20,4*
pellet, non-condensing	*119,1*	*25,2*
pellet, condensing	*111,8*	*25,2*

From all advanced heating configurations, pellet furnaces have the lowest total life cycle costs, i.e. 19% - 21% lower compared to heat pumps. In the case of existing remote houses where gas supply is not available, these relatively new systems are good alternatives for oil boilers. Furthermore, over a life span of 60 years pellet furnaces can even compete with condensing gas boilers. Similar conclusions can be drawn for a life span of the dwelling of 120 years.

6.3.2 Production type and storage of domestic hot water

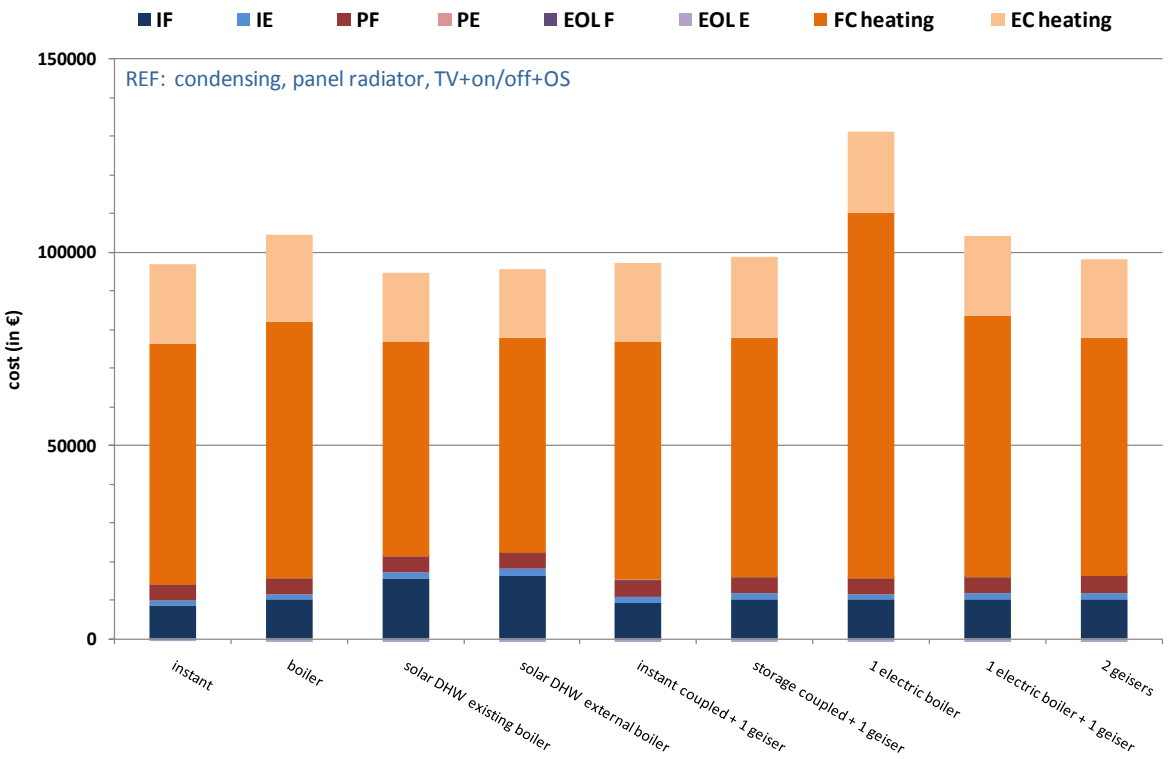

Figure 11 Comparison of production type and storage sub systems of domestic hot water systems (in €) for the well-insulated dwelling (K20) with a life span of 60 years

There is no substantial difference in overall costs between coupled and separate DHW systems over a life span of the dwelling of 60 years. Nor is there a clear preference for solutions with or without heat storage of water. Nevertheless, two distinct observations can be made. First, DHW systems with an electric boiler have to be avoided, due to the high energy prices for electricity (see Table 1). Secondly, the benefit of conserving energy by using a solar boiler is almost cancelled out, due to its higher financial investment cost. Similar conclusions can be drawn for a life span of the dwelling of 120 years.

