ECONOMICAL AND ENVIRONMENTAL IMPACT OF LOW ENERGY HOUSING RENOVATION

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INTRODUCTION

CONTEXT
Improving the living comfort and repairing or renewing outdated building components are the main reasons for thorough renovation works. Improving the energetic performance of the envelope and the building’s installations can also be a reason and is stimulated by (financial) incentives by the authorities.

Besides comfort and aesthetics, an important decision criterion in a renovation project is the optimal spending of the budget available, or the cost efficiency of the measures taken. This criterion is even more important when one decides to go further than the standard building practice’ (which is reparation of leaks, replacement of windows, insulating non-insulated walls/roof/...). Additional investments need to weigh up against expected savings and/or other benefits. Usually, an investment decision is (directly or indirectly) made from a ‘life cycle’ perspective. This means the investor will compare the investment cost to the costs that will occur in the future: energy consumption costs, maintenance costs, replacement costs, other possible costs …

Another aspect gaining more and more interest in the building sector is the environmental impact of construction activities. Adding insulation will save energy but also implies a certain material consumption, emissions and energy consumption during manufacture, transport, placing, at the end-of-life (disposal, ...). Calculating the environmental impact is done by a ‘life cycle analysis’ or LCA.

RESEARCH QUESTION
Prior to the LEHR-project only limited knowledge on economic and environmental impact of energy-efficient renovation was available in Belgium. Therefore, this report brings together literature data and a detailed analysis on an existing Belgian case study in order to gain a better inside into the following questions:

- Is a thorough energetic renovation interesting from a financial point of view? How far should one go in his efforts to achieve a low-energy-consumption level (Passive House standard, very low energy retrofit, low energy, standard renovation, …)?
- Depending on the chosen ambition level, what is the environmental impact generated (or avoided) by the renovation?
- Can both cost and environmental aspects be combined in order to choose for a ‘best value’-solution?

Additionally, methodological aspects in determining cost efficiency and environmental impact in the context of housing renovation are discussed. Through literature, also the question of retrofitting or ‘rebuilding’ is discussed.

APPROACH
As a starting point, a literature review on cost efficiency, life cycle costing and environmental impact, was executed focusing on energetic renovation projects, but also considering the option of demolition and reconstruction. This literature review permitted to collect most relevant existing sources and conclusions from existing research on costs
and environmental aspects of energetic renovations. It also allowed to set a working methodology for life cycle costing and life cycle analysis to be used in the case study: parameters used, influencing choices in the methodology, attention points, etc. …

Case studies take a central place within the LEHR-project. Therefore, in addition to the literature review, a case study was analysed in terms of cost efficiency and environmental impact. Indeed, for a given renovation project, alternative renovation scenarios with different ambition levels were analysed in order to identify the most cost efficient and environmentally friendly solutions for low energy retrofitting.

RESULTS
The research work and the resulting conclusions are structured in the following report in two main parts.

The first part summarizes the results from the literature review. It is divided into 3 chapters, with each chapter handling a different subject: cost efficiency of energy saving measures (chapter 1), environmental impact of retrofitting house (chapter 2) and cost efficiency and environmental impact of demolition and reconstruction versus renovation (chapter 3).

Each of those three chapters is subdivided into two sections. The first section handles methodological aspects (sources of data, calculation methods, boundary conditions) and the second section presents conclusions drawn from existing studies. This allows the reader who is familiar with the methodology to skip these parts, or one who wants to do LCC or LCA calculations to have an overview of existing resources.

The second part of the report is dedicated to the case-study: the retrofit scenarios considered, the methodology used for the LCA and LCC analysis and the case specific results on cost efficiency and environmental impact.

Finally, some general conclusions are stated.

LIMITATIONS
The literature review revealed an important diversity in source of data, methodological choices, and objectives amongst the consulted studies (studies on European level or on national/local level, using different climate data and cost figures, evaluation of particular renovation measures or complete case studies,…).

Also, concerning the results from the performed case study, it is important to note that they are only representative of that specific case (ideally oriented, executed by an experienced architect, and going a lot further than a simple renovation (with also the creation of 50 m² additional living space),…) and that there are various sources of uncertainty inherent to the LCC and LCA methodologies themselves and to the data used for the analysis.

For example, a LCA implies modelling the future, which means average scenarios had to be developed concerning end-of-life conditions and energy production in Belgium. Those elements are very likely to evolve over the course of the building’s life (e.g. recycling and renewable energy sources are likely to gain importance), but as no clear information is available on how exactly they will evolve, we chose to model them based on actual conditions (e.g. only materials that are recycled today, where considered as such, and we used the actual electricity supply mix). The same applies for forecasting future energy
and other prices (e.g. innovative techniques may become cheaper when more widely spread).

Moreover, as an LCA/LCC on the building level requires a huge amount of information, simplifications had to be made and average values had to be used (e.g. regarding transport distances to the construction site, unit prices,...). Also some aspects were modelled in a simplified way (e.g. energy consumption based on EPB-calculation) which results in approximate figures that are likely to differ from the real ones.

An LCA is not an exact science and methodological choices (e.g. allocation procedures, choice of LCIA methodology, aggregation method,...) can have an impact on the conclusions. Also, the LCC results on cost efficiency might change when different methodological choices (costs in/excluded) are made.

For all those reasons, conclusions drawn from the case study performed as part of the LEHR project should not be generalized to other cases, but should rather be considered as a first exploration in developing and applying LCC and LCA methodology on the building level within the Belgian context, and as a first indication of possible results.
PART 1
EXISTING KNOWLEDGE ON COST EFFICIENCY AND ENVIRONMENTAL IMPACT OF ENERGY SAVING RETROITS: METHODOLOGY, DATA AND CONCLUSIONS

Three aspects are considered: cost efficiency of energetic retrofits, environmental impact of energetic renovation and finally the financial and environmental impact of demolition and reconstruction versus renovation.

1. EXISTING RESEARCH ON COST-EFFICIENCY OF ENERGY-EFFICIENT HOUSING RETROFIT

This chapter gives a summary of existing studies on costs and benefits (savings) of renovation measures (results independent of specific projects), and of some case studies (project specific results). In the first subchapter (1.1), conclusions of existing studies are summarized. The following subchapter (1.2) gives an overview of sources that can be used and methodological choices to be made in an economic-efficiency analysis, based on the literature review. That part will also serve as basis for the performed case study.

1.1 ECONOMIC EFFICIENCY OF ENERGETIC RENOVATION MEASURES AND PROJECTS

During the last couple of years, energy saving measures in the existing building stock have become more and more popular due to rising prices of energy fuels, governmental incentives, and so on. In the scientific and architectural world, some cost-benefit analyses (mostly based on case studies) have been executed in order to assess the economic potential of energy saving measures such as insulation of walls, floors and roofs, improved glazing, more efficient energy (heating) production systems, etc. The following paragraphs give a summary of the general conclusions that can be drawn from a number of reviewed studies [(EcoFys, Cost-Effective Climate Protection in the EU Building Stock, 2005), (EcoFys, 2007), (Feist, 2005), (3E & KULeuven, 2005), (Verbeeck, 2007), (3E,KULeuven, PHL, 2008), (Gustafsson, 2000), (Brannon, 2007), (Jordan, 2007), (Audenaert, 2008), (Versele, 2008), (CERAA, 2008), (Renard F., 2008)]. On request, a summary of these studies is available – see Annex.

1.1.1 General conclusions on cost efficiency of energy saving renovation measures

1) Individual measures

Despite the differences in approach and methodology (see further) of the different studies on individual retrofit measures similar results are obtained:
1. It is cost effective to invest in (individual) energy saving insulation measures. The payback time for individual measures is rather low (usually less than 10 years) and thus justifies the investment.

The table below, adapted from the PHI-study (EcoFys, Cost-Effective Climate Protection in the EU Building Stock, 2005) illustrates that the optimal U-values (first column) are generally much lower than the legally required values to achieve the EnEV-standard (anno 2005). The table also shows the price per saved kWh, which is generally lower than the cost per consumed kWh (+- 5 c€/kWh), hence showing the economic efficiency of measures applied in two scenarios (current economic conditions and future energy price scenario).

<table>
<thead>
<tr>
<th>Measure</th>
<th>Optimal U-value (Study)</th>
<th>Equivalent price of saved kWh</th>
<th>2005 EnEV-legislation max. value</th>
<th>Optimal U-value for the future (Study)</th>
<th>Equivalent price of saved kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W(m²K)</td>
<td>€Cent/kWh</td>
<td>W(m²K)</td>
<td>W(m²K)</td>
<td>Cent/kWh</td>
</tr>
<tr>
<td>Pitched roof</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insulation below and between rafters</td>
<td>(0,16)</td>
<td>2,0</td>
<td>0,30</td>
<td>(0,16)</td>
<td>2,0</td>
</tr>
<tr>
<td>Insulation on top of rafters</td>
<td>0,16</td>
<td>1,7</td>
<td>0,30</td>
<td>0,11</td>
<td>2,0</td>
</tr>
<tr>
<td>Insulation on top and between rafters</td>
<td>0,15</td>
<td>1,9</td>
<td>0,30</td>
<td>0,10</td>
<td>2,1</td>
</tr>
<tr>
<td>Flat roof</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Additional insulation in roof structure (warm roof)</td>
<td>0,18</td>
<td>3,2</td>
<td>0,25</td>
<td>0,12</td>
<td>3,5</td>
</tr>
<tr>
<td>Insulation on top of roof (waterproofing) (inverse roof)</td>
<td>0,22</td>
<td>2,9</td>
<td>0,25</td>
<td>0,16</td>
<td>3,3</td>
</tr>
<tr>
<td>Attic floor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insulation (non accessible attic)</td>
<td>0,14</td>
<td>0,7</td>
<td>0,30</td>
<td>0,12</td>
<td>0,9</td>
</tr>
<tr>
<td>Insulation (accessible attic)</td>
<td>0,14</td>
<td>1,6</td>
<td>0,30</td>
<td>0,12</td>
<td>1,7</td>
</tr>
<tr>
<td>Exterior wall</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>External insulation (incl. putty renovation)</td>
<td>0,17</td>
<td>1,3</td>
<td>0,35</td>
<td>0,13</td>
<td>1,6</td>
</tr>
<tr>
<td>External insulation (new lining)</td>
<td>0,17</td>
<td>2,3</td>
<td>0,35</td>
<td>1)</td>
<td>2,5</td>
</tr>
<tr>
<td>Curtain wall with additional insulation (renewal of formwork)</td>
<td>0,18</td>
<td>2,0</td>
<td>0,35</td>
<td>0,13</td>
<td>2,3</td>
</tr>
<tr>
<td>Inside insulation with airtight screen (new coated wallpaper)</td>
<td>(0,28)</td>
<td>2,0</td>
<td>0,45</td>
<td>(0,28)</td>
<td>1,0</td>
</tr>
<tr>
<td>Inside insulation with airtight screen (renewal of inside plastering)</td>
<td>(0,28)</td>
<td>1,0</td>
<td>0,45</td>
<td>(0,28)</td>
<td>1,0</td>
</tr>
<tr>
<td>Cellar wall</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insulation with airtight screen (renewal of inside putty)</td>
<td>(0,27)</td>
<td>2,5</td>
<td>0,50</td>
<td>(0,27)</td>
<td>2,5</td>
</tr>
<tr>
<td>Floor above cellar</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insulation from the bottom</td>
<td>(0,27)</td>
<td>2,5</td>
<td>0,40</td>
<td>(0,27)</td>
<td>2,5</td>
</tr>
<tr>
<td>Heat distribution and hot water pipes</td>
<td>2)</td>
<td></td>
<td>2)</td>
<td>2)</td>
<td></td>
</tr>
<tr>
<td>Pipe insulation</td>
<td>100% x DN</td>
<td>0,9</td>
<td>100% x DN</td>
<td>200% x DN</td>
<td>1,5</td>
</tr>
</tbody>
</table>

Note: The economical U-values are lower than those listed between brackets. The values between brackets are the limit values that can be achieved without causing practical problems to the indoor environment

1) No request for EnergySavingDecree (EnEV)
2) Thickness of the insulation referred to diameter of pipes DN.

Table 1 - Optimal U-values for cost efficiency (EcoFys, Cost-Effective Climate Protection in the EU Building Stock, 2005)
For insulation of floors, roofs and walls, EcoFys (EcoFys, U-values for better energy performance of buildings, 2007) determined the following optimal U-values in a Brussels context, considering 2 energy price scenarios:

<table>
<thead>
<tr>
<th>City</th>
<th>Country</th>
<th>City</th>
<th>Country</th>
<th>City</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brussels</td>
<td>Belgium</td>
<td>0.18</td>
<td>0.14</td>
<td>0.23</td>
<td></td>
</tr>
</tbody>
</table>

*Table 2 - Optimal U-values for Belgium in two energy price scenarios (EcoFys, U-values for better energy performance of buildings, 2007)*

2. The cost efficiency of energy saving measures increases when:

- No energy efficient building component are present prior to renovation (eg. no insulation), or in other words when there is a large difference between the old and the new situation in terms of heat loss and energy consumption (Delta U-value).
  This also means that when a renovation takes place, it is best to insulate as much as possible as adding insulation in a second phase, eg. ten years later, will be less cost effective.

- The energy saving measures are combined with other renovation measures like renewal of finishing elements. If a renovation has to take place anyway (e.g. for aesthetical reasons), only the extra investment cost for extra insulation/… can be accounted for in a cost efficiency calculation, resulting in a better economic result (due to a lower ‘real’ investment cost). This also makes investing in better windows and glazing or in efficient heating installations cost efficient (EcoFys, Cost-Effective Climate Protection in the EU Building Stock, 2005).

3. Looking at individual energy saving insulation measures, the cost-optimum curve shown as ‘total costs’ (per year) in function of the thickness of the additional insulation (cm or R-value), runs rather flat around the optimal value. This means that a range of insulation thicknesses lead to a similar total cost. Thus, thicker insulation layers are almost as cost-effective as the cost optimum. This becomes even more interesting in case energy prices keep rising at high rates.
Figure 1 - Annual costs of external wall insulation in a moderate climate compared to the additional thickness of the insulation applied (total cost, incl. finishing) (EcoFys, Cost-Effective Climate Protection in the EU Building Stock, 2005)

Figure 2 - Annual cost of roof insulation retrofit per m². (Orange = annual cost for energy, Purple = annualized investment cost, Green = total annual cost) (EcoFys, U-values for better energy performance of buildings, 2007)
On Belgian level, 3E et al (3E,KULeuven, PHL, 2008) show that most insulation measures have very low payback times (couple of years, max. 12.5 years), except window replacement. Optimal U-values for components are between 0.25 and 0.3 W/m²K for each part of the envelope.

2) Projects - Concepts

When it comes to the analysis of different concepts or ambition levels in a (real) project, most studies [(EcoFys, Cost-Effective Climate Protection in the EU Building Stock, 2005), (3E & KULeuven, 2005), (Verbeeck, 2007), (3E,KULeuven, PHL, 2008), (Brannon, 2007), (Jordan, 2007), (Audenaert, 2008), (Versele, 2008)] indicate that a low energy house is a good investment at this moment.

The passive house becomes more interesting when:

- energy prices rise more than 10% per year
- primes for passive houses are much higher than for low energy houses.

G. Verbeeck indicates that from an economic viewpoint, the optimal solution (for new buildings, but also for renovation) for a single family house consists of the following hierarchy (3E & KULeuven, 2005):

- The economic optimal insulation level lies around K25-K30 (or $U_{\text{mean}} = 0.3-0.4$ W/m²K for a compactness of 1.5-2). The economic optimal level of insulation for renovation will be somewhat higher than for new construction.
- A high efficiency boiler or condensing boiler is a good solution for the heating system. When a larger budget is available, a heat pump is a good alternative.
- A ventilation system with heat recovery and/or a solar driven system (solar collector or PV-system) can further decrease energy consumption, but are beyond the economic optimum.

These results appeared to be very robust as they are valid for different assumptions of energy price evolution, discount rates, ...

More recent research (3E, KULeuven, PHL, 2008) shows that for renovation projects, the economic optimum lies very far on the energy savings curve (up to 80% savings compared to the reference scenario).

Similar conclusions for renovation and new construction are drawn respectively by A. Versele et al (Versele, 2008) (for renovation) and A. Audenaert et al (Audenaert, 2008) (for new construction). With the current energy prices and evolutions, a low energy house shows to be the most economically viable option. A passive house becomes interesting only in case the energy prices rise at 10% a year over a period of 30-40 year.

![Figure 4 - Total Present Value comparison: Normative (K45 E98), Common Practice (K35 E67), Low Energy (K30 E38), Passive House (K20 E23) for 3 different energy forecasting scenarios (Versele, 2008)](image)

1.1.2 Methodology used for evaluation
During the literature review, it became clear that there are many methodological choices, and that those can influence the results of the study. Therefore, a short overview of the differences between the various studies is given.

Scope and objectives
All studies have more or less a similar objective: investigating cost effectiveness of energy saving measures. However, a lot of differences exist between the studies, not only in the data used, but also in the methodology, aspects being considered/excluded, the calculation method, the evaluation criteria ...

Economic indicators- Evaluation criteria
The easiest criterion for the evaluation of the economic efficiency of measures is the Amortisation period or Simple Payback Time where the extra yearly energy savings are weighed up against the extra investment cost of the measure. This can also be a dynamic payback time, when energy prices vary over time and the time value of money is taken into account (discounting).
Most economic evaluation criteria take into account a certain period of time, during which several costs (investment, energy cost, replacements, maintenance) occur. Those costs are then recalculated to a base point in time, resulting in a Net Present Value (when only counting with additional or differential costs) or a Total Present Value (calculating all costs). The NPV (or TPV) enables to compare different scenarios where different costs occur at different moments in time. In those scenarios several options are possible: a fixed energy cost, a yearly increase, maintenance included or not, … An extra option is to express all costs in ‘annual costs’ using an annuity factor. This results in a total yearly cost that can be compared with other alternatives.

When energy costs are included in the NPV, the current energy price is usually included in the calculations. An alternative way to demonstrate cost effectiveness is to calculate the ratio of the total yearly cost of the energy saving measure (€ per m²) and the total energy amount saved (kWh). This criterion is independent of the energy price and can be compared to it. If the (annualized) investment cost per saved kWh is lower than the current energy price, the measure is cost effective.

Another approach is to assume that a family has to borrow a certain amount of money that needs to be reimbursed within a certain time frame (eg. 20 years). This starting point is then used to analyse the impact of the initial investment and the saved energy costs on the yearly or monthly family budget.

Parameters and data used
From the literature review, it is clear that for each and every parameter several choices can be made, going from a different calculation period (20-30-40 years) over other cost data, different energy prices and energy price evolution scenarios (even fixed prices without rising), to other component service lifetimes, other ambition levels, …

The only solid conclusion that can be drawn at this point is that these choices are to some point arbitrary and thus ‘free to choose’ or variable due to changing location or rising prices or other objectives of the study. In any case, a sensitivity analysis should be undertaken in order to check the robustness of the results for varying parameters (eg. evaluation period, different energy cost scenarios, …). Most studies solve this by incorporating different energy cost evolution scenarios (low-average-high) in the analysis.

Inclusion/exclusion of elements - Cost Breakdown Structure
The analysed studies show that the influence of including/excluding cost elements can be very large.

Total cost vs. energy relevant cost: When a distinction is made between energy relevant and other investment costs (eg. the renewal of the wall finishing, new roof covering, …), the cost efficiency of extra insulation becomes better due to lower relevant investment costs.

Subsidies and other financial incentives are sometimes not taken into account. However, they can have a very beneficial influence on the cost effectiveness of energy saving measures.

Calculating the ‘rest value’ of measures with a long service life time (like insulation) can be interesting when the analysis period chosen is rather short.
This means that part of the investment cost can be deducted or recuperated from the total cost of the project.

Maintenance and replacement costs are usually not taken into account. Either because the different scenarios would have similar costs, or just because these costs are not considered to be relevant. For the evaluation of installations however, maintenance costs are usually taken into account.

Other costs, like CO$_2$-mitigation costs, are sometimes also included as indicators of environmental impact. Another cost element included in some studies is the ‘discomfort cost’ due to overheating or inefficient cooling installations.

1.2 REFERENCES AND SOURCES OF DATA FOR ECONOMIC EFFICIENCY EVALUATION

When taking an investment decision, usually a trade-off is made between the costs (investment, maintenance, replacement, …) and the benefits (comfort, energy consumption, …) over a certain period, since not all costs/benefits occur at the same time. This analysis is always a certain form of ‘life cycle costing’ (LCC), which is a technique used for predicting and assessing the cost performance of constructed assets and comparing several alternatives in terms of costs. Based on the literature review, at least following aspects should be considered: which elements should be included in the analysis, which parameters apply, what is the decision criterion used, what data should be used? The following paragraphs give an overview of possible data and methods to can be used in an LCC-analysis.

1.2.1 Methodology

Several attempts to harmonise the existing life cycle costing techniques and methods have lead to standard documents concerning Life Cycle Costing, that provide a good base for a LCC-exercise:

- ISO 15686-5 Building and construction assets - Service-life planning - Part 5: Life-cycle costing. - 06/2008
- NBN EN 15459 - Energy Efficiency for Buildings — Standard economic evaluation procedure for energy systems in buildings, 02/2008
- EU – Life cycle costing (LCC) as a contribution to sustainable construction: a common methodology – Davis Langdon Management Consulting for the EU DG Enterprises – Construction, 05/2007

Countries like Germany, the U.K., U.S.A. … have their own standards or guidance documents for LCC, for example:

- Lebenszykluskosten von Gebäuden - DIN 18960:2008-02, Nutzungskosten im Hochbau
- VDI 2067 - Part 1 : Economic Efficiency of Building Installations: Fundamentals and economic calculation
- SIA 480 – Calcul de rentabilité pour les investissements dans le bâtiment
- Önorn M 7140 – Economic comparison calculation of energy systems based on the extended annuity method – Definitions, calculation scheme
These documents usually describe the process of doing a LCC analysis (scope definition, steps to undertake, reporting framework, possible decision criteria, dealing with uncertainty,…), the cost structure (which aspects to include or not) and eventually some references to data sources. However, there is still an important degree of freedom as typically the LCC analysis is ‘client-oriented’ which means the client decides what to include and what not. Also, some aspects (eg. data to use) are not really addressed in the LCC standards.

The scope of a LCC analysis can be to:

- Draw up a detailed cost overview of a project
- Compare alternatives with a different cost-in-time profile : decision aid

There are several economic indicators that can be used:

- Static Payback Time – Dynamic Payback Time – Amortisation period
- Net Present Value – Total Present Value
- Internal Rate of Return – Modified Internal Rate of Return
- …

An interesting document published on calculation of cost-optimal levels in renovation (Hermelink A., 2009) discusses some distortions that can make the investment from the owner’s / investor’s viewpoint look better or worse than it is in practice. This document mainly addresses the need to apply a life cycle costing approach and a Net Present Value-calculation, using correct data and scenarios.

1. Some co-benefits of energy efficiency measures are not considered in a cost calculation:
   a. Higher independency from energy imports
   b. Mitigation of externalities like global warming
   c. Higher quality energy services resulting in better health (thermal comfort & indoor air quality)
   d. Risk reduction (less risk of damaging the building construction; less poverty risk in case of steeply increasing energy prices).

2. Positive distortion 1: Static calculations

Static calculation means no interest rates are taken into account. In reality; however, a return on investment is required. For example, an additional investment for energy efficiency of 1000 €, with a lifetime of 10 years and resulting in annual savings of 100€, would result in a profit of 0€ in a static calculation. In that case, there would be no money left to pay for the interest. This will result in a loss.

The better option is to do a Net Present Value calculation, where all costs in the future are discounted to current costs.

3. Positive distortion 2: Exponential energy price increase
Based on historic price developments, small annual price increases are applied. When assuming a yearly increase of 5%, a barrel of crude oil that costs 60€ now would cost more than 400€ in 40 years. ‘This would result in enormous virtual energy savings in retrofit, that most probably will never occur as long as the energy markets work.’ Once a certain price is reached, other energy alternatives become more viable and thus will the price stagnate somewhere. The author suggests that it is realistic to assume substitution processes for fuels from a certain price level on. Therefore, he suggests to use an average price level for the period under consideration.

An alternative approach is to keep costs and benefits of energy efficiency investments separate, and express them in a way that is easily understandable for an investor, based upon his personal judgment on future energy prices. Therefore, one can calculate the ‘investment per saved kWh of final energy’ : €/kWh. This cost can then be compared to the (expected) cost for energy in €/kWh.

4. Negative distortion 1: Application of payback method

The alternative with the shortest payback may not be the one that yields the highest profit. Payback calculations tend to prefer cheaper investments that not only tend to result in smaller savings, but also to have shorter lifetimes. Therefore a NPV approach would be more appropriate.

5. Negative distortion 2: High interest rates

Using high interest rates (eg. 10%) reflects the rate on investment required in private investments in higher risk projects. A better alternative is to calculate with the mortgage interest rate and eliminate inflation.

6. Negative distortion 3: Questionable alternatives

The best time for a major renovation or for improvement of components is when a renovation has to be done anyway. The cost of these non-energy ‘anyway investments’ has to be subtracted from the energy efficiency investments as they are not resulting from them. A major mistake in many calculations is that ‘doing nothing’ would be a real option for another couple of decades. It is not correct to balance the whole investment (incl. the ‘anyway measures’) against the energy savings.

7. Negative distortion 4: Zero residual values or too short life-times

It is not correct to allocate the whole investment cost for a long-lasting measure to a calculation period which is much shorter than the measure’s lifetime (e.g. Insulation lasts 40 years, cost calculation considers only 20 years). It is better to only allocate the share of the energy efficiency investment that delivers savings within the calculation period. This can be done by calculation annuities (e.g. with a 40 year lifetime) and only accounting for the considered years (e.g. 20 years). The residual value (e.g. the remaining 20 years) is not taken into account.
1.2.2 Sources for data, parameters, setting up scenarios ...

Two large elements play a role in a LCC analysis: costs and time. Costs include investment and construction costs (design, construction, material and man hours, ...) at the start of the project, as well as costs made during the service life of the building: maintenance, replacements and operational costs for energy consumption and water consumption.

'The real world we are living in is a world of uncertainty, a world whose future occurrences and conditions we are, in most cases, not able to predict.' (Jovanovic, Application of sensitivity analysis in investment project evaluation under uncertainty and risk, 1999). Investment is to be done under uncertain circumstances, with absence of a priori information necessary for solutions thereof. 'The lack of any possibility to predict future events and parameters, largely affects correct evaluation of investment projects and decreases the realistic possibilities of investment decision-making.' (Tak, 1979). We are thus unable to make optimal investment decisions, due to necessary predictions. ‘However, better knowledge of decision-making process in cases of uncertainty, and of decision-making criteria offered by theory as well, surely exerts influence by improving choices and by minimizing the possibility of decision-making.’ (Jovanovic, Investment Management, 1991). One of the most reckoned methods to solve the above sketched problem is ‘sensitivity analysis’. This is ‘the calculating procedure used for prediction of effect of changes of input data on output results of one model’. (Jovanovic, Application of sensitivity analysis in investment project evaluation under uncertainty and risk, 1999).

To improve the reliability of an analysis, the best data available should be used and the data used should be documented. Therefore, an overview of the base hypotheses and sources of data that can be used in a cost analysis are given below.

Service lifetime – period of analysis

The period of analysis is the period for which costs are considered and not necessarily the remaining service life of the building. In an environmental impact assessment usually the whole life cycle of the building is taken into account (60 to 120 years, including the disposal of the building), but from an investor’s viewpoint, usually a shorter period is taken into account.

ISO 15686-5 states that the preferred period of LCC-analysis is ‘the period of foreseeable need or occupation of the constructed asset’. This can be translated as ‘the period in which one generation intends to use the building’ (3E & KULeuven, 2005). This period can thus be chosen within the range of 20 to 40 years. People won’t invest in measures from which they cannot benefit themselves (and thus that would exceed their own life). Also, after 30 to 40 years, it is likely that the building will be thoroughly renovated again or demolished.

Choosing larger timeframes for economical analysis also causes costs occurring in the latest years of the analysis to be discounted to such a degree that they become irrelevant (a cost occurring at year 50, with a 5% discount rate, will be discounted with a factor 0.087, which means only 8.7% of the cost is accounted for). Besides, predictions in a 30 or 40 year framework are already difficult and very uncertain, going beyond that point makes it even more impossible to make reliable forecasts of costs.

Some of the measures applied in the building will have a normal service life that exceeds the analysis period (e.g. insulation). When doing a thorough renovation, it can be
estimated that these measures will be kept in the building after the analysis period, and thus have a certain value (cfr. ‘end-of-life’).

**Discount rate**

As other sources have already noticed, the discount rate expressing the time value of money, is dependent on the viewpoint of the analysis. For a government, this parameter will be based on the long term interest rate, while an individual investor will rather use the current interest rates for mortgage loans and saving accounts (3E & KULeuven, 2005). In a ‘sustainability evaluation’, the discount rate could be set at zero, to express the fact that the future is as important as the present. The market rate is corrected with a general inflation level.

\[
R^* = \frac{R - R_i}{1 + R_i}
\]

\[R_R = \text{Real Discount Rate}, \ R = \text{Real market rate}, \ R_i = \text{inflation rate} \ [\text{NBN EN 15459}]\]

**Inflation**

Prices are ‘real prices’ and are not corrected for inflation levels. ‘Excluding inflation from the forecast makes it clear that an increase in costs or benefits is an actual increase, and not simply an increase due to inflation’ (Gregory Michel, 2001).

**Construction costs**

In order to make an assessment prior to the project, sufficient reliable and qualitative data on the construction costs (labour, materials, installations) need to be available. Several sources for this ‘cost data’ can be used:

- Historic data: from previous projects, from literature and research (like E-retrofit-kit(E-Retrofit-kit)), estimations of the architect, …
- Cost databases: most relevant sources in Belgium are probably ASPEN-index (and Livios.be), but also the UPA-BUA Borderel van eenheidsprijzen, Bouwunie – Kostprijsberekening voor aannemers, … are relevant sources
- Product catalogues, producers’ information
- Websites and forums of retailers and users
- Real price offers of contractors should be available when starting the project.

Usually, these unit prices include material, delivery and installation costs.

Not only the basic price (often in €/m² or €/m³) is of relevance, also aspects like Do-It-Yourself (DIY), VAT and subsidies are of importance in a cost calculation from a clients’ viewpoint.

- DIY: can save costs, but must be included in order to be comparable to other projects
- VAT: there is a difference in VAT on projects for renovations (6%) and new construction (21%) which favours renovation
- Financial incentives: subsidies for renovation, passive house primes and fiscal deductions, several support mechanisms for (energy saving) measures like double glazing, insulation in walls, roofs, …
In any case, one should be careful using reference prices. An example is shown below. Several references have stated a cost price for ‘external insulation plus stucco on the façade’:

- **E-Retrofit Kit: External insulation + Plaster (2008)**: 79-134 €/m² wall
- **PHI (German passive house institute - 2005):** External insulation + Plaster: 73 €/m²
- **CERAA – Application of passive house measures on the Brussels’ building stock (2008)**
  - EcoFys (2005): ± 92 €/m² (of which 42 €/m² for insulation)
  - Bouwinfo (consumers’ internet forum) (2008): 90-125 €/m² for 12-14 cm EPS + plaster

This also means that when using reference prices in a LCC-study, the results are always an approximation, since the real price may in practice vary due to specific circumstances.

In general, it is believed that unit prices for retrofitting are higher than prices for new construction. This is due to the extra labour and efforts required because of stricter circumstances (fitting a window, adapting the insulation material to fit against the existing wall, …).

Another aspect to include in a cost calculation for retrofit projects is the so called hidden or extra costs. These are costs that need to be made at a certain moment in the project when (normally) unforeseen problems arise or additional measures need to be taken to implement the foreseen measures (eg. the cutting of all walls and floor slabs from the front façade to avoid thermal bridges). There is little literature available about these hidden costs. They are usually very project-specific, and it is difficult to express them in general terms.

**Energy Consumption Costs**

a) **Energy consumption**

Several software tools or methods exist to calculate the energy consumption due to heating, hot water use, electricity, … In the context of this project, the two most used tools are the (Flemish) EPB-software and the PHPP-software, designed to calculate energy consumption in passive houses.

When the EPB-software is used as a basis for calculations, it must be clearly stated that there are limitations and that assumptions are made (eg. climate conditions (monthly national average), efficiency of DHW and heating installations) which can lead to figures
that are only in the same order of magnitude as the real figures. This is especially true when using more innovative technologies.

b) Energy costs

Based on the (primary) energy consumption (from an EPB-calculation), energy costs can be calculated. Therefore, unit prices (per MJ or kWh or litre or m³) are needed. These figures can be obtained from different sources:

1 national statistic data (FOD Economie\(^1\)) or European statistics (Eurostat)
2 simulation tools from the energy regulators in the different regions (CWAPE, VREG, BRUGEL…)
3 based on historic data before the renovation and thus the real energy bills

The energy cost is usually a composition of different cost elements: a fixed cost for distribution, transmission, taxes, the cost for energy itself, others (profits etc.). Based on this composition, an average price in €/kWh can be calculated.

c) Evolution of energy prices

Past years have shown that predicting price evolutions on the energy market is very difficult. For example studies from 2005 are already outdated when it comes to scenarios for 2008 (Taal, 2003). Therefore, several price evolution scenarios should be foreseen from the beginning of the project analysis. Sensitivity analysis should be executed in order to test robustness of the results.

Basic scenarios can be obtained from national or international study work. The European study ‘European energy and transport – scenarios on key drivers’, EC, DG Energy and Transport, 2004 gives a general overview of energy cost trends and a forecasting of energy prices till 2030. This study has been updated in 2007 in order to take into account, amongst other elements, the high energy import price environment in recent years.\(^2\)

In 2004, the two scenarios put forward were a ‘basic scenario’ and an ‘elevated price scenario’.

<table>
<thead>
<tr>
<th>%/year (excl. inflation)</th>
<th>Basic scenario</th>
<th>Elevated price scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas</td>
<td>2.1</td>
<td>4.3</td>
</tr>
<tr>
<td>Electricity</td>
<td>2.1</td>
<td>4.3</td>
</tr>
<tr>
<td>Oil</td>
<td>1.9</td>
<td>3.2</td>
</tr>
<tr>
<td>Pellets</td>
<td>1.9</td>
<td>3.2</td>
</tr>
</tbody>
</table>

*Table 3- Evolutions in energy prices (Renard F. , 2008)*

For more recent data, reference is made to the study work of 3E, KUL and PHL for VEA, (3E,KULeuven, PHL, 2008):

\(^1\) [http://mineco.fgov.be/energy/home_nl.htm](http://mineco.fgov.be/energy/home_nl.htm)
\(^2\) [http://ec.europa.eu/dgs/energy_transport/figures/scenarios/index_en.htm](http://ec.europa.eu/dgs/energy_transport/figures/scenarios/index_en.htm)
“D. Devogelaer and D. Gusbin\textsuperscript{3} assume two scenarios for the evolution of the energy prices. The ‘average’ scenario puts forward an average linear increase of 3.47\% for natural gas (and also for electricity – due to the production with STEG-installations) and an increase of 1.48\% for oil (more limited increase due to already very high prices).