6.3.3 Emission of space heating

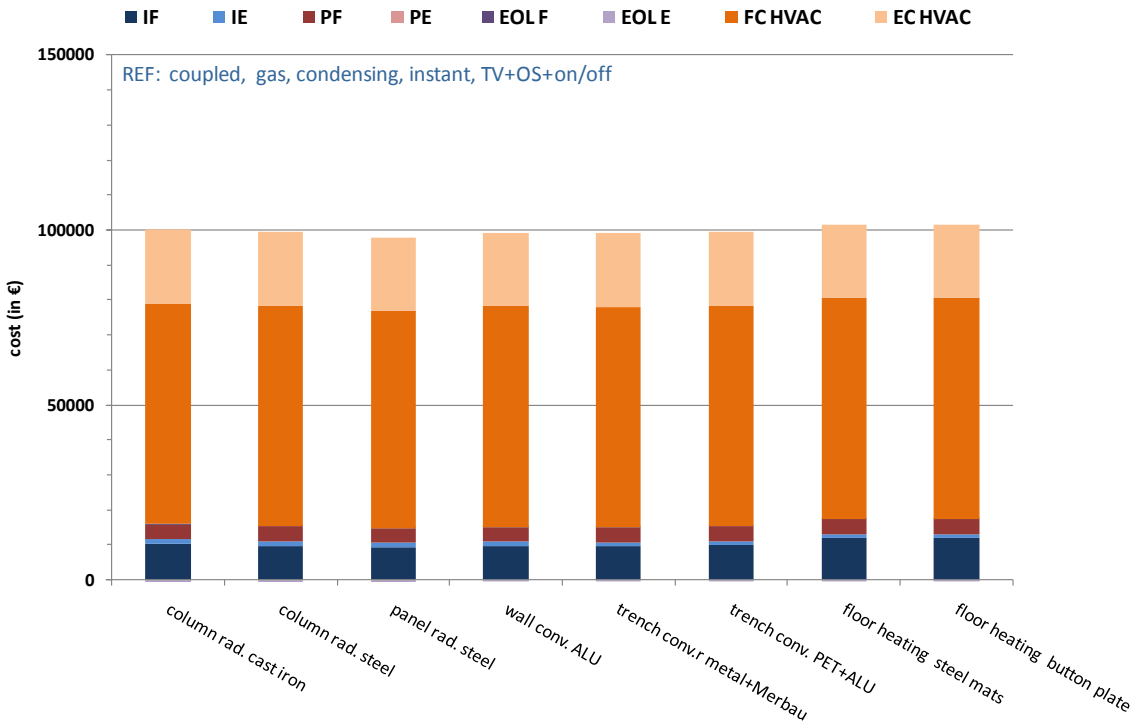

Figure 12 Comparison of emission sub systems of space heating systems (in €) for the well-insulated dwelling (K20) with a life span of 60 years

Although low temperature emission systems are more energy performing than high temperature ones, no substantial differences in the overall cost profile are discerned between all studied emission systems.

6.3.4 Control of space heating

Based on interdependency of heating sub systems (see §4.2.1), different sets of control systems are analysed. For a (modulating) condensing boiler, the influence of room thermostat and manual valves (whether or not combined with an outside temperature sensor) is analysed on the life cycle cost profile. Alternatively, for a (non-modulating) gas burner, the influence of thermostatic valves and a clock control (whether or not combined with an outside temperature sensor) is analysed.