The ‘high’ scenario is used as an alternative. Due to increased economic growth of countries as China and India, a faster depletion of resources is expected, resulting in higher prices. The ‘high’ scenario puts forward a linear growth of 5.87\% for gas and electricity and 3.26\% for oil.” (3E,KULeuven, PHL, 2008)

Another approach is calculating the average increase of prices per year, based on historic data and trends of the last 5, 10, 20 or 30 years. For example, Infomazout.be gives an overview of energy prices 1997-2006 in c€/kWh.

![Figure 5 - Average fuel prices in Belgium between 1997 and 2006 (infomazout.be)](image)

Taking into account only the last 3 or 5 years (for instance) will result in much higher increases of prices than what the above mentioned EU study forecasts. For example, a Brussels study(CERAA, 2008) on application of PH measures in renovation, shows the following trends:

- the unit price for 1m³ of natural gas has risen 5\% per year in the past 15 years (kept as base value, no recalculation for inflation)
- the unit price for 1m³ of natural gas has risen 15\% per year in the past 3 years, or with abstraction of the general inflation: 13.28\%

This last approach is however not without risk of overestimation. For example the oil price in the summer of 2008 nearly reached the point of 1 €/l but at the end of 2008, the price was back to 0.5€/l (incl. taxes etc.). Thus, it is better to work with long-term evolutions for predictions and test the robustness of the results.

\textsuperscript{3} Federaal Plan Bureau – Long term energy and emissions’ projection for Belgium, with the PRIMES model, 2006
Maintenance and replacement costs

A LCC exercise can be ‘absolute’ or ‘relative’. In an absolute scenario all costs should be included to give a global financial picture of the project. Later on, the absolute costs can serve as guidance for planning of maintenance and replacement.

Relative analysis means that several projects or alternatives are being compared. In this case, costs that are estimated to be equal or at least very similar in all scenarios can be omitted from the evaluation. Maintenance of the structural works and finishing elements are usually alike in all scenarios.

For installations; however, larger differences between the scenarios can exist, especially when there is an installation in one case and none in the other. Usually, maintenance costs of installations are expressed as a certain percentage of the investment cost of an installation component.

Also replacement costs for strongly varying alternatives can be important (eg. triple glazed windows vs. double glazed windows) for elements that last shorter than the building service life or the period of analysis.

Several sources exist for data on service life time and maintenance costs. The most important source (for installations) is NBN EN 15459 - Energieprestatie van gebouwen - Economische beoordelingsprocedure voor energiesystemen in gebouwen (2008). Other sources are:

- producers information
- other normative documents (national : SIA, Önorm, ... international : CEN)
- handbooks for maintenance
- LCA data and LCA tools (Eco-Quantum, EcolInvent database)

End-of-life cost

The costs occurring at the end of the life of the (renovated) construction (disposal, demolition, ...) are mostly attributed to the successor of the building and not to the initial investor. Therefore these costs are not necessarily included in an evaluation.

However, renovation a building improves its value in two ways:

- Rest value of measures: insulation materials have not reached their service lifetime at the end of an investment time frame of 30 years. Therefore the concept
of ‘rest value’ is proposed. This rest value (e.g. a linear depreciation of the value of the insulation over its lifetime of 60-80 years) can be considered as an ‘income’ at the end of the analysis period, since these elements still have a value.

- When (thoroughly) renovating an outdated building to low energy or passive house standard, the property rises in value. This added value can be accounted for at the end of the analysis period, stating that the building has a higher sales price. In literature, two references to Lithuanian publications are found (Zvadskas, 2004)(Martinaitis, 2007). In general, it is clear that the value of the renovated house will never exceed the value of a comparable new house. The value of the house is also influenced by surrounding elements like location (city centre, ...), quality of the neighbourhood, ...

G. Verbeeck has investigated both approaches in her doctoral thesis: Linear depreciation results in a discounted total value from 2000 to 16000 € (in projects up to 200,000 €). The ‘surplus value’ of extremely low energy houses, estimated with a ‘home value estimation’ tool is calculated at 13,000 – 14,000 €, depending on the location. G. Verbeeck concludes that ‘in comparison with the total present value, both approaches produce residual values that are a factor 10 smaller than the total present value of the building envelope. The impact on the economic objective in the optimisation process will be limited. (…) Which approach will approximate most to the reality of the market of energy conserving buildings will strongly depend on the future evolution of the energy prices and of the energy policy, such as the way the energy certificate will be introduced.’(Verbeeck, 2007)

**Financial incentives**

From an investor’s or home owner’s point of view financial incentives (tax deductions, subsidies,...) can influence the decision on energy saving measures. R. Almstalden et al (Amstalden, 2007) conclude that for the current economic assessment of energy-efficient retrofitting, two relevant factors can be identified: “First, the expected energy price has a significant influence on the outcome of the investment analysis. Second, the inclusion of financial energy policy support in the investment is crucial.” Even in case the energy prices would stay low, thorough energetic retrofits would become profitable when using the full economic potential of financial incentives.

Of course, it must be remarked that financial incentives are rather volatile and that they evolve over the years (change in priorities, change in available budget, ...).

**Other cost aspects: whole life costs**

Besides the actual construction and operational costs other cost items can also be included in the analysis: financing, income, ... but also the recognition of the wider impact of decisions on the society. ‘Market prices for construction might not value the social, environmental or business costs or benefits of production and consumption.’(ISO, ISO 15686-5, 2008)

For some elements, a real cost can be identified (e.g. taxes due to impact on the environment), other costs can be ‘monetarized’. However, ISO 15686-5 advises not to monetarize non-economic costs/benefits.

A good example of this is the CO2 ‘cost’. In terms of sustainable development and climate change, a certain ‘cost’ or mitigation cost can be adhered to the energy
consumption of a building (in terms of €/tCO₂). ISO 15686-5 states clearly that this cost should only be included if it is actually to be paid.

Another aspect mentioned in literature is the so-called 'discomfort cost', due to installations not working or due to overheating.
2. ENVIRONMENTAL IMPACT OF ENERGY-EFFICIENT HOUSING RETROFIT

At first, the present chapter gives some general information on Life Cycle Analysis (LCA), a method that enables to quantify the environmental impact of product systems taking into account their entire life cycle, and that will be used to analyse the case study in part 2 of the present report. Then, a brief overview of the specificities of LCA on the building level is given. Finally, the chapter presents some results and conclusions from existing literature on the environmental impact of energetic housing renovation measures.

2.1 METHODOLOGICAL FRAMEWORK FOR LIFE CYCLE ASSESSMENT

LCA (Life Cycle Analysis) is an internationally recognized technique, used to evaluate the potential environmental impact (use of resources and possible consequences of releases) of a product system throughout its life cycle. It consists in a compilation of all the inputs (energy, resources, land use) and outputs (waste, emissions) that occur during each phase of a product system’s life cycle, from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle to grave), and a subsequent evaluation of the corresponding contribution to various environmental issues (e.g. climate change, ozone layer depletion,…) (ISO, ISO 14040, 2006) (ISO, ISO 14044, 2006)(CMHC, 2004).

The fundamentals of this methodology are laid down in following ISO standards:


According to ISO 14040 an LCA must be performed in 4 phases:

- Goal and scope definition;
- Inventory Analysis;
- Impact Assessment;
- Interpretation.

Figure 7 illustrates the relation between these phases and shows how they are interdependent and in direct relation with the intended use of the study. For each of these phases of the LCA, the requirements of ISO 14044 must be applied. Each stage is described into more detail in the next paragraphs.
2.1.1 Goal and scope definition

This first stage is very important for the LCA as it sets out the question to be answered by the study and provides the initial plan for conducting the life cycle inventory phase. It starts with the definition of the goal, that is determining the reason for carrying out the LCA, its intended use, to whom the results of the study are intended to be communicated, and whether the results are intended to be used in comparative assertions intended to be disclosed to the public\(^4\). (ISO, ISO 14044, 2006)

Once the goal is clearly defined, the next step consists in defining the extend (scope) of the study or with other words what will be included within the parameters of the study and what is not possible or desirable to include. The scope should be sufficiently well defined to ensure that the breadth, the depth and the detail of the study are compatible and sufficient to address the stated goal. (Spirinckx, 2007) (ISO, ISO 14044, 2006) Therefore, the following items should at least be considered and clearly defined in the scope definition. Note that these basic definitions have to be carried out carefully, as the results obtained will only be valid for them.

**Product system**

The product system models the life cycle of the product under consideration in the LCA study. It is composed of unit processes with elementary product flows, performing one or more defined functions.

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\(^4\) According to ISO 14040 a comparative assertion is “an environmental claim regarding the superiority or equivalence of one product versus a competing product that performs the same function”. ISO 14044 contains some specific requirements for that type of assertion, e.g. the comparison shall be conducted category indicator by category indicator and the evaluation shall include a critical review conducted by a panel of interested parties.
**Functional unit**
The functional unit quantitatively defines the required (temporal, geographical and technical) performance of the product under consideration. It is the unit for which input and output data are collected and which will serve as basis for comparison. Therefore it is important that it is applicable to different product alternatives and that it does not contain the product itself but rather the function that needs to be fulfilled. For example, the functional unit for an LCA study of linoleum could be to cover 2000m$^2$ office floor area over a period of 20 years in Belgium. (Putzeys K., 2008)

**System boundaries**
Ideally an LCA shall include the entire life cycle of the product system and all unit processes that are linked to it, but depending on the goal of the study it may not be necessary to do so, or in practice there may simply not be sufficient time, data or resources to conduct such a comprehensive study. Therefore, decisions have to be made (and clearly documented) regarding which life cycle stages and unit processes from the product system will be included within the LCA (eventually the reason of omission of certain stages of processes), which inputs and outputs shall be included and the level of detail of the LCA (cut-off criteria). They key here is achieving the best compromise between practicability of the study and validity of the results. (CMHC, 2004)

**Allocation procedures**
Allocation procedures are needed when dealing with multiple output processes (systems that generate more than one product). Indeed in such case, the inputs (raw materials and energy flows) to the system and the resulting environmental impacts need to be divided amongst the various product outputs. An example thereof is the production of steam and electricity in a power plant, the environmental impact of the power plant (ex. Infrastructure, fuel), needs to be divided amongst the 2 products (steam and electricity).

Also for recycled materials or by-products the allocation issue arises. In the case of recycling for example, the environmental benefits (avoided raw materials extraction) and burdens (collection of waste, energy use during the recycling process) need to be divided amongst the process that generates the waste (primary product system) and the process that will use the recycled fraction (secondary product).

For processes where allocation is necessary the allocation procedure should be clearly stated and justified and it shall be applied uniformly to all similar in- and output streams in the system. ISO 14040/44 gives following basic rules for allocation (ISO, ISO 14044, 2006)(Putzeys K., 2008):

1. The sum of the allocated in en outputs of a unit system must be equal to the sum of the in and outputs before allocation (so-called 100% rule).
2. Wherever possible allocation should be avoided by:
   - dividing the unit process that is shared by 2 or more systems in sub-processes and collecting the input and output data related to these sub-processes;
   - expanding the system boundaries so that the inputs/outputs remain inside the system;
   - reduce the system boundaries in order to exclude the process that raises the allocation issue.
3. In case allocation is unavoidable, in- and outputs of the shared unit system should be divided amongst the various product systems according to their physical-
chemical relationship (the allocation procedure reflects variations in in-and outputs that results from variations in products or functions of the product system).

4. If the allocation procedure cannot be based on physical relations, the in- and outputs of the shared unit system can be allocated amongst the resulting products according to other relations within the system (for example relative economical value, weight or volume of the resulting products).

**Data quality requirements**

The quality (precision, completeness, representativeness) of the data used has a significant impact on the results of an LCA. Therefore, it is necessary to establish requirements about the data quality and to extensively describe the consulted data sources.

**Others**

Other elements that shall be considered in defining the scope of an LCA:

- LCIA (life cycle impact assessment) methodology and choice of impact categories (see 2.1.3)
- interpretation to be used
- assumptions
- value choices and optional elements
- limitations
- type of critical review (if any)
- type and format of the report required for the study

### 2.1.2 Inventory analysis

The life cycle inventory analysis (LCI phase) is the second phase of a LCA. At first, it gives an overview of all processes that are included within the system boundaries (see goal and scope definition). Next, for each of these unit processes an inventory of input (energy, raw materials, land use,…) and output (waste, by-products, products, releases to soil, water, air) data is made and related to the defined functional unit of the product system that is to be modelled. In case some unit processes are shared with other product systems than the one under study, the in- and output data shall be divided amongst the various systems according to the pre-determined allocation procedures. (ISO, ISO 14044, 2006)(Putzeys K., 2008)(Desmyter, 2001)

The quality of the LCI data and results should be sufficient to conduct the life cycle impact analysis (third phase of the LCA) in accordance with the goal and scope definition of the study. (ISO, ISO 14044, 2006)

### 2.1.3 Impact assessment

The third phase of an LCA is the life cycle impact analysis (LCIA). It is destined to provide additional information to help assess a product system’s LCI results so as to better understand their environmental significance (ISO, ISO 14044, 2006). It provides information for the life cycle interpretation phase and consists of following elements:

*Selection of impact categories and category indicators*
LCIA is not a complete assessment of all environmental issues of the product system under study. It will only address the environmental issues that are specified in the goal and scope of the study. Impact categories are environmental issues that are of concern to the society and to which LCI results may be assigned. To each impact category corresponds a category indicator, a unit used to quantify the potential impact. (ISO, ISO 14040, 2006)(ISO, ISO 14044, 2006)

One very well known impact category is for example climate change. All emissions that contribute to climate change (all greenhouse gases) can be assigned to that impact category, as for example CO\textsubscript{2}, CH\textsubscript{4}, CFK, O\textsubscript{3}, N\textsubscript{2}O. A commonly used impact indicator for that category is kg of CO\textsubscript{2}.

The ISO 14044 does not prescribe any impact categories but gives some general recommendations for the selection of impact categories. A problem with some of the existing impact categories (for example land use and human toxicity) is that the methodology used to model the impact is still in development. However, some categories and corresponding category indicators are already generally recognized and used in most LCA studies: global warming in CO\textsubscript{2} equivalent, ozone depletion in kg CFC11-equivalent, acidification potential in SO\textsubscript{2}-equivalent, nitrification potential in PO\textsubscript{4}-equivalent, photochemical ozone creation potential. Given the significant consumption of resources in the construction sector, impact categories related to the depletion of non-renewable resources are also particularly relevant for building (materials) related LCA studies. (Desmyter, 2001)

Classification

Within the classification phase, the LCI data are grouped according to the chosen impact categories. Some substances can be part of more than one categories. For example, CFC’s contribute to climate change and ozone depletion, so these substances will be classified in both impact categories. (Desmyter, 2001)(Olivier, 2006)

Characterization

Characterization is the actual translation of LCI data into potential impacts through the calculation of category indicator results. Within each impact category, the relation between the LCI data classified within that category and the resulting change in the corresponding category indicator is determined by a characterization model and corresponding characterization factors. For example, a commonly used impact category is climate change. The category indicator result here is expressed in CO\textsubscript{2} equivalent. Therefore, to quantify the potential contribution of the system under study to climate change, all the inventoried greenhouse gases need to be translated into CO\textsubscript{2} equivalents. The commonly used characterization factor to do so is the global warming potential (GWP\textsubscript{100})\textsuperscript{5} calculated with the Baseline model of 100 years of the Intergovernmental Panel on Climate Change (characterization model): for example CH\textsubscript{4} has a GWP\textsubscript{100} of 25, so 1kg of CH\textsubscript{4} is equivalent to 25kg of CO\textsubscript{2}.

\textsuperscript{5} Global warming potential (GWP) is a measure of how much a given mass of greenhouse gas is estimated to contribute to global warming, in comparison to an equal mass of CO\textsubscript{2}. It is calculated over a specific time interval as it not only takes into account the ability of a substance to absorb infrared radiation but also its atmospheric lifetime. For example, GWP\textsubscript{100} is the global warming potential calculated over a 100 year horizon.
The environmental profile of a system gives an overview of the category indicator results for all the considered impact categories.

**Optional elements**
In addition to the 3 steps described above, the LCIA can also include following optional steps (ISO, ISO 14044, 2006):

- Normalization
- Grouping
- Weighting

Normalization is the calculation of the magnitude of the individual category indicator results relative to reference information (for example, relative to the impact caused by an average European during a year). The aim of this step is to gain a better understanding of the relative size of an effect (for example, the impact category that contributes the most to the European impact can be seen as more critical).

Grouping is the assignment of impact categories into one or more groups as predefined in the goal and scope definition. Impact categories can be sorted on a nominal basis (e.g. global, regional, local scale) or ranked in a given hierarchy (e.g. high, medium, low priority). Ranking always implies some value-choices, so depending on the organization that performs the grouping different ranking results can be achieved based on the same indicator results. (ISO, ISO 14044, 2006)

Weighting is the process of multiplying the category indicator results by a numerical factor (weighing factor) based on value choices. Eventually, the converted results can then be aggregated to one single score. This can be very useful for decision making. Indeed, in case the goal of an LCA is to compare various alternative product designs, it is very unlikely that the LCA results will be straightforward in favour of one alternative (e.g. alternative A may contribute less to climate change, but more to acidification than alternative B).

Weighting and aggregation makes it easier to interpret the results; however it irremediably implies some value choices and loss of information. Therefore, ISO 14044 recommends not to use weighting and aggregation in LCA studies intended to be used in comparative assertions intended to be disclosed to the public. In any case the weighing and aggregation step have to be done in a transparent way and data and indicator results reached prior to weighting should be made available together with the weighting results. Also in an LCA, it may be desirable to conduct a sensitivity analysis to assess the consequences of the different weighting factors (value-choices) on the LCIA results. (Desmyter, 2001)(ISO, ISO 14044, 2006)

### 2.1.4 Sensitivity analysis
Finally a sensitivity analysis can be performed in the impact assessment phase to estimate the effect of choices made regarding methods and data on the outcome of the study
2.1.5 Interpretation

The last step of an LCA is the interpretation. Results obtained from previous phases are analyzed, conclusions are drawn, limitations of the LCA are described and recommendations are formulated.