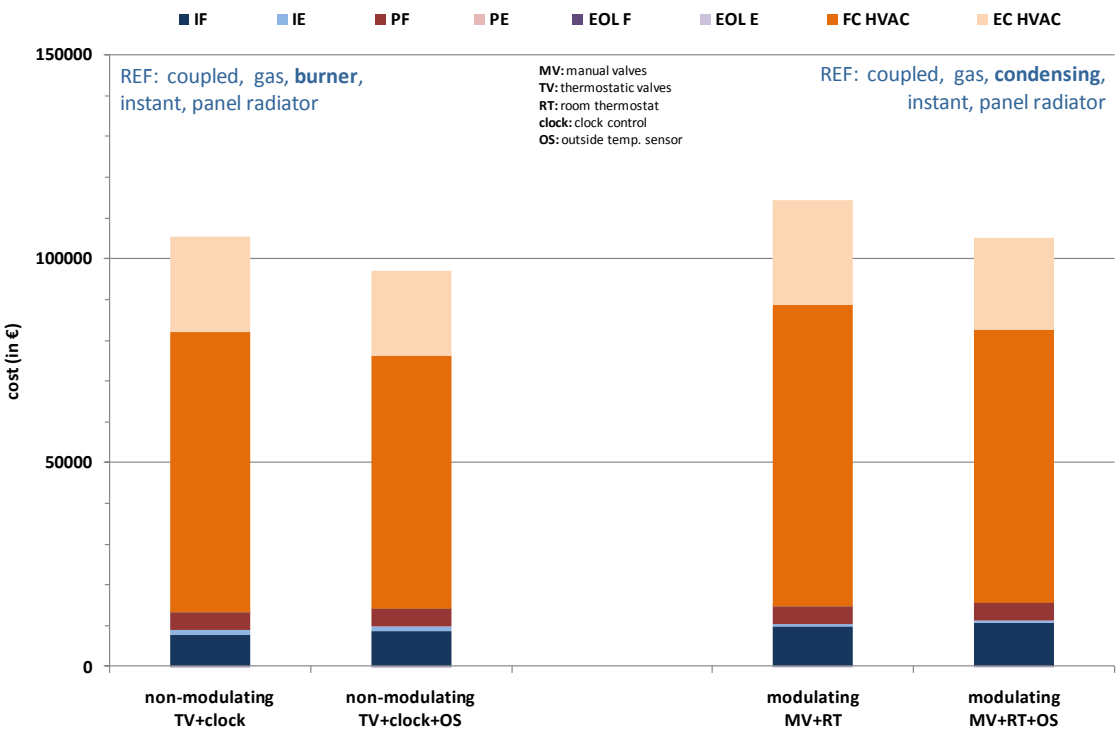

Figure 13 Comparison of control sub systems of space heating systems (in €) for the well-insulated dwelling (K20) with a life span of 60 years: (left) non-modulating gas burner; (right) modulating gas burner

The relatively small initial costs of control components (less than 10% of IF and 3% of IE) disappear in the total life cycle profile. Nevertheless, the initial selection of a heating control system does have a significant influence on the overall heating efficiency – and thus also the energy consumption over the life span of the dwelling. As shown in Figure 13 a more sophisticated control system – i.e. using an outside temperature sensor – for a well-insulated dwelling is responsible for a reduction of circa 7% of LF and 13% of LE – for both a modulating and a non-modulating boiler.

7 Concluding Recommendations

For the representative Belgian dwelling, assessed in this research, heating services and the related energy are responsible for 9-18% of LF and 55-78% of LE of the dwelling. Such diverse figures justify the necessity to better understand heating services and to seek solutions to reduce financial and environmental costs, without loss of dwelling qualities. In order to do so, systemic and parametric modelling is used to evaluate different heating measures on element level.

7.1. Recommendations on element level

From an environmental viewpoint, one of the most important measures to reduce life cycle costs is to enhance the **thermal insulation level** of the dwelling. By halving the net energy demand the environmental life cycle costs are on average reduced by 46%. Due to the relatively low financial energy prices the life cycle financial costs are only reduced by 4%. As a result, a good selection of heating services is crucial to further decrease life cycle costs. Choosing appropriate heating configurations can lead to a reduction of financial life cycle costs of 10% for the K100 dwelling and of 8% for the K20 dwelling.