2.2 The Specificity of LCA on the Building Level

The ISO standards give general rules for LCAs but still leave some space for interpretation. Indeed all LCAs have a common basis but still differ in some ways depending on their purpose or the system under study.

The life cycle of a building can be broken down in following phases and related processes (depending on the goal and scope definition some phases or processes can be left out):

1. **Production**: manufacturing of construction materials (incl. raw materials extraction, internal transport, manufacturing processes)
2. **Construction**: transport of materials to the construction site, construction process
3. **Use**: maintenance (incl. necessary replacement of building components), energy use, water use, and eventually other building related processes (e.g. transport of occupants, domestic waste,..)
4. **Demolition**: demolition of the building
5. **End-of-life**: evacuation and treatment of demolition waste

Some issues specific to LCA’s on the building level are (CMHC, 2004)(Kotaji, 2003):

- Buildings have a much longer, but more difficult to predict life span than consumption goods. This causes a lot of uncertainties, especially for the evaluation of the use and end-of-life phases (e.g. energy production, end-of-life processes,... are very likely to evolve over the lifespan of the building, but these evolutions are very difficult to predict. Therefore data will generally be based on actual practice).
- The impact of the use phase is not only very dependant on the assumed service life of the building, but also on the occupant's behaviour. As the latest is very difficult to predict, average values or scenarios usually have to be used.
- Buildings and building components vary greatly in their composition and function.
- The building’s performance is influenced by it’s surroundings (climate, orientation, proximity of infrastructures (e.g. waste treatment facilities, transportation infrastructure,...)).
- Part of the environmental impacts generated by the building are locally specific: e.g. neighbourhood impacts (e.g. micro-climate, glare, wind patterns,...), indoor environment (e.g. indoor air quality, thermal comfort,...), impact on local ecology (e.g. connected green spaces) and urban infrastructure (e.g. carrying capacity of transportation system, water supply). Local impacts can not be measured with traditional LCA methods and are therefore usually not considered.
A common allocation issue and discussion point for LCA on the building level is the allocation for recycling. After demolition of the building (and as materials are replaced during the use phase), some materials will be sent to recycling. Now, as mentioned before, the impact from recycling needs to be allocated between the building that generates the waste to be recycled and the next building that will use recycled materials.

2.3 RESULTS AND CONCLUSIONS FROM EXISTING STUDIES ON THE ENVIRONMENTAL IMPACT OF ENERGY-EFFICIENT HOUSING RETROFIT

Only limited results are available on the environmental impact of energetic renovation measures.

Dutch research (Itard L., Milieueffecten van renovatieactiviteiten, 2007) discusses some methodological aspects of environmental impact assessment of renovation measures. The service lifetime of a building can be a very decisive parameter in the (environmental) impact of renovation measures, whereas the building lifetime can vary between 40 to 100 years or more. Therefore, it is important to evaluate the environmental impact in function of the service life considered, instead of showing it as an absolute value. The research group OTB of TUDelft has therefore developed the concept of ‘environmental pay-back time’ as the number of years needed to compensate the environmental burden resulting from an energy retrofit measure by the resulting savings in environmental impact from energy use.

Several retrofit measures have been investigated in that study:

- Insulation of facade, roof, and floors to U =0.44 W/m²k (with mineral wool insulation)
- Replacement of windows (single & double glazed) by HR++-glazing
- Replacement of VR-boiler by:
  o HR-combi-boiler & HT radiators
  o HR-combi-boiler & LT radiators
  o Heat pump combi with LT radiators (COP=2 for DHW)

The results (environmental pay-back time) are shown in the table below, for each of the considered environmental effects.

Table 4- Environmental Pay-back time and % of savings over 30 y (insulation) and 15 y (installations) for the measures investigated (Itard L., Milieueffecten van renovatieactiviteiten, 2007)
Insulation measures:

- Facade insulation has a payback time for all indicators lower than 7 years
- Roof insulation scores even better with a maximum payback time of 3 years
- Floor insulation is not performing as well. Indeed, because of its lower energy savings potential it results in negative effects for some indicators.
- The results are more or less independent of the insulation material considered in the study
- Replacement of glazing has positive effects on the environment

Installations:

- For most impact categories, replacing an installation is less efficient than insulating. However, considering all effects together, using LT radiators, results in a positive end result. The most positive effects are on energy savings or greenhouse gas effects.

Heat pump:

- The installation of a heat pump has a negative impact on all categories, despite the rather good energy savings. This is due to the switch to electricity as energy source. Indeed, there are still considerable progressions in terms of fuel mix for electricity consumption and efficiency of the heat pump system.

In another paper, L. Itard (Itard L., Passieve huizen: hoe milieuvriendelijk zijn energiebesparende maatregelen?, 2008) discusses also the embodied energy of retrofit measures. This is estimated to be very low: after 30 years the embodied energy of retrofit measures is a small percentage of the total energy consumption (< 6%). The payback time is very good. The author estimates that the same conclusion is valid for passive house measures.

She investigated 6 renovation alternatives:

1. Insulation of facade (to U=0.35 W/m²K) roof (U = 0.31) and floor (U = 0.34)
2. Replacement of double glazing by HR++ glazing (U = 1.7 W/m²K)
3. Replacement of boiler by HR107-boiler
4. Replacement of boiler by HR107-boiler & heat pump for DHW
5. Replacement of boiler by HR107-combi boiler and 2.7 m² solar boiler
6. Installation of system D with heat recuperation

The positive effects are lower than what would be expected from energy savings alone. The insulation variants (1 & 2) clearly have a better score than the others. Variants 4 & 6 cause a deterioration for 6 out of 10 of the environmental effects, mainly due to the increase of electricity use.
3. RENOVATION OR DEMOLITION AND RECONSTRUCTION

An argument often raised when discussing energetic renovation is that it is more interesting to demolish the building and build a new one in its place. In literature some research conclusions exist on the economical and environmental benefits of retrofitting, compared to replacement (demolition+construction) or doing nothing at all.

3.1 METHODOLOGICAL ISSUES
Before drawing conclusions, some methodological considerations must be made:

- What will be compared?
  - The aspects of service life were already mentioned. G. Klunder (Klunder, Search for the most eco-efficient strategy for sustainable housing transformation) proposed to use the ‘average yearly environmental impact’ to compensate for the different service life of certain measures. The payback time can be calculated by comparing the environmental impact generated to the one saved (by saving energy).
  - Comparison with the old building is not useful. The decision ‘refurbish or replace’ will only take place when a refurbishment is necessary anyway. On the other end of the spectrum, a comparison can be made against a ‘standard’ new house, or a low energy (or even) passive house.
  - Attention is brought to the fact that comparing to a new building, the functional unit will be different (Trusty, 2004), due to different lay-out, different functions and performance, ...
  - One can assess the ‘likely affects associated with demolition, material production and new construction’ (benchmark approach) or assess the estimated avoided impact by saving & rehabilitating the building (and compare this to the extra cost needed for it) (avoided impacts approach).

- Using energy consumption savings (or GHG) as only indicator for environmental benefits is not correct. There are other aspects to consider as well in an environmental analysis (Trusty, 2004).
- When assessing benefits, one must keep in mind that a part of the savings (up to 30%) would be absorbed as comfort improvement by the residents due to the rebound effect.
- Other research (Delguhst, 2009) also points out that using a generic energy consumption calculation tool as basis for ‘existing energy consumption’ could provide a false idea of possible gains. The real energy consumption in poorly insulated houses will be lower, due to adapted user behaviour (lower indoor temperature, less heating of parts of the building, ...)

3.2 CONCLUSIONS FROM RESEARCH
The replacement or refurbishment decision is usually made on primary decision criteria: technical constraints (and costs linked to it), tenant views and opinions (comfort and health issues) rather than considering possibilities for energy savings etc (Palmer, 2003). Moreover, usually a good energetic performance of the building can be technically achieved in a renovation project as well. Other important decision aspects are market factors and legislation.
‘Energy efficiency refurbishment is an order of magnitude cheaper than replacing a building (1/10 of the costs of rebuilding in terms of energy savings/pound) with a same energetic performance’ (Palmer, 2003). The conclusion that refurbishment is beneficial to new construction is supported by other research (Itard L., 2007) (De Jonghe).

Additional energy savings in retrofit require a higher marginal cost. Therefore, focus should be on the low-cost improvements of the inefficient dwellings (Palmer, 2003).

The only example where new construction proved to be the better option, was where the old building was hard to adapt, and the possibility for energy performance improvement was limited from an energy demand of 524 kWh/m²y (old) to 300 kWh/m²y (refurbished), whereas the new building would have a energy requirement of 85 kWh/m²y (Ronning, 2009).

This shows that the old building should allow for a decent transformation. This vision is supported by Dutch research (Klunder, Milieueffecten van woningtransformatie gekwantificeerd, 2004), showing the benefits on costs and environment when doing a decent refurbishment instead of replacement.

Within the SOLANOVA-project, A. Hermelink (Hermelink A., 2006) redefined the concept of ‘sustainable development’ and based on other research (ao. Zimmerman 2005) defines what is ‘green enough’, limits for residential energy consumption (new houses):

<table>
<thead>
<tr>
<th>Energetic purpose</th>
<th>Final energy Switzerland 1990 (kWh/m²a)</th>
<th>Final energy Sustainable level (kWh/m²a)</th>
<th>Primary energy Sustainable level (kWh/m²a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat (Space heat &amp; DHW)</td>
<td>175</td>
<td>26</td>
<td>40</td>
</tr>
<tr>
<td>Household Electricity</td>
<td>38</td>
<td>15</td>
<td>56</td>
</tr>
<tr>
<td>Embodied energy</td>
<td>27</td>
<td>23</td>
<td>43</td>
</tr>
<tr>
<td>TOTAL</td>
<td>240</td>
<td>64</td>
<td>139</td>
</tr>
</tbody>
</table>

*Table 5 - Key figures on Sustainable Limits for Residential Energy Consumption (Hermelink A., 2006)*

This raised the question what, from a strictly environmental point of view, would be the better option for an exemplary case study, SOLANOVA:

- RETROFIT: to do a retrofit, matching the total sustainable limit in the table above, or
- REBUILD: to tear down the old building and build a new one (Passive House Standard)

Renovation will imply a lower amount of embodied energy, allowing a larger share for energy consumption for heating & DHW. Several scenarios and assumptions on energy consumption (for retrofit & rebuild – embodied energy, energy consumption) were calculated, resulting in the conclusion that ‘taking sustainability seriously, a space heat consumption between 25 and 40 kWh/m²a should be aimed at in retrofit. This is drastically lower than what is usually connected with green buildings of any shade, especially in retrofit. Only if this level is not feasible, rebuilding or using a greater share of
renewable energy on the supply side, should seriously be considered; as in the end, the
decisive number is the primary energy consumption.'

These figures led to the measures taken in the SOLANOVA project, where passive
house philosophy and solar thermal support for DHW were combined. One year after
finishing the renovation works, the space heat consumption remained below 40
kWh/m²a.

On a broader scale, Anne Power conducted research on the policy of structurally
demolishing old buildings and replacing them by new high performance buildings, or
refurbishing existing stock (Power, 2008) based on existing other research and example
projects. “A broad range of benefits (social, economic and environmental) of
refurbishment compared with demolition were identified: a reduction in the transport
costs, reduced landfill disposal, greater reuse of materials, reuse of infill sites and
existing infrastructure, reduced new building on flood plains, local economic
development, retention of community infrastructure, neighbourhood renewal and
management. “(Power, 2008)

“These benefits were weighed against the full costs of demolition and rebuilding,
involving much higher capital costs, higher material wastage, greater embodied carbon
inputs, the polluting impact of particulates, greater use of lorry transport for materials and
waste, greater use of aggregates, more noise and disruption. On the social issues of
housing need and fuel poverty, it is argued that refurbishment and infill building are
socially more acceptable, cheaper and create far lower environmental impact, while
reducing fuel poverty.” (Power, 2008)

“Many arguments remain unclear, but the overall balance of evidence suggests that
refurbishment most often makes sense on the basis of time, cost, community impact,
prevention of sprawl, reuse of existing infrastructure and protection of existing
communities. It can also lead to reduced energy use in buildings in both the short and
long term. Many factors will influence what happens in practice, but it seems unlikely
under any scenario that the rate of demolition will accelerate far above current levels.
Upgrading the existing stock is likely to gain in significance for environmental, social and
economic reasons. Adopting policies that aid the retention and upgrading of the existing
stock will help develop the necessary skills and technologies, save materials and land,
and enhance the integration of existing communities in need of regeneration.” (Power,
2008)
4. CONCLUSIONS FROM THE LITERATURE REVIEW

It became clear from the review that a wide variety of methodological approaches exist when it comes to determining cost efficiency and environmental impacts of energetic retrofits of buildings. On the one hand, boundary conditions can be chosen to a certain degree (what is in- and excluded from the evaluation, which are the decision criteria, ...), on the other hand, data for evaluation is not always available, variable or is uncertain, especially when it comes to future forecasts.

Despite these varying methodological choices, some common conclusions can be drawn from the consulted studies.

- Energetic renovation insulation measures are usually cost efficient. Applied measures result in a cost savings in a rather short period (small pay-back time, good return on investment, annual savings).

- The cost efficiency rises when ‘general renovation cost’ is not considered, eg. when renovation of the finishing layer had to be done anyway, or when windows or boilers should be replaced at the end of their service life. This logic makes investing in very efficient windows and heating systems also cost efficient.

- The optimal cost curve for individual insulation measures runs rather flat, which means that many solutions nearby the optimum have a similar cost efficiency, also going further than the optimum. The optimum U-value lies in many cases further than the legislative minimum requirement.

- The cost efficiency becomes better when no insulation or other well performing component was present before. This means when a large difference between the old and the new situation can be realised. This implies that when doing a retrofit, one should go as far as possible, since eg. adding insulation after 10 years will not result in the same efficiency.

- Depending on the methodology, data used and boundary conditions (costs included/excluded, eg. tax deductions; energy price scenarios) the optimum solution in terms of cost efficiency in projects or case studies is a ‘Low Energy’ renovation or even a Passive house renovation.

- From an environmental point of view, renovation measures have a positive impact due to lower energy consumption. However, this is not valid for all environmental impacts considered. The electricity consumption plays an important role in this.

- Renovation is considered to be more efficient (for environment & from costs point of view) than demolition and reconstruction, on the condition that a thorough retrofit is technically possible (a good energy savings should be achievable).
PART 2
CASE STUDY: RENOVATION OF AN OUTDATED SINGLE-FAMILY ROW-HOUSE TO PASSIVE HOUSE STANDARD: LCC AND LCA OF DIFFERENT RENOVATION SCENARIOS

1. INTRODUCTION
The goal of the case study is to investigate the environmental impact and cost of different renovation scenarios. Indeed, usually in a renovation project the higher the ambition to reduce the future energy consumption, the more renovation materials are needed (with corresponding costs and environmental impact). So, it can be questioned to which extend this ‘extra investment’ is compensated on the long run by the resulting savings in costs and environmental impact from energy use.

To gain a better inside into that question, a comparative analysis is done of different energy-saving scenarios for an existing renovation project.. These alternatives, with varying heat demand levels and installations for heating and warm water production (see section 2) are compared using LCA and LCC, thus based on quantified environmental impact and life cycle cost.

Both the environmental impact and the life cycle cost are discussed individually. Afterwards a combination of both is made to investigate whether a ‘best value’-option could be identified, taking into account economical and ecological considerations.

2. SCENARIOS FOR RENOVATION
The starting point of the study is an existing renovation project that consists in the thorough renovation of a single-family row-house in Eupen. The original part of the building (dating from the 19th century) was conserved, but various annexes that were built in the course of time were demolished and replaced by one big extension, almost fully glazed towards the south. The roof was replaced and raised in order to create additional living space in the attic, and the whole interior space was renovated (new kitchen, bathroom,...). Finally, the whole building was insulated to the passive house standard (with special attention to air-tightness and thermal bridges), a mechanical ventilation system with heat recovery was installed, and the existing furnace was replaced by a pellet furnace and a solar system for hot water. Consequently, the building was not only completely renovated, with a substantial increase in living surface, but the energy performance of the building was also drastically improved (the original heat demand was reduced by 95%).
Figure 8 – Design and pictures (before renovation on the left and after on the right) of the studied case in Eupen
Based on the existing renovation plans, 10 alternative renovation scenario’s were defined with varying levels of heat demand in a first time and varying equipments (energy carriers) for heating and warm water production in a second time. All elements that are not part of the building shell, e.g. kitchen, bathroom, interior walls, storey floors,… were supposed to remain the same amongst the defined alternatives and were therefore not considered for the LCC and LCA study. In other words, only the elements composing the building shell (ground floor, windows, common walls, outer doors, exterior walls), the equipments and energy use for ventilation, warm water production and heating, were considered for this study.

The energy demand was calculated with the Flemish EPB software. Several assumptions had to be made in the EPB calculation process:

- Some installations are difficult to implement correctly in the EPB-software.
  - The ‘ground-air heat exchanger’ (pre-heating or pre-cooling) is not included in the calculation.
  - The production of DHW is considered to be independent of the production of heat.
  - The pellet stove is possibly more efficient than the ‘wood stove’ that is used in the EPB-calculation, but no document showing equivalence exists.

- External shading and solar protection has been added to minimise the overheating risks. This external solar protection will in reality be provided by natural vegetation and solar panels.

- Thermal bridges are not calculated. For the PH-case this is no problem, since the thermal bridges were minimised. Also in the other alternatives, thermal bridges were minimised (especially for the new extension to the building).

It is clear that the EPB-calculation only gives an indication of real consumption, which will also be dependent on user behaviour and real climatic circumstances.