For the selection of a **space heating system** a commonly used condensing gas boiler combined with a sophisticated control system (i.e. thermostatic valves combined with a clock and an outside temperature sensor) is preferred based on merely financial costs. Focusing only on the environmentally costs, advanced alternatives such as a heat pump and a condensing pellet furnace can compete with the previously named configuration, but only for a highly insulated dwelling (considering a dwelling life span of 60 years). Although heat pumps are characterised by a higher initial environmental cost, their corresponding life cycle costs are lower compared to non-renewable production systems. Looking at the total life cycle costs, once again, the common configuration with the condensing gas boiler is preferred above others. A condensing pellet furnace is the best advanced solution for the highly insulated dwelling. Based on environmental and total (life cycle) costs, we can conclude that there is no clear preference for any of the studied emission types. Although the emission type does not play a significant role in the life cycle cost profile, over-dimensioning of the emission components will lead to efficiency losses. Also the capacity of production systems dwellings needs to be chosen correctly. For highly insulated dwellings this is, however, problematic since small condensing gas and oil boilers are not (yet) available on the Belgian market. One of the measures to change this is to strongly involve the heating industry and installers into the determination of energy performance of dwellings.

For the supply of **domestic hot water** electric boilers should be avoided – if possible – due to the relatively high environmental costs, related to Belgian energy mix. When only initial costs are taken into account, solar boilers cannot compete with an instant system (coupled to CH) with or without a separate geyser in the kitchen or bathroom. However, from a life cycle perspective – including financial, environmental as well as total costs – these advanced systems can compete with the commonly used ones.

7.2. Recommendations on dwelling level

Besides the selection of appropriate SH and DHW and enhancing the thermal insulation level of the dwelling, a good implementation of dwelling characteristics such as building morphology, size and orientation as well as window area will further enhance energy performance of the dwelling. Since these characteristics are strongly related to the location of the dwelling, these aspects have not been taken into account in this paper. More information about these dwelling characteristics can be found in (Allacker 2010).

7.3 Internalisation of environmental costs

The environmental life cycle cost proves to contribute on average 6% to the total life cycle cost (with a minimum of 3% and a maximum of 10%). The contribution of the environmental cost to the initial cost equals on average 5% (with a minimum of 5% and a maximum of 6%). This implies that the **internalisation of environmental costs**, will not lead to unaffordable housing – provided that the energy demand of the dwelling remains low.

Since the monetisation of environmental impacts is based on the concept of "willingness to pay" for environmental damage, it is likely that the importance of environmental life cycle cost will increase in the future. In that case, environmental and total optima and sub optima will have to be adjusted. Some advanced heating systems, which are for the moment not interesting from a total life cycle cost point of view, would benefit from this change in public opinion.

8 Acknowledgements

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References

Allacker, K., De Troyer, F. (2006), Evaluation of the environmental impact of buildings, including quality and financial cost. In Proceedings of 13th CIRP International Conference on Life Cycle Engineering, May 31st – June 2nd, Leuven, Belgium.

Allacker, K., De Troyer, F., Spirinckx, C., De Nocker, L, Vercalsteren, A., Tomasetig, B., Putseys, K. (2008), Striving for a more sustainable Belgian dwelling stock, In Proceedings of 5th International Conference on Urban Regeneration and Sustainability, September 24 – 28, Skiathos, Greece.

Allacker, K. (2010), Sustainable Building: the development of an evaluation method, doctoral dissertation, K.U.Leuven, Leuven, Belgium.

Ammar, C., Longuet, M. (1980), Belgian Requirements About Buildings Service Life, Durability of Building Materials and Components, ASTM, STP 691, Sereda and Litvan, American Society for Testing and Materials, 77-90.