### 2.1 Alternatives with Varying Heat Demand Levels — Fixed Energy Carrier

Four renovation scenarios were defined with varying heat demand levels but a fixed energy source (gas) for heating and warm water production (see Table 6). The first level represents a standard renovation where only the finishing elements, outer windows and doors are replaced in the existing part of the building, while the new part is insulated in accordance to the current insulation standards (Flemish regulations (anno 2008) on the energy performance of buildings (e.g. $U_{\text{walls}}<0.6 \ W/m^2K$, $U_{\text{roof}}<0.4 \ W/m^2K$)). In the following alternatives the insulation level of the existing and new part increases gradually towards the passive house standard.

As we tried to compare realistic configurations, not only the insulation level but also the nature of the materials and the type of equipments vary amongst the alternatives. For example, in the standard (SR) and low energy (LE) renovation the main insulation material is mineral wool and the bearing structure for the extension is made out of bricks, while in the very low energy (VLE) and passive house (PH) renovation the main insulation material is cellulose and a timber structure is used for the extension (cfr. the
real case scenario). However, whenever possible similar finishing elements were used for all alternatives (e.g. roof, floor and façade coverings, nature of window frames). An overview of the main considered building elements and their corresponding composition in function of the considered heat demand level is given in annex.

In all 4 alternatives, a condensing gas boiler is used for heating and warm water production, but the size of the boiler and the heat delivery system varies according to the heat demand level. For example, in the standard renovation the condensing boiler is only placed after 10 years, as the existing boiler was still usable. On the other hand, as the capacity of the existing boiler was estimated to be too high and its efficiency too low for the lower heat demand levels, in those cases the existing boiler was directly replaced by a smaller boiler and a storage tank for warm water. Also, the ventilation system becomes more complex as more care is given to the insulation and air tightness of the building:

- SR alternative: natural ventilation (system A)
- LE: natural supply, demand controlled mechanical extraction (variant of system C)
- VLE and PH: system D (mechanical supply and extraction) with heat recovery unit.

Finally, as the VLE and PH alternatives have less thermal capacity (wood skeleton instead of brick) but a very high insulation level, they were also provided with a ground heat exchanger (40m PE tube, embedded in the garden, through which the incoming air passes prior to entering the ventilation unit) to improve thermal comfort in summer.

<table>
<thead>
<tr>
<th></th>
<th>SR-Gas</th>
<th>LE-Gas</th>
<th>VLE-Gas</th>
<th>PH-Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>K-peil</td>
<td>64</td>
<td>33</td>
<td>28</td>
<td>17</td>
</tr>
<tr>
<td>E-peil</td>
<td>118 -105*</td>
<td>59</td>
<td>51</td>
<td>45</td>
</tr>
<tr>
<td>Ventilation system</td>
<td>A</td>
<td>C with demand controlled extraction</td>
<td>D with heat recovery</td>
<td>D with heat recovery</td>
</tr>
<tr>
<td>Condensing gasboiler</td>
<td>12-37kW</td>
<td>4.9-13kW</td>
<td>4.9-13kW</td>
<td>4.9-13kW</td>
</tr>
<tr>
<td>Warm water reservoir</td>
<td>none</td>
<td>150 l</td>
<td>150 l</td>
<td>150 l</td>
</tr>
<tr>
<td>Heat delivery</td>
<td>radiators</td>
<td>radiators</td>
<td>radiators</td>
<td>3 warm water batteries on the ventilation</td>
</tr>
<tr>
<td>Bruto energy demand</td>
<td>132943-111400*</td>
<td>43550</td>
<td>19435</td>
<td>6684</td>
</tr>
<tr>
<td>Heating (MJ/year)</td>
<td>28968</td>
<td>32186</td>
<td>32186</td>
<td>32186</td>
</tr>
<tr>
<td>Warm water (MJ/year)</td>
<td>1332</td>
<td>911</td>
<td>3791</td>
<td>3661</td>
</tr>
<tr>
<td>Electricity (MJ/year)**</td>
<td>1332</td>
<td>911</td>
<td>3791</td>
<td>3661</td>
</tr>
</tbody>
</table>

* The energy demand for heating decreases when the existing boiler is replaced by a new, more efficient boiler (after 10 years)
**operation of the ventilation system and the gas boiler

Note: The small differences in E-peil are mainly due to the increased cooling load (0 – 3303 – 9167 – 13294 MJ/a for SR – LE – VLE – PH)

**Table 6 - Main characteristics of the alternatives with varying heat demand levels and gas as energy source for heating and warm water production: standard (SR), low energy (LE), very low energy (VLE), and renovation to passive house standard (PH)**
2.2 ALTERNATIVES WITH VARYING ENERGY CARRIERS FOR HEATING AND HOT WATER

Based on the PH-Gas alternative defined above, four additional PH alternatives were defined with varying installations (heat carriers) for heating and hot water production. In the first alternative (PH-Elect) the condensing gas boiler and warm water batteries on the ventilation are replaced by an electric boiler and electrical heating batteries on the ventilation. The following three alternatives have a solar system for hot water (8m² flat plat collector with South orientation) but use alternatively electricity (PH-ElectSun=PH-Elect + solar system for hot water), a condensing gas boiler (PH-GasSun = PH-Gas + solar system for hot water) or a pellet furnace (PH-PelletSun=PH-GasSun but the condensing gas boiler is replaced by a pellet furnace) for space heating and as backup system for the production of warm water.

Finally, a solar system for hot water was placed in the LE-Gas and VLE-Gas alternatives defined above, resulting in two additional alternatives: LE-GasSun and VLE-GasSun. The energy performance of all these alternatives is given in Table 7.

<table>
<thead>
<tr>
<th></th>
<th>PH GasSun</th>
<th>PH PelletSun</th>
<th>PH Elekt</th>
<th>PH ElektSun</th>
<th>LE GasSun</th>
<th>VLE GasSun</th>
</tr>
</thead>
<tbody>
<tr>
<td>K-peil</td>
<td>17</td>
<td>17</td>
<td>17</td>
<td>17</td>
<td>33</td>
<td>28</td>
</tr>
<tr>
<td>E-peil</td>
<td>31</td>
<td>32</td>
<td>65</td>
<td>43</td>
<td>45</td>
<td>37</td>
</tr>
<tr>
<td>Bruto energy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>demand for</td>
<td>6684</td>
<td>7249</td>
<td>6067</td>
<td>6067</td>
<td>43550</td>
<td>19435</td>
</tr>
<tr>
<td>heating (MJ/year)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>DHW</td>
<td>13529</td>
<td>13529</td>
<td>20691</td>
<td>8698</td>
<td>13529</td>
<td>13529</td>
</tr>
<tr>
<td>Electricity*</td>
<td>4166</td>
<td>4222</td>
<td>3595</td>
<td>4099</td>
<td>1413</td>
<td>4294</td>
</tr>
<tr>
<td>(MJ/year)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* operation of the furnace, ventilation system, solar system for hot water

Table 7 Main characteristics of the alternatives with varying installations

3. LIFE CYCLE ANALYSIS: METHODOLOGICAL ASPECTS

The next sections present the goal and scope of the conducted LCA and some methodological choices that were made for this specific study. For more general information on LCA methodology we refer to Part 1, sections 2.1 and 2.2 of the present report.

3.1 GOAL DEFINITION

3.1.1 Reason for the LCA and intended application

The aim of the LCA study is to evaluate and compare the environmental impact related to various energetic renovation scenarios for a given row house in Eupen (see section 2 Scenarios for renovation). The comparison is intended to analyze in which way the predefined sets of measures taken to reduce the heat demand of the building across the alternatives, and the choice of installations for heating and production of warm water influence the environmental impact of the renovated building over its life cycle, and consequently identify the most interesting alternatives from an environmental point of view. Furthermore, the LCA results are intended to be compared with the life cycle costing results in order to indentify which of the defined alternatives are optimal from an environmental and financial point of view.
3.1.2 Communication audience
The results are intended to the commissioner of the LEHR project in the first place, but are also intended to be disclosed to the public through the LEHR website, conferences, publications...

3.1.3 Comparative assertion
The LCIA results are intended to be used in a comparative assertion (comparison of various renovation alternatives) intended to be disclosed to the public. However, the study deviates from the ISO 14044 requirements for comparative assertion intended to be disclosed to the public in two ways:

- the study does not include a critical review process conducted by a panel of interested parties
- in the end the results are weighted and aggregated to a single score

Aggregation of the various indicators to a single score was necessary to achieve the goal of the LCA study, that is to identify the best renovation alternatives (sets of renovation measures) from an environmental point of view and to produce results that are combinable with the results from the LCC study. In any case, the weighting and aggregation method is done in a transparent way and indicator results reached prior to weighting are made available together with the weighted (single score) results. Moreover, a sensitivity analysis was conducted in order to assess the influence of the weighting factors and the choice of the evaluation and aggregation method on the results.

3.2 Scope definition
3.2.1 Functional unit
One of the primary purposes of the functional unit is to provide a reference for the collection of input and output data and so to serve as a basis for comparison. In the present case the functional unit is the renovation of a given row house in Eupen according to the plans designed by the owner (given layout, window surface), as described in section 2 Scenarios for renovation, and for an intended service life of 80 years (= reference study period ). Since the study intends to compare different levels of energetic performance, that aspect (as well as aspects directly related to the energy performance of buildings, e.g. thermal comfort) is not part of the functional unit.

3.2.2 System boundaries
For each building renovation alternative under study, following phases and related unit processes are considered:

- Production and construction phase of materials and equipments that are installed as part of the renovation project:
  - extraction of raw materials
  - transport from extraction to the production site
  - production process
  - transport from the production (or extraction) to the construction site
- Use phase:
  - replacements: end-of life treatment (incl. transport to the treatment location) of materials/equipments that need to be replaced during the reference study period and production phase of the new units
  - energy use

In other words, the environmental impact of the renovated building is an aggregation of life cycle impacts (production, transport, demolition, EOL) of materials and equipments and of environmental impacts related to energy consumption.

As the aim of the project is to compare the environmental performance of different levels of energetic renovation, only the materials, equipments and energy consumptions that vary amongst the various alternatives are taken into consideration, that is:

- Materials from elements composing the building shell (exterior walls and common walls with the neighbour, roofs, ground floor, exterior glazing and doors), that were not present prior to renovation
- Installations for the production of warm water, heating, ventilation
- Energy use for the production of warm water, heating, ventilation

3.2.3 Reference study period
A service life of 80 years for the renovated building was assumed. This assumption is based on the recommendations of a study from BBRI (Development of a normalized evaluation method for the environmental impact of buildings), which included an extensive review of literature and existing LCA tools for buildings. This value was initially determined for new buildings, but as the renovation is very thorough and includes a considerable extension of the building (new construction), it was assumed to be also applicable to the present study.

Anyway, as 80 years is only an assumed lifetime, a sensitivity analysis was conducted to better understand the impact of this assumption.

3.2.4 Allocation procedure for recycling of building materials
The impact from recycling is threefold:

- Avoidance of waste treatment (landfill, incineration)
- Impact from the recycling process itself
- Benefit of reduced raw material extraction.

Allocation methods for recycling vary from cut-off at the recycling processes (the impact from the recycling process is fully allocated to the next system) to a full subtraction of avoided impacts (expansion of system boundaries), with many variations in between.

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6 The avoided impact approach consists in allocating the benefit of future recycling to the building under study, by subtracting the assumed avoided impact (reduced raw material extraction). For example, if it is assumed that from the 2 t of the aluminium used in a building 1.5 t will be recycled after demolition, the impact from the production of 1.5t of primary aluminum will be subtracted from the assessed building in order to account for the fact that in the future the aluminium scrap resulting from the building will reduce the need for primary aluminium by 1.5t.
(burdens and benefits from recycling are partly allocated to the system that generates the waste and partly to the system that uses the recycled fraction).

Within the LEHR project, the system boundary cuts off the recycling process itself. In other words the impact up to and including the sorting plant is allocated to the materials (building) that generates the waste, while the transport to the recycling facility and the recycling process itself are allocated to the next system (the one that uses the waste as primary resource). Consequently, for waste that goes directly from the demolition site to the recycling facility (e.g. inert waste that goes directly to the crushing facility), only the burden from demolition is allocated to the first system.

This approach implies that the benefits of recycling are partly allocated to the recyclable materials (waste generated during demolition of the assessed building), as they are relieved of the burden of disposal, and partly to the recycled materials (second system) through reduced impact from raw materials extraction (e.g. secondary aluminium is burdened with the impact from collecting, sorting, preparing (cleaning, pressing,…) aluminium scrap but not with the more important impact from extraction of aluminium ore (that is allocated to primary aluminium).

The reasons for choosing this allocation procedure are:

- The LCI database used within LEHR (Ecoinvent v.2) follows the same allocation procedure for recycling. Using the same procedure limits the risk of not complying to the 100% rule (the sum of the allocated in en outputs must be equal to the sum of the in and outputs before allocation). (Althaus, 2007)(Doka, 2007)
- Perhaps a more precise procedure would have been to allocate part of the impact from recycling, up to the economical turning point (point were the waste has a positive value and thus is no longer considered as waste but rather as a resource), to the first system, or in other words to fix the system boundaries at the economical turning point. However, too little information is available to make reasonable assumptions concerning the economic turning point of all building materials.
- The most independent instruments and LCA tools on the building level tend to favour exclusion of system expansion and subtraction (avoided impacts) because of the incomparable system boundaries. (Kotaji, 2003)
- The avoided impact approach may be appropriate for non-durable consumer goods (e.g. paper or plastic bottles) but it is not recommended for highly durable goods like buildings as:
  - the longevity of buildings means that, effectively, recycling may have negligible affect on the environmental impacts of concern today. Indeed, the benefits of future recycling are generally calculated based on current conditions, while in fact scarcity, ecological carrying capacity, energy mixes and other factors are certain to change radically in the future (e.g. the present production processes are usually subtracted to account for avoided impact from raw materials extraction, however in the future (at the time of recycling) the processes may be much cleaner).(CMHC, 2004)(Kotaji, 2003)
  - the beneficial effect of recycling buildings constructed today is only effective in the future. Therefore, the benefits cannot be credited against consumption today as this would imply that current environmental impact...
is allocated to future generations, which would favour the consumption of primary materials today. (CMHC, 2004)(Kotaji, 2003)

- in order to account for down cycling, information would not only be needed on the fraction of primary materials that will be recycled, but also on the raw materials they will replace in the next system (e.g. concrete will not replace concrete but aggregates, so the avoided impact related to the recycling of concrete is not the production of concrete but the extraction of gravel).

### 3.2.5 LCIA methodology

Within LEHR, the LCI results were interpreted using the Eco-indicator 99 method. This method was developed by PRé consultants (by order of the Dutch Ministery of Housing, Spatial Planning and the environment (VROM), as part of the Integrated Product Policy) in collaboration with various LCA experts from different organisations in the Netherland and Switzerland. The reason for choosing this methodology is that it is well documented, widely known and used, and that it enables to present the results as a single score indicator (to achieve the goal of the LEHR study, the LCA results needed to be aggregated to a single unit score). The basic principles of this methodology are presented in the next sections. For a complete overview of the methodology we refer to the methodology report (Goedkoop, The Eco-indicator 99: A damage oriented method for Life Cycle Impact Assessment, Methodology report nr 1999/36A, 2001) available online.

**Impact categories and characterization model**

The Eco-indicator99 method uses different procedures (damages models) to establish the link between the inventory table and the potential damage to Human Health, ecosystem quality, and resources (3 damage categories). These 3 damage categories can then eventually be weighted and aggregated to a single score (eco-indicator). However, intermediate results (quantification of environmental sources for the damage) can also be obtained. For example, to quantify the damage to human health models have been developed for the effects of climate change (causes infectious diseases, cardiovascular diseases and respiratory diseases, as well as forced displacements), ionising radiation (cause of cancer), ozone layer depletion (cause of cancer and eye damages), respiratory and carcinogenic effects. Now, the quantification of the effects of climate change, ozone layer depletion,...on human health can be obtained separately (before aggregation to the damage category human health).

A general overview of the method is presented in Figure 9 and a list of the effects considered for the 3 damage categories (the so-called intermediate or characterization results) is given in Table 8.
Figure 9 General representation of the Eco-indicator 99 methodology.

<table>
<thead>
<tr>
<th>Category</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carcinogens</td>
<td>DALY</td>
</tr>
<tr>
<td>Resp. organics</td>
<td>DALY</td>
</tr>
<tr>
<td>Resp. inorganics</td>
<td>DALY</td>
</tr>
<tr>
<td>Climate change</td>
<td>DALY</td>
</tr>
<tr>
<td>Radiation</td>
<td>DALY</td>
</tr>
<tr>
<td>Ozone layer</td>
<td>DALY</td>
</tr>
<tr>
<td>Ecotoxicity</td>
<td>PAF*m².yr</td>
</tr>
<tr>
<td>Acidification/eutrophication</td>
<td>PDF*m².yr</td>
</tr>
<tr>
<td>Land use</td>
<td>PDF*m².yr</td>
</tr>
<tr>
<td>Minerals</td>
<td>MJ surplus</td>
</tr>
<tr>
<td>Fossil fuels</td>
<td>MJ surplus</td>
</tr>
</tbody>
</table>


Model uncertainties

During the development of this methodology many subjective choices had to be made on issues that have significant effects on the results. For example the choice of the time horizon to consider in the damage model, or the level of scientific proof required to include an effect (e.g. to assess the damage caused by carcinogenic substances, do we consider only substances for which carcinogenic effects are proven (group 1 from IARC classification) or also all substances for which carcinogenic effects are probable or possible (IARC classification 2A, 2B), or do we go even further and include all

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7 International Agency for Research on Cancer of the World Health Organisation (WHO)
substances that are not classifiable as to their carcinogenicity (IARC group 3). In order to deal with the uncertainties related to these subjective choice 3 different versions of the methodology were developed using 3 archetypes of perspectives extracted from the Cultural Theory Framework (Goedkoop, The Eco-indicator 99: A damage oriented method for Life Cycle Impact Assessment, Methodology report nr 1999/36A, 2001):

- the egalitarian perspective
- the humanitarian perspective
- the individualist perspective


- **Egalitarian perspective**
  - extremely long-term time perspective
  - includes data on which consensus is lacking: substances are included if there is just an indication regarding their effect (e.g. all carcinogenic substances in IARC class 1, 2a, 2b and 3 are included, as far as information was available).
  - damages cannot be avoided and may lead to catastrophic events.
  - in the case of fossil fuels the assumption is made that fossil fuels cannot be substituted. Oil, coal and gas are to be replaced by a future mix of brown coal and shale.
  - in the DALY calculations age weighting is not included.

→ this is the most comprehensive version, but also the one with the largest data uncertainties.

- **Hierarchist perspective:**
  - long-term time perspective
  - substances are included if there is consensus regarding their effect (e.g. all carcinogenic substances in IARC class 1, 2a and 2b are included, while class 3 has deliberately been excluded).
  - damages are assumed to be avoidable by good management: e.g. the danger people have to flee from rising water levels is not included.
  - in the case of fossil fuels the assumption is made that fossil fuels cannot easily be substituted. Oil and gas are to be replaced by shale, while coal is replaced by brown coal.
  - in the DALY calculations age weighting is not included.
- Individualist perspective:

- short-term time perspective (100 years or less).
- substances are included if there is complete proof regarding their effect (e.g. only carcinogenic substances in IARC class 1 are included, while class 2a, 2b and 3 have deliberately been excluded).
- damages are assumed to be recoverable by technological and economic development.
- In the case of fossil fuels the assumption is made that fossil fuels cannot really be depleted. Therefore they are left out.
- In the DALY calculations age weighting is included (a person is valued higher at the age between 20 and 40 years).

Within LEHR, the Hierarchist version of the Eco-indicator 99 model was used as this is the most recommended one (In general value choices made in the Hierachist version are scientifically and politically accepted). (Goedkoop, Simapro 7 Database manual, method library, 2004) (Goedkoop, The Eco-indicator 99: A damage oriented method for Life Cycle Impact Assessment, Methodology report nr 1999/36A, 2001) However, the two other perspectives will be used in the sensitivity analysis.

Optional elements
The calculation of the three damage categories concludes the environmental modeling. In cases where a single score is required (as in the LEHR project), the following optional steps can be applied.

Normalisation
The three damage categories have different units. To enable aggregation these 3 categories are made dimensionless by using a normalization step. The Eco-indicator uses the European normalization values.

Weighting
In the eco-indicator method the weighing is applied to the normalized damage category results. The weighted results can then be aggregated to a single score: the eco-indicator. For each perspective a different weighting set can be used (these were developed based on a panel approach). As recommended in the eco-indicator 99 methodology report, within LEHR we used the following average weighting sets:

- Damage to ecosystem quality: 40%
- Damage to human health: 40%
- Depletion of resources: 20%

3.3 LIFE CYCLE INVENTORY ANALYSIS
3.3.1 Generic data
As mentioned before, each renovation system can be broken down in a certain number of unit processes related to the production, transportation and EOL of building materials
and equipments, and to the use of energy for heating, ventilation and production of warm water. For the collection of in- and outputs related to these unit processes generic data from the ecoivent database v.2.0 was used. This database was developed by the Swiss Centre for Life Cycle inventory and contains LCI datasets for about 4000 unit processes often used in LCA case studies (e.g. in and output related to the production of 1kg of aluminum). Most datasets are representative of the Swiss or Western European situation in the year 2000. However, in some cases more country specific datasets are available (e.g. country specific electricity supply mixes) and the most recent and updated datasets use the year 2004/2005 as reference year (e.g. electricity mixes). Older data has only been used in exceptional cases due to reduced data availability. All LCI datasets for wood products suppose that the wood comes from sustainably managed forests (Frischknecht, 2007).

Preference was given, whenever possible, to the datasets representative of the Western European situation. For specific building materials and equipments where no generic dataset was available, a new LCI dataset was created by adapting or combining existing datasets according to the available product information. Concerning the electricity consumed during the use phase of the building under study (for the ventilation system and installations for heating and warm water production), a LCI dataset representative of the Belgian electricity supply mix was used. It is representative of the year 2004/2005 and takes into account the share of domestic electricity production by technology and imports from neighbouring countries (Table 9), the transmission network, and distribution losses.

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard coal</td>
<td>9,1%</td>
</tr>
<tr>
<td>Oil</td>
<td>1,7%</td>
</tr>
<tr>
<td>Natural gas</td>
<td>21,4%</td>
</tr>
<tr>
<td>Industrial gas</td>
<td>2,3%</td>
</tr>
<tr>
<td>Hydropower</td>
<td>1,6%</td>
</tr>
<tr>
<td>Nuclear</td>
<td>46,6%</td>
</tr>
<tr>
<td>Wind power</td>
<td>0,1%</td>
</tr>
<tr>
<td>Cogen ORC 1400kWth, wood</td>
<td>0,5%</td>
</tr>
<tr>
<td>Cogen with biogas engine</td>
<td>0,2%</td>
</tr>
<tr>
<td>Production mix, France</td>
<td>8,0%</td>
</tr>
<tr>
<td>Production mix, Luxembourg</td>
<td>2,5%</td>
</tr>
<tr>
<td>Production mix, Netherlands</td>
<td>4,7%</td>
</tr>
</tbody>
</table>

Table 9 Composition of the Belgian electricity mix, situation of the year 2004/2005 (Ecoinvent v.2.0).

3.3.2 Project specific data
The ecoinvent database contains LCI datasets for the production of various common building materials (cradle to gate LCI data = impacts from material extraction, transport to the production site, production process and infrastructure), and separate datasets for the different disposal options (incineration, landfill or recycling), as well as for various transportation modes (different types of trucks, train, boat,…). The reason for not linking
these different stages of the building materials life cycle (providing cradle to grave datasets) is the fact that unlike the materials production process, the transport to the construction site (mean of transport and distance), as well as the end of life destination are very site specific.

Therefore, in order to model the full life cycle of building materials and equipments, scenarios representative of the Belgian situation had to be elaborated for the transportation of the materials (average distances and means of transport) to the construction site, and for the end-of-life phase (choice of waste treatment process + transport to waste treatment facility).

Finally, as the process system under study for this project is the life cycle of the renovated building, we also have to take into account the fact that some materials/components will probably need to be replaced before the end of the reference study period (80 years). Therefore assumptions also had to be made regarding the reference service life of each material/component. Based hereon, a replacement factor (and so the number of life cycles to be considered for the study) could then be calculated for the materials/components with a reference service life under the reference study period.

**Transport of materials to the construction site**

The transport scenarios that were used for the transportation of construction materials and equipments were developed as part of the Sufiquad (Sustainability, Financial and Quality evaluation of dwelling types) project. They are based on the results of an inquiry sent to different Belgian stakeholders (contractors, construction products dealers, producers and distribution centres) regarding the average distances and transport modes used for the transportation of 8 categories of building materials from the factory to the construction site in Belgium. (Putzeys K., 2008)

The main two limitations of those scenarios are:

1. the response to the inquiry was limited, so the outcomes of the inquiry may not fully reflect the actual average situation in the sector.
2. the scenarios represent only the transportation of materials from local (Belgian) producers or distributors to the construction site, but neglect the environmental impact related to the transportation of imported products from the original production location to Belgium.

**End of life**

Concerning the environmental impact related to the end-of-life phase following elements were considered:

- Impact of demolition
- Transport from the demolition site to the waste treatment facility
- Impact of sorting plant
- Waste treatment process

The assumptions that were made regarding these elements are presented in the following sections.

**Impact of demolition/dismantling**
Adhering to the Eco-invent approach (Doka, 2007), only following elements were considered for the inventory of in and outputs related to the demolition phase:

- Particulate matter (PM) emissions during demolition
- Amount of energy used for dismantling

For all mineral building materials (e.g. concrete, brick, gypsum, mineral wool,...) a constant amount of PM emissions were considered per kg of material. Emission occurring during demolition of non-mineral materials (e.g. wood, glass, metals, plastics) were considered as negligible.

The energy use for dismantling was only considered for structural materials because non-structural materials are supposed to disintegrate after the structural part is dismantled. It is expressed as MJ diesel burned in a building machine/ kg material and varies according to the resistance of the materials (e.g. the demolition energy for reinforced concrete is higher than for non-reinforced concrete). The Ecoinvent dataset "MJ diesel burned in building machine" considers the impact of the building machine (infrastructure), lubricating oil, fuel consumption and some measured outputs (Doka, 2007)

**Transport of building waste to waste treatment**

After demolition, building waste needs to be transported to the appropriate waste treatment facilities. Within the LEHR project, it is assumed that all demolition waste is transported to a sorting plant or crushing facility first, and then redistributed amongst the various waste treatment facilities according to the defined end-of-life scenario (see next section). In accordance to the boundary settings (allocation rule for recycling), transport from the sorting plant to the recycling facility is not considered for the present building. Also no EOL life transport is included for the fraction of inert material that is supposed to be recycled, as it is assumed that it goes directly from the demolition site to the crushing (recycling) facility or that it will be crushed directly at the sorting plant (the sorting plant is then considered as the recycling facility). Of course, for the fraction of inert waste that goes to landfill, the transport to the crushing facility or sorting plant, and the subsequent transport to landfill is included in the assessment.

For the modeling of the transport from the demolition site to the sorting plant and from there to landfill or incineration, fixed values were used regarding transport distances and means of transport. These values were mostly based on the fixed values given in the Dutch norm NEN 8006 (Environmental data of building materials, building products and building elements for application in environmental product declaration - Assesment according to the Life Cycle Assessment (LCA) methodology) (NEN, 2004). Only the distance from the demolition site to the sorting plant or crusher deviates from the Dutch value, as the given value (50km) was considered to be too large for the Belgian situation.

**Sorting plant**

Based on the ecoinvent report on building material disposal (Doka, 2007), following elements were considered for the inventory of in and outputs related to the sorting plant:

- Infrastructure, land use and heating of the sorting plant
- Impact of the skid-steer loader used to charge and discharge waste at the plant (infrastructure, lubricating oil and fuel consumption)
- Energy demand for the conveyor belt (Belgian electricity mix)
- Energy demand for the crusher (Belgian electricity mix)

As the recycled fraction of inert waste is supposed to go directly from the demolition site to the recycling facility, the impact of the sorting plant is not considered for this fraction.

The energy demand for the crusher is only applicable to reinforcing steel in concrete, and to the landfill stream of inert materials. For the recycled inert material fraction, the crushing is not considered as it is part of the recycling process (outside of the system boundaries) and for the remaining materials (insulation, metals, wood, gypsum plaster boards, ...) it is not considered as they are assumed to cause no resistance in crushing or to be sorted out prior to crushing.

**Waste treatment processes**

The final destination of building waste (recycling, landfill, incineration or reuse) does not only depend on the waste fraction (materials characteristics), but also on the type of construction, procedures in utilisation of the material and site-specific disposal logistics. As it is impossible to predict how the situation will be at the time of demolition, an end of life (EOL) scenario (scenario that divides waste streams into streams that are sent to landfill, incineration, or to recovery (recycling, reuse)) had to be developed based on current practices. The EOL scenario that was used within LEHR is mainly based on the fixed values given in the Dutch norm NEN 8006 (NEN, 2004).

However, the values for the main waste fractions were checked with concerned parties in Belgium (FEBEM, Federplast, OVAM, BBRI, SPANO, ...) and where necessary (e.g. for waste fractions like wood were the recycling possibilities are very different in Belgium than in the Netherlands) adapted to the Belgian situation.

All Ecoinvent records for building materials (cradle to gate records) that include packaging also include the EOL treatment of the packaging. Therefore, packaging was not included into the developed EOL scenario.

**Replacements**

**Reference service life (rsl)**

In order to take into account replacements of materials/components that will probably occur during the life cycle of the renovated building, assumptions had to be made regarding the probable service life of these materials/components. The assumed values were based on standard values used in the ecoinvent database v2.0 (only available for equipments), and existing LCA tools, as well as values found in literature. (Eco-Quantum), (DIN), (EN, 2007), (SIA, 2004), (CWA, 2007), (SBR, 1998), (Blom, 2005), (NIBE, 2003), (INIES, 2007), (BRE, 2000), (IVAM, 2003).

**Replacement factor**

Materials/components that have a reference service life inferior to the considered reference study period for the building will have to be replaced a certain number of times. For each material/component, the number of replacements can be obtained by dividing
the reference study period (rsp) of the building by the reference service life (rsl), and then subtracting one (the initial placement) from the obtained result. If the resulting number is an integer, then it represents the number of replacements (e.g. the ventilation unit is supposed to have a rsl of 20 years, so the number of replacements for a rsp of 80 years=80/20-1= 3.

However, in some cases the resulting number is not an integer. For example if the ventilation unit would have a rsl of 25 years instead of 20, then the calculated number of replacements would be 80/25 – 1= 2.2. In real situation, the ventilation unit will be replaced at 25, 50 and 75 years, or maybe it will not be replaced at 75 years.

In LCA practice the main ways to deal with those not integer numbers are pro-rating and not pro-rating. Pro-rating means that the calculated number will not be adapted, and consequently that 3.2 ventilation units life cycles will be considered in the calculation of the environmental impact of the building (1 initial, 2.2 replacements). In case of not prorating, the number of replacements will be rounded to an integer and so 4 ventilation units will be used.

Both methods have pros and cons and there are some variations possible on each. An argument against prorating is that it is a theoretical value that does not reflect the real situation (in reality a fraction of a window will not be placed). An argument in favour of prorating is that there are high uncertainties in the service life of the component, the building and the exact year of replacement, and that prorating reflects these uncertainties. It represent the average situation: in some cases the ventilation unit will be replaced at 75 years and in some cases it will last not. Moreover, it makes the results less sensitive to the reference study period of the building (e.g. if prorating is not applied, for a rsp of 80 years a window with a rsl of 25 years will be replaced 2 times and for a reference study period of 75 years only 1 time). For these reasons, prorating is often applied in LCA software tools for buildings (NEN, 2004)(Eco-Quantum)(Kotaji, 2003).

Prorating was also applied within the LEHR project, so for each material/component within the system boundaries, the number of replacements (R) was calculated as following:

\[
\text{If } rsl \geq rsp: R = 0 \\
\text{If } rsl \leq rsp: R = \frac{rsp}{rsl} - 1
\]

Where rsl=reference service life of materials and components

\[
\text{rsp}=\text{reference study period (80 years)}
\]

\[
\text{R}=\text{number replacements}
\]

This means that for each material component R +1 life cycles (impact of resource extraction, production, transport, EOL) where considered to contribute to the environmental impact of the building.
4. LIFE CYCLE ANALYSIS: RESULTS

In the following sections, the environmental impact from materials, equipments, and energy use of the standard (SR), low energy (LE), very low energy (VLE) and passive house standard (SR) renovation alternatives will be compared at first. The comparison of these four alternatives with varying heat demand (insulation) levels, but similar types of installation for the production of hot water and heat (condensing gas furnace), is intended to analyze to which extent the environmental impact from the measures taken to reduce the heat demand (materials and equipments) are compensated by the environmental impact related to the energy savings.

Secondly, 5 alternatives with a same heat demand (passive house standard), but varying installations (energy vectors) for the production of hot water and heat will be compared in order to analyze to which extent, for a given heat demand (insulation level), the environmental impact of the renovation can be influenced by the choice of installation. The impact of the various installations themselves will be compared first, then the impact of the resulting energy use, and finally the total impact. As all alternatives are based on the Passive house renovation alternative, the impact from materials is the same for all alternatives.

In both cases, the comparison of the impact from materials, equipments, and energy use, is conducted firstly based on the results from the characterization phase (Eco-indicator 99 H intermediate results) and secondly based on the aggregated weighted results (Eco-indicator 99 (H/A) single score). Moreover, based on the aggregated results, an environmental payback time is calculated in the first section for the sets of measures taken to reach a lower energy demand level and in the second section for the solar system for hot water.

Finally, in the third section, the aggregated results (Eco-indicator 99 (H/A) single scores) from all the above compared alternatives are put next to each other, together with some extra combinations of energy levels and installations (VLE and LE alternatives combined with a solar system for hot water), in order to gain a better inside into the relative impact of the studied sets of measures (varying insulation levels and choice of installation) on the final score.

4.1. LCA OF ALTERNATIVES WITH VARYING HEAT DEMAND - FIXED ENERGY VECTOR

4.1.1 Indicator results (before aggregation)

Impact from materials
For most impact categories, the environmental impact of materials increases with the insulation level (see Figure 10). Indeed for 7/11 categories the materials score increases gradually from SR to PH and for 9/11 categories the PH materials have the highest impact. However, the differences between the alternatives are sometimes small and the gradually increasing trend from SR to PH is not systematically true for all categories. For example, for 3/11 categories (depletion of mineral resources, climate change, ozone layer depletion), going from LE to VLE has a positive impact on the score, despite the increase in insulation level. This can be explained by the fact that LE and VLE utilize very different materials (e.g. LE uses mineral wool and brick where VLE uses wood and cellulose) and that for some categories this transition seems to have a positive effect on the score (which overrules the negative effect of the increase in insulation level).
Figure 10 Varying heat demand, fixed energy vector (gas): comparison of the impact from materials (80 years) per category indicator. For each indicator, the results are normalized to 100% of the highest score.

**Impact from equipments**

For most impact categories the impact related to the equipments increases gradually from SR to VLE (with the highest increase between LE and VLE because of the installation of the mechanical ventilation system), and slightly decreases from VLE to PH (because the radiators are replaced by 3 warm water batteries on the ventilation system)(Figure 11). The equipments from SR score best on all impact categories as there is no storage tank for warm water, nor ventilation system (only natural ventilation), and the gas furnace is replaced only after 10 years.