Belgian Institute for Normalisation (BIN) (2003), NBN EN 12831: Heating systems in buildings - Method for calculation of the design heat load.

Bickel P., R. Friedrich (2005) ExternE Externalities of energy: Methodology 2005, update. DG Research, EUR 21951, 270p. Retrieved on August 2008, from http://europa.eu.int/comm/environment/climat/studies.htm

Brown, V. J. (2003), Give Me Shelter. The Global Housing Crisis, Environmental Health Perspectives, 111(2), 92-99.

Battle, G. (2007), Sustainable cities. In Burdett R. and Sudjic D (Ed.).The Endless City, 386-393, London, UK, Phaidon Press Ltd.

ecoinvent (2007), ecoinvent database version 2.0, accessed on June 2008; from www.ecoinvent.ch/.

Fernandez, J.E. (2003), Design for change: Part 1: diversified lifetimes. Architectural Research Quarterly Volume 7: 169-182.

Flanagan, R., Tate, B. (1997), Cost control in Building Design, Oxford, Blackwell.

Goedkoop M., Spriensma R. (Pré Consultants B.V.) (2001), The Eco-indicator 99 - A damage oriented method for Life Cycle Impact Assessment -Methodology Report (Third edition), in order of Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer (VROM), nr. 1999/36A, 132p.

Guinée, J.B., M. Gorrée, R. Heijungs et al. (2002), Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards. Dordrecht, The Netherlands.

Hens, H. (1996), Toegepaste Bouwfysica 3 – Gebouwen en installaties, Leuven: ACCO.

ILO (2010). Green Jobs Creation Through Sustainable Refurbishment in the Developing Countries, Retrieved on 28 August 2010, from:
www.ilo.org/public/english/dialogue/sector/papers/construction/wp275.pdf

International Standards Organisation (2006a), ISO 14040 Environmental Management - Life Cycle Analysis - Principles and framework.

International Standards Organisation (2006b), ISO 14044, Environmental management - Life cycle assessment Requirements and guidelines.

Nationaal Instituut voor Statistiek (NIS) (2001), Socio-economische enquête (SEE2001). Retrieved in December 2008, from http://aps.vlaanderen.be/sgml/largereeksen/1106.htm

CEN (2003): EN12831: Heating systems in buildings - Method for calculation of the design heat load, European Standard.

Ott, W, Baur, M, Kaufmann Y, Frischknecht, R, Steiner, R (2006), Assessment of Biodiversity Losses, Deliverable D.4.2.- RS 1b/WP4 - July 06 Needs project, Ecoconcept and ESU, Retrieved on August 2008, from www.needs-project.org

REGENER (1997), European methodology for the evaluation of Environmental impact of buildings - Life Cyc1e Assessment: application of the life cyc1e analysis to buildings, Regener project, final report, 145p.

SETAC (2003), Life-Cycle Assessment in Building and Construction: A state-of-the-art report, SETAC Press, North Carolina, 86p.

Spirinckx, C., Vercalsteren, A., Allacker, K., De Troyer, F., Putzeys, K., Sustainable Building: The Search for an Integrated Method to Evaluate the Sustainability of Different Dwelling Types, In the Proceedings of the 6th Australian Conference on Life Cycle Assessment, February 16-19, Melbourne, Australia.

UNEP (2006), Sustainable Building and Construction Initiative: 2006 – Information note: United Nations Environment Programme.

UNEP (2007), Buildings and Climate Change: Status, Challenges and Opportunities. (Lead authors P. Huovila, M. Ala-Juusela, L. Melchert, and S. Pouffary), UNEP Sustainable Buildings and Climate Initiative, Paris

Van der Veken, J., Hens, H. (2007), Determination of the heating efficiency at building level, Proceedings of the 9th REHVA World Congress Clima2007, Helsinki, 2007. REHVA World congress CLIMA2007, Helsinki, 10-14 June 2007. Helsinki, Finland: FINVAC