Figure 11 Varying heat demand, fixed energy vector (gas): comparison of the impact from equipments (80 years) per category indicator. For each indicator, the results are normalized to 100% of the highest score.
**Impact related to energy use**

The impact related to the energy use is the sum of the impacts resulting from the consumption of gas for heating and warm water and from the consumption of electricity for the operation of the furnace and the ventilation system (Figure 12).

For all considered impact categories, LE scores better than SR, and PH scores better than VLE (because of reduced heat demand). However for 7/11 categories the impact related to energy use increases from LE to VLE, despite the lower heat demand. This can be explained by the fact that for those impact categories the effect from the increase in electricity demand for the operation of the mechanical ventilation system, overrules the positive effect of the reduced heat demand (gas consumption). Consequently, thanks to its low electricity use and relatively low gas consumption, LE scores best on 5/11 impact categories (PH scores best on the 6 remaining ones).

![Figure 12 Varying heat demand, fixed energy vector (gas): comparison of the impact from energy use for heating, warm water production and ventilation (80 years) per category indicator. For each indicator, the results are normalized to 100% of the highest score.](image)

**Total environmental impact**

The total impact represents the sum of the impacts from materials, equipments, and energy use (Figure 13).

For 3 impact categories (land use, carcinogens, ecotoxicity) SR has the lowest total impact. For those impact categories, the increased impact from materials, equipments and electricity consumption of the lower energy alternatives is not compensated by the resulting reduction in gas demand.

PH scores best on the impact categories that are dominated by the heat demand (gas consumption): climate change, ozone layer depletion, depletion of fossil fuels resources,
respiratory organics. For those categories, the impact is uniformly decreasing from SR to PH (as does the heat demand).

LE scores best on the 4 remaining impact categories, mainly because of its low electricity use and relatively low gas consumption and use of materials and equipments. VLE is never the best alternative as it has a relatively high impact from equipments, materials, and electricity use, but not the lowest heat demand.

![Graph showing varying heat demand, fixed energy vector (gas): comparison of the total impact (sum of the impact from materials, energy use, equipments for 80 years) per category indicator. For each indicator, the results are normalized to 100% of the highest score.](image)

**Figure 13** Varying heat demand, fixed energy vector (gas): comparison of the total impact (sum of the impact from materials, energy use, equipments for 80 years) per category indicator. For each indicator, the results are normalized to 100% of the highest score.

### 4.1.2. Eco-indicator 99 (H/A) single score

Although this was not true for all considered impact categories, the Eco-indicator 99 (H/A) score of the materials univocally increases with increasing insulation levels (from SR to PH +888ptn). The Eco-indicator 99 (H/A) score of the equipments increases from SR to LE (+110ptn), but mostly from LE to VLE (+409ptn) because of the installation of the mechanical ventilation system, and slightly decreases (-13ptn) from VLE to PH as the radiators are replaced by warm water batteries on the ventilation system.

The global score related to the energy use univocally decreases from SR to PH (-31961 ptn), despite the negative influence of the increased electricity consumption resulting from the operation of the mechanical ventilation system on various impact categories. This can be explained by the fact that the energy use mainly contributes to the European average impact on the depletion of fossil fuels and climate change (two impact categories for which the score mainly varied with the heat demand (decrease from SR to PH)), and that the global score of the energy use is therefore mainly determined by the performance on these two categories.
For the considered reference study period, the increases in global Eco-indicator 99 (H/A) score from materials and equipments are very small relative to the resulting decreases from energy use. Consequently, the total aggregated ecoindicator 99H score follows the same trend as the energy use: it decreases uniformly from SR to PH.

![Graph showing eco-indicator 99 (H/A) scores for SR, LE, VLE, and PH]

**Figure 14** Varying heat demand, fixed energy vector (gas): comparison of the total impact (sum of the impact from materials, energy use, equipments for 80 years) expressed in eco-indicator score.

**Environmental payback time of the sets of measures taken to reduce the heat demand**

Based on the above eco-indicator 99 H single score results, it is clear that the higher environmental impact from materials and equipments required to achieve lower heat demand levels is compensated by the benefits resulting from the reduced heat demand. Now, the question is after how much time is it compensated, or in other words what is the environmental payback time of the sets of measures taken to achieve lower heat demands?

To answer that question, we calculated the additional impact from materials and equipments (one full life cycle, excl. replacements) needed to go from one heat demand level to the next lower level, and divided it by the corresponding yearly saving on environmental impact from energy use. The resulting environmental payback times are very low (see Table 10): in all cases the increased impact from materials and equipments is paid back in less than 3 years by the resulting decrease in environmental impact from

---

8 If the calculated payback time is greater than the smallest reference service life of the materials and equipments, replacements would need be taken into account for the calculation of this payback time.
energy use\(^9\). Off course, as going to a lower heat demand does not have a positive effect on all impact category indicators, this will not be true for all considered impact categories.

<table>
<thead>
<tr>
<th></th>
<th>LE-SR</th>
<th>VLE-LE</th>
<th>PH-VLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase in impact from materials (A)</td>
<td>440 pts</td>
<td>42 pts</td>
<td>119 pts</td>
</tr>
<tr>
<td>Increase in impact from equipments (B)</td>
<td>101 pts</td>
<td>148 pts</td>
<td>-6 pts</td>
</tr>
<tr>
<td>Yearly saving on impact from energy use (C)</td>
<td>268 pts</td>
<td>80 pts</td>
<td>51 pts</td>
</tr>
<tr>
<td>environmental payback time = (A+B)/C</td>
<td>2,02 years</td>
<td>2.37 years</td>
<td>2.2 years</td>
</tr>
</tbody>
</table>

Table 10 Calculation of environmental payback time for energy saving measures

### 4.2. LCA OF ALTERNATIVES WITH VARYING ENERGY VECTOR - FIXED HEAT DEMAND

#### 4.2.1. Indicator results (before aggregation)

**Impact from equipments**

Installing a **solar system for hot water** obviously increases the impact of the equipments for all considered impact categories, as in this case it is just an addition to the existing system for hot water and heating (e.g. compare the impact of equipments from PH-Elect with PH-ElectSun and PH-Gas with PH-GasSun).

Within the alternatives without solar system (PH-Elect and PH-Gas), and with solar system (PH-ElectSun, PH-GasSun, PH-PelletsSun), the equipments of the Elect-alternatives generally have the lowest impact since they do not contain a furnace.

As the ecoinvent records are not primarily suited for direct comparison between products but are rather intended for integration and comparison between complete life cycle systems no conclusion can really be made concerning whether the gas or the pellet furnace have the lowest environmental impact.

**Impact related to energy use**

Adding a **solar system for hot water** to the PH-Elect alternative, has an univocally positive influence on the environmental impact related to the energy use. Indeed, in PH-Elect the energy use corresponds to the electricity consumption and thanks to the solar boiler this consumption is reduced by 38%, so the score for all impact categories will be reduced accordingly. For the PH-Gas alternative, the effect of the solar system on the impact of the energy use is less univocal: for 8/11 categories it results in a decrease in impact (PH-GasSun<PH-Gas), but the decrease is of more variable magnitude (between 3 and 40%), and for 3/11 impact categories it even results in a slight increase in impact (from 3 to 8%). This can be explained by the fact that in the case of PH-Gas, the installation of a solar system for hot water not only results in a reduction in gas consumption but also in an increase in electricity consumption (aid energy for the solar system).

\(^9\) only the filters for the ventilation system have reference service life inferior to 2 years, but this small simplification has no real influence on the calculated payback time
Figure 15 Renovation to passive house standard - varying energy vectors for heating and warm water production: comparison of impact from energy use. The results are normalized to the highest score per impact category.

Within the alternatives with or without solar system, the energy use of the elect-alternatives results for 10/11 categories in a higher impact than the corresponding gas-alternatives. The only impact category for which the elect alternatives are better than the gas-ones is “depletion of fossil fuels” (because of the high proportion of nuclear energy in the Belgian electricity mix).

Finally, within the PH alternatives with a solar system for hot water, the energy use of PH-PelletsSun scores best on climate change, ozone layer depletion, and depletion of fossil fuels and PH-GasSun on the 8 remaining impact categories. On the other hand, the energy use of PH-PelletsSun has also the highest score for land use, respiratory inorganics and carcinogens (primarily because of the emissions during combustion and the resulting waste from combustion), while PH-ElectSun has the highest score for the remaining categories.

**Total impact**

In the case of PH-Elect the higher impact of equipments that results from the installation of a solar system is compensated for 10/11 categories by the resulting positive influence on the energy use. So, for 10/11 category (all categories but “depletion of mineral resources) the total impact of PH-ElectSun is smaller than that of PH-Elect.

On the other hand, in the case of PH-Gas the negative effect of the solar system on the impact of equipments is compensated by the resulting decrease in energy use for only 5/11 categories. Indeed, in that case the decrease in impact from energy use was not as marked as in the case of PH-Elect, so it is more difficult to compensate for the increase in impact from equipments.

Concerning the PH-Gas and PH-Elect alternatives, the differences in impact from equipments (in favour of PH-Elect) are smaller than the differences in impact from energy
use (in favour of PH-Gas). Therefore, the PH-Gas alternatives score better on all categories, but depletion of fossil fuels, than the PH-Elect alternatives.

Within the alternatives with a solar system for hot water (PH-GasSun, PH-ElectSun, PH-PelletsSun), the differences between the impact from equipments are very small compared to the differences in impact from energy use. Therefore, the results are determined by the impact from energy use: PH-PelletsSun has the best score for climate change, ozone layer depletion, and depletion of fossil fuels and PH-GasSun for the 8 remaining impact categories. PH-PelletsSun has the highest (worst) score for land use, respiratory inorganics and carcinogens (primarily because of the emissions during combustion and the resulting waste from combustion), while PH-ElectSun has the highest score for the remaining categories.

![Figure 16 Renovation to passive house standard - varying energy vectors for heating and warm water production: comparison of total impact (sum of impact from materials, energy and equipments). The results are normalized to the highest score.](image)

**4.2.2. Single score Eco-indicator 99 (H/A)**

For both PH-Elect and PH-Gas, the solar system for hot water has a positive effect on the global Eco-indicator 99 (H/A) score related to the energy use, which largely compensates for the increase in impact from equipments. So, the total Eco-indicator 99 (H/A) score of the alternatives with a solar system for hot water (PH-GasSun, PH-ElectSun) is better than that of the alternatives without one (PH-Gas, PH-Elect).

For the other alternatives, the differences in global score from equipments are also very small compared to the resulting differences in global score from energy use. Therefore the final ranking of the alternatives (based on the total score) is determined by the ranking of the Eco-indicator 99 (H/A) score related to the energy use.
Despite the fact that the energy use of the PH-Elect alternatives scores worse than the PH-Gas alternatives for 10/11 categories, the global score of the former is better. The main 2 reasons for this surprising result are:

1. the energy use contributes essentially to the impact category “depletion of fossil fuels”, which is the only category on which PH-elect had a better score.

2. the standard efficiency-factor given in the EPB for warm water production with an electric boiler (0.7) is much higher than that given for a gas boiler (0.45), and in the studied cases (PH-alternatives) the energy demand for warm water is much greater than for heating. A sensitivity analysis shows that if the gas boiler has an efficiency factor of 0.6 or higher (instead of 0.45) for the preparation of warm water, then the environmental impact related to the PH-gas alternative is better than that of the PH-electric alternative.

Comparing all PH-alternatives, PH-PelletsSun has the best global Eco-indicator 99 (H/A) score, mainly because of its good performance on the categories “depletion of fossil fuels” and climate change (two categories that seem determinant for the global score related to the energy use, and seen the relatively small differences in impact of equipments, also for the final ranking).

![Graph](image)

**Figure 17 Renovation to passive house standard- varying energy vectors for heating and warm water production: comparison based on total eco-indicator 99 (H/A) score.**

*Environmental payback time of Solar system for hot water*

From the above global eco-indicator 99 (H/A) results it is clear that the installation of a solar system for hot water results in an increase in impact from equipments, but that this additional impact is compensated by the resulting savings in energy use. Now, again the
question is after how much time is it compensated, or in other words what is the environmental payback time of the solar system for hot water?

When dividing the environmental impact of the solar system (one full life cycle) by the resulting yearly saving on environmental impact of energy use (both expressed in eco-indicator points), we find an environmental payback time beneath 4 years (see Table 10).

Note that those values are not valid for all impact categories. In the case of PH-Elect, the calculated payback time varies, depending on the impact category between less than one year to 19 years, and for the category “depletion of mineral resources” it is superior to the service life of the solar system. On the other hand, in the case of PH-Gas, the impact of the solar system is compensated by the reduction in impact from energy use for only 5 categories (climate change, ozone layer depletion, depletion of fossil fuels, respiratory organics, acidification), and for those categories the payback time varies from 1 year to 21 years.

<table>
<thead>
<tr>
<th></th>
<th>PH-GasSun vs PHgas</th>
<th>PH-ElectSun vs PH-Elect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase in impact from equipments (A)</td>
<td>239 pts</td>
<td>239 pts</td>
</tr>
<tr>
<td>Yearly energy saving on impact from energy use (B)</td>
<td>71.5 pts</td>
<td>61.3 pts</td>
</tr>
<tr>
<td>environmental payback time =A/B</td>
<td>3.35 years</td>
<td>3.9 years</td>
</tr>
</tbody>
</table>

Table 11 Calculation of environmental payback time of a solar system for hot water

4.3. LCA OF ALTERNATIVES WITH VARYING HEAT DEMAND AND ENERGY VECTOR

From the above comparisons, we can conclude that both striving to a lower heat demand level (PH-standard), and using renewable energies (solar system for hot water and pellet furnace) have a positive influence on the total aggregated score (aggregation of impacts from materials, equipments, energy use for the reference study period (80 years)). But if for some reason it is not possible to optimize both sets of measures, what would be the best choice from an environmental point of view? To answer that question, we ranked all the defined alternatives (including the VLE and LE alternatives with a solar system for hot water) according to their Eco-indicator 99 (H/A) score.

Based on the aggregated total Eco-indicator 99 (H/A) scores (Figure 18), it seems that till the VLE energy level is not attained, it is still more interesting to go to a higher insulation level (reduce the heat demand) than to install a solar system for hot water (e.g. going from LE-Gas to VLE-Gas results in a greater saving than going from LE-Gas to LE-GasSun). However, on the VLE-level, the energy demand for heating is already so small that greater savings can be achieved by reducing the energy demand for hot water through the installation of a solar system (going from VLE-Gas to VLE-GasSun), than by going to the passive house standard insulation level (reduce the heat demand even more by going from VLE-Gas to PH-Gas).
For this case, and based on the eco-indicator 99H results, the best combination seems to be the PH insulation level, with solar system for hot water and a pellet furnace as back-up system for heating.

4.4. SENSITIVITY ANALYSIS

4.4.1. Reference study period
The results were also calculated for a reference study period of 30 years instead of 80 years. The measured differences between the alternatives (expressed in eco-indicator points) become smaller, but the final ranking, based on the Eco-indicator 99 (H) score, remains the same (cfr. Figure 18). For a reference study period above 80 years, the final ranking would also remain, as the difference between the alternatives would only get bigger (because the absolute difference in total energy use increases with the years).

4.4.2. Selection of weighting factors
Weighting is one of the most controversial steps in a life cycle impact assessment and to be avoided in comparative assertions intended to be disclosed to the public. In the eco-indicator method, the weighting is applied to the normalized damage category results (damage to human health, ecosystems and energy resources). For the LEHR project, we used the humanitarian set of weighting factors. However, in order to evaluate to which extent the conclusions are dependent on that choice the triangle method was applied. The triangle method makes it possible to graphically depict the outcome of the comparison between 2 renovation alternatives for all possible weighting sets, and so identify combinations of weighting sets (areas on the triangle) for which one renovation alternative is favourable to another renovation alternative and vice versa.
The conducted analysis shows that the conclusions concerning the optimal heat demand level (SR, VLE, LE or PH) are almost completely independent of the choice of weighting factors (e.g. the comparison that is the most vulnerable for the choice of weighting factor is LE versus VLE and even in that case the combination of weighting sets for which the conclusions would be different is extremely small (in case less than 2% weight is given to the damage category resources and less than 50% to the damage category human health, Figure 19).

The conclusion concerning the benefit of the solar system is also independent of the choice of weighting factors.

However, the area on the triangle for which PH-Gas is better than PH-Elect is not negligible (Figure 21), this means that the conclusion whether PH-Gas is better than PH-Elect is relatively more dependent on the chosen set of weighting factors than the other conclusions. Finally, PH-PelletsSun has a higher environmental load than the PH-GasSun only if less than 10% weight is given to the impact category “Resources’ (Figure 22).

Figure 19 Triangle method: LE versus VLE (the area in blue represents sets of weighting factors for which the single score of VLE would be higher than that of LE and thus the conclusions would be different from the ones drawn in the Lehr project)
Figure 20 Triangle method: PH-gas versus PH-gasSun (the area in blue represents sets of weighting factors for which the single score of PH-gas would be higher than that of PH-gasSun)

Figure 21 Triangle method: PH gas versus PH elect (the area in blue represents sets of weighting factors for which the single score of PH elect would be higher than that of PH gas)
4.4.3. LCIA methodology

In order to assess the consequence of the choice of LCIA methodology on the conclusions of the study, the same alternatives (LCI data) were analyzed with 6 additional LCIA methods (and their respective sets of weighting factors):

- EPS 2000 D v2.04
- ECOPOINTS 1997 (ecological scarcity)
- EDIP 2003 v.1.01
- Ecological footprint v1.00
- Eco-indicator 99 (E/E)
- Eco-indicator 99 (I/I)

All these methods allow a comparative weighting and aggregation of the results, but they differ in the selection of impact categories and category indicators, characterization factors, reference basis for normalization, and weighting factors. The last two methods (ecoindicator 99 E and ecoindicator 99 I) are variations of the ecoindicator 99 H methodology (see section 0) and were used with their particular set of weighting factors instead of the average set.

The aggregated total score of the alternatives, calculated with these various methods are presented in Figure 23 to Figure 28. Note that the alternatives are presented in the same order as they were in Figure 18. The comparison between methods can only be applied to the relative position of the renovation alternatives and not to the absolute values, since the impact categories and characterisation factors differ amongst the methods.
Figure 23 Total aggregated score (EPS2000 v2.04) for various renovation alternatives (rsp=80 years)

Figure 24 Total aggregated score (ECOPONTS1997 method) for various renovation alternatives with varying insulation levels and installations for the production of hot water (rsp=80 years)
Figure 25 Total aggregated score (EDIP 2000 v1.01) for various renovation alternatives (rsp=80 years)

Figure 26 Total aggregated score (ECOLOGICAL FOOTPRINT v1.00) for various renovation alternatives (rsp=80 years)
From the comparison of the various sets of results obtained with the different methodologies (Figure 18 to Figure 28), following observations can be made:
Comparison of varying energy levels with fixed energy vector (SR-Gas, LE-Gas, VLE-Gas and PH-Gas)

- According to all 7 sets of results, LE is a better alternative than SR, and for all but one set (EDIP 2000 method) SR it is the worst alternative.
- The best alternative is, depending on the method, either LE (ecopoints, EDIP 2000, Ecoinde icator 99 (I)) or PH (EPS 2000, Ecological footprint, Eco-indicator 99(H), Ecoinde icator 99(E)), but never SR nor VLE.

Comparison of varying installations for a given energy level

- Impact of the solar system for hot water:
  - According to all but one method (Eco-indicator 99 (I)) it is interesting to install a solar system for hot water in (partial) replacement of an electric boiler (PH-electSun scores better than PH-elect).
  - For 5/7 sets of results (Ecopoints, EDIP2000, Eco-indicator 99E, Eco-indicator 99(H), ecological footprint), the GasSun alternatives score better than their corresponding energy level gas alternatives (e.g. PH-GasSun scores better than PH-Gas, VLE-GasSun scores better than VLE-Gas).

- Gas or electricity as energy vector for the passive house standard renovation: comparison of PH-Gas versus PH-Elect and PH-ElectSun versus PH-GasSun:
  - For all but one set of aggregated results (Eco-indicator 99 (H/A)), the gas alternatives perform better than the elect alternatives.
  - Given the fact that based on the non-aggregated Eco-indicator 99 (H/A) results, the elect alternatives also performed worse than the gas alternatives for 10/11 considered impact indicators, it is probably more recommended to use gas as energy vector for the production of warm water and heating rather than electricity.

Final ranking (comparison of all alternatives, with varying methods)

- No alternative comes out worst or best on all sets of results, however from the 10 considered alternatives, only 3 alternatives ever have the worst score and 3 the best score:
- Depending on the method, the best alternative is either PH-PelletsSun (Eco-indicator 99H, Eco-indicator 99E, EPS2000, Ecological footprint), LE-GasSun (Eco-point, EDIP 2000), or LE-Gas (Eco-indicator 99 (I))
- The worst alternative is either PH-ElektSun (Eco-indicator 99 (I)), SR-Gas (Eco-Indicator 99(E)), Eco-indicator 99(H)), EPS 2000)), PH-Elect (EDIP 2000, Ecopoints)

Conclusion

Although the results are clearly influenced by the choice of LCIA method, within the range of methods considered some general trends can still be observed for the present case study:

- the optimal energy level is either PH or LE, and the worst one SR.
• electricity (Belgian electricity supply mix) is certainly not the preferred energy vector for heating and warm water production.
• the solar system for hot water is recommended, especially in cases where it helps reduce the consumption of electricity (electric boiler)
• according to all methods where PH is the best energy level, PH-PelletsSun is the best choice of installation

4.5. CONCLUSIONS
The LCA study was intended to compare the environmental impact of various renovation alternatives, with varying heat demand and installations for heating and warm water, for a 19th century row house in Eupen. Based on the obtained results (evaluation of the environmental impact according to the Eco-indicator 99 (H/A) method), striving to a lower heat demand level and using renewable energies (solar system for hot water and pellet furnace) has a positive effect on the aggregated environmental score. However this is not true for all impact categories (no alternative comes out best on all impact categories considered). Indeed for some categories, the additional impact from materials and equipments overrules the reduced impact from energy use. Moreover, special care should be paid to the electricity consumption of auxiliaries (e.g. ventilation system, furnace, pumps) as the Belgian electricity supply mix has a negative effect on many impact categories which in some cases overrules the benefits of the reduced heat demand. According to the results of the sensitivity analysis, these conclusions seem to be relatively independent of the considered life span of the building (e.g. 30 years instead of 80 years), weighting factors (used to aggregate the various impact indicator results to one single score), and choice of impact assessment method.
5. LIFE CYCLE COSTS OF RETROFIT SCENARIOS

5.1 METHODOLOGICAL ASPECTS
The basis for evaluation of cost effectiveness of the retrofit scenarios analyzed is a calculation of the Net Present Value or Total Present Value of different cost aspects. Costs occurring during the considered service life are discounted to the present and added up (accumulated and discounted costs over the period of analysis). The scenario with the lowest Total Present Cost is considered as the most cost efficient. A limited sensitivity analysis on some parameters is executed, in order to test the robustness of the results obtained.

The cost analysis is done from the viewpoint of the investor or home owner who wants to decide how far to go in a renovation project. It is assumed that the amount of money to invest is available. No ‘mortgage simulation’ will be executed, the impact on the family budget will not be studied.

The elements included in the analysis (Cost Breakdown Structure) and the data used for the calculations are as following:

1. Investment costs
   a. As in the LCA, only the relevant elements are taken into account: the envelope (incl. finishings, air tightness) and the costs for installations for heating, ventilation and hot water.
   b. For all relevant elements a cost is calculated based on elemental units (m² roof, power of the heating installation, …). The ‘elements’ do not change from one scenario to another. For all cases, the same general building layout and surfaces (walls, roofs, floors, windows) are used in the calculations. Surfaces, materials applied, quantities and types of installations were obtained from the last detailed PHPP-calculation available from O. Henz (the architect and home-owner), due to lack of building plans and detailed drawings. This means that some secondary effects (thicker foundation needed, slightly changing surfaces due to more or less insulation thicknesses, …) are not taken into account. Other aspects (eg. exterior insulation requires changing the windowsills, internal insulation requires cutting the floors from the walls and supporting them, …) due to renovation activities were taken into account.
   c. The investment cost is calculated using unit prices from real offers and reference works [ASPEN, LIVIOS, Bouwunie, UPA].
   d. The works done by the house owner himself were recalculated towards a cost as it would have been executed by a contractor.
   e. The base date of the considered costs is March 2008.
   f. Financial incentives for energy saving measures are calculated separately in order to study their influence. Primes and fiscal deductions are calculated based on the situation in 2008. Regional (Walloon region) and federal grants are included. It is assumed that the whole project is a
This means that insulation measures (and efficient windows) for the newly constructed annex cannot benefit from tax deductions or primes. Only the renovated (or renewed) parts can apply for financial support.

Remarks:
- Non-construction costs, costs for architectural and design work are not taken into account
- Demolition works are only taken into account when they differ from one scenario to another
- For internal walls (new and existing), no calculations were made.
- Costs that are not included in this calculation: solar protection screens (natural vegetation foreseen), ventilation tubes (no info available), foundation works for newly constructed annexes.
- It should be noted that in the real project, also local and additional financial incentives are valid:
  - extra primes and rewards for solar energy
  - elevated local prime for rehabilitation of outdated buildings.

2. Energy costs
   a. The energy costs are based on an EPB-calculation (Flemish software version 1.2). Only the energy use for heating, domestic hot water and aid energy are considered in the cost calculation. The calculated fictive cooling load is not taken into account in the calculations.\(^\text{10}\)
   b. Unit prices from a simulation tool from March 2008\(^\text{11}\) were used to calculate energy consumption costs.
   c. Several scenarios for the future fluctuation of the energy prices were established and tested in a sensitivity analysis.

3. Maintenance costs
   a. For installations, a yearly maintenance cost is included in the form of a certain percentage of the investment cost, with reference to NBN EN 15459.

4. Replacement costs
   a. For the relevant elements (mainly the technical installations) a full reinvestment cost is included in the analysis if the service lifetime of the component is shorter than the analysis period. No subsidies/grants/… are included in the re-investment cost.

\(^\text{10}\) In the PH- and VLE-scenarios, where a high fictive cooling load exists, this is compensated by the cost of the ground/air-tube installed before the ventilation system.
\(^\text{11}\) [www.cwape.be](http://www.cwape.be), average prices for Eupen. It should be noted that at that time, prices were almost at their highest level. The economical crisis at the end of 2008 caused prices to drop significantly.
b. The service lifetimes are the same as defined in the LCA-analysis (see higher in this report).

5. End-of-life-cost / rest value
a. In the calculation of the Net Present Value, no end-of-life costs or values are taken into account. The rest value of a building is more dependent on its location and its general state of condition than it is determined by the insulation applied or the installations used.
b. The rest value for the different alternatives is calculated for informative reasons for the following components:

- Measures lasting longer than the analysis period (insulation, structure, …)
- Replaced elements with a remaining service life time at the end of the analysis period

The rest value will be calculated per material, with a linear depreciation formula.

6. Externalities / other costs
a. Elements as discomfort costs, CO2-mitigation costs etc. are not incorporated in the LCC-calculation. Environmental impact will be discussed using an LCA.

b. Extra investment costs for sustainability can be incorporated. This mainly addresses the saving of water, the use of ecologic materials, … These topics are not specifically addressed here.

The following economic parameters are used in the case study.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period of analysis</td>
<td>30 years**</td>
</tr>
<tr>
<td>Base date</td>
<td>March 2008</td>
</tr>
<tr>
<td>Market interest rate</td>
<td>5 %</td>
</tr>
<tr>
<td>Inflation (excluded from calculations)</td>
<td>2%</td>
</tr>
<tr>
<td>Real interest rate (used in calculations)</td>
<td>2.98 %</td>
</tr>
<tr>
<td>VAT for renovation</td>
<td>6%</td>
</tr>
<tr>
<td>VAT new construction</td>
<td>21%</td>
</tr>
<tr>
<td>Energy costs</td>
<td></td>
</tr>
<tr>
<td>Natural gas</td>
<td>0.066 €/kWh</td>
</tr>
<tr>
<td>Oil</td>
<td>0.074 €/kWh</td>
</tr>
<tr>
<td>Electricity</td>
<td>0.160 €/kWh</td>
</tr>
<tr>
<td>Pellets</td>
<td>0.050 €/kWh</td>
</tr>
<tr>
<td>Yearly increase of energy costs above inflation</td>
<td>+ 4%/year**</td>
</tr>
</tbody>
</table>

**alternative scenarios verified in sensitivity analysis

Table 12 - Overview of economic parameters used
It should be clearly noted that the prices used are only approximations. Real prices will vary from project to project.

It is also important to note that the presented results are only valid for this particular case, considering the boundary conditions presented, and are not necessarily valid for other cases.

5.2 LIFE CYCLE COSTS OF ALTERNATIVES WITH VARYING HEAT DEMAND - FIXED ENERGY VECTOR

In first instance the 4 alternatives containing a gas installation for heating and hot water production are compared: SR-Gas, LE-Gas, VLE-Gas and PH-Gas. These 4 scenarios differ in insulation materials and thicknesses, ventilation system and air tightness efforts. The resulting life cycle costs over 30 years are shown below.

The life cycle costs are summarized in the table below.

<table>
<thead>
<tr>
<th></th>
<th>SR-Gas</th>
<th>LE-Gas</th>
<th>VLE-Gas</th>
<th>PH-Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment cost</td>
<td>82,925</td>
<td>104,128</td>
<td>120,172</td>
<td>127,438</td>
</tr>
<tr>
<td>Envelope</td>
<td>80,182</td>
<td>92,992</td>
<td>108,625</td>
<td>117,853</td>
</tr>
<tr>
<td>Installations</td>
<td>2,743</td>
<td>11,136</td>
<td>11,547</td>
<td>9,585</td>
</tr>
<tr>
<td>Energy Consumption (30y)</td>
<td>99,471</td>
<td>51,861</td>
<td>40,462</td>
<td>31,771</td>
</tr>
<tr>
<td>Maintenance &amp; Replacement (30y)</td>
<td>8,055</td>
<td>7,479</td>
<td>7,586</td>
<td>7,345</td>
</tr>
<tr>
<td>Net Present Value</td>
<td>190,451</td>
<td>163,469</td>
<td>168,219</td>
<td>166,555</td>
</tr>
<tr>
<td>------------------</td>
<td>---------</td>
<td>---------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td>Financial incentives</td>
<td>5,553</td>
<td>8,494</td>
<td>9,994</td>
<td>16,753</td>
</tr>
<tr>
<td>Netto NPV</td>
<td>184,898</td>
<td>154,975</td>
<td>158,225</td>
<td>149,801</td>
</tr>
</tbody>
</table>

Table 13 – Summary of costs during analysis period

The table shows that:

- Investment costs are higher when striving for lower energy consumption. This is due to a higher insulation level and thus a higher cost for the envelope. The costs for installations however, do not follow the same trend. The installation cost for the SR-Gas-scenario is low, since the existing gas boiler is only replaced after 10 years, which is reflected in the higher replacement costs for SR-Gas. The LE-Gas scenario has a less expensive ventilation system, but this is compensated by the need for more radiator power. Therefore, the costs for installations in the VLE-Gas scenario (with a system D & heat recovery) are of the same order due to the need of fewer radiators. The PH-Gas installation costs are even lower, since space heating here is done with batteries on the ventilation, and no longer with radiators.

- Since the energy consumption lowers from SR-Gas to PH-Gas, it is logical that the costs for energy consumption lower as well.

- Looking at the maintenance and replacement costs, it is clear that for the 3 more ambitious scenarios, the costs will be more or less alike, since the investment cost is also in the same order of magnitude, and the replacement cost and maintenance cost are function (a certain percentage) of the investment cost.

- When adding these 3 cost elements together to calculate the Total Present Value, one sees that the LE-Gas option turns out to be the most viable option over 30 years (163500€), before the PH-Gas (166500 €) and the VLE-Gas (16800 €), in the given conditions (5% discount rate, 4% yearly increase in energy costs). The differences are rather small (all 3 alternatives in a range of ±5000 €). Only the SR-Gas scenario, with a bad energy saving performance scores a lot worse.

- When taking into account primes and more specifically the fiscal deduction over 10 years for a certified passive house (assuming this is the case), the table shows that the “Netto NPV” is the lowest for the PH-Gas alternative, due to the ±7000 € higher financial incentives (tax deductions for passive houses).

- The VLE-alternative is never the best option. It can be considered as a suboptimal solution.

The accumulated life cycle cost is shown in the graph below.
Figure 30 - Discounted accumulated life cycle cost for 4 considered alternatives (left = without financial support, right = with support)

The pay-back time for the 3 ambitious scenarios against the SR-Gas scenario is summarized in the table below, showing the influence of the financial stimuli.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>No financial stimuli</th>
<th>With financial stimuli</th>
</tr>
</thead>
<tbody>
<tr>
<td>LE-Gas</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>VLE-Gas</td>
<td>17</td>
<td>14</td>
</tr>
<tr>
<td>PH-Gas</td>
<td>19</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 14 - Dynamic Pay-Back Time for alternatives considered

Another aspect shown is that the pay-back time gives a different order of ‘best options’ than the NPV-calculation over 30 years.

5.3 LIFE CYCLE COSTS OF SCENARIOS FIXED HEAT DEMAND - VARYING ENERGY VECTOR

In a second phase, the influence of installing different techniques for heating and domestic hot water production is investigated. It should be noted that the calculations for energy consumption were performed with the EPB-software Vlaanderen and are for some elements approximate.

1) Influence of solar boiler for hot water production in LE-Gas and VLE-Gas scenarios

The life cycle costs are summarized in the table below.

<table>
<thead>
<tr>
<th>€</th>
<th>LE-Gas</th>
<th>VLE-Gas</th>
<th>LE-GasSun</th>
<th>VLE-GasSun</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment cost</td>
<td>104,128</td>
<td>120,172</td>
<td>110,263</td>
<td>126,359</td>
</tr>
<tr>
<td>Envelope</td>
<td>92,992</td>
<td>108,625</td>
<td>92,992</td>
<td>108,625</td>
</tr>
<tr>
<td>Installations</td>
<td>11,136</td>
<td>11,547</td>
<td>17,271</td>
<td>17,734</td>
</tr>
<tr>
<td>Energy Consumption (30y)</td>
<td>51,861</td>
<td>40,462</td>
<td>40,260</td>
<td>28,860</td>
</tr>
</tbody>
</table>
It is clear from the table that the extra cost for the installation of the solar boiler (+6000 €) and its maintenance & replacement (+2600€) are largely compensated by the lower energy costs (-11600 €) and the extra prime (-2000€).

2) Different heat and hot water production systems in the PH-configuration

With the same costs for the envelope, different installations can be applied in the PH-configuration, as described in paragraph 2.2. The costs are summarized in the table below.

<table>
<thead>
<tr>
<th></th>
<th>PH-Gas</th>
<th>PH-GasSun</th>
<th>PH-PelletSun</th>
<th>PH-Elect</th>
<th>PH-ElectSun</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Investment cost</strong></td>
<td>127,438</td>
<td>133,625</td>
<td>138,541</td>
<td>124,764</td>
<td>131,734</td>
</tr>
<tr>
<td><strong>Envelope</strong></td>
<td>117,853</td>
<td>117,853</td>
<td>117,853</td>
<td>117,853</td>
<td>117,853</td>
</tr>
<tr>
<td><strong>Installations</strong></td>
<td>9,585</td>
<td>15,772</td>
<td>20,687</td>
<td>6,910</td>
<td>13,881</td>
</tr>
<tr>
<td><strong>Energy Consumption (30y)</strong></td>
<td>31,771</td>
<td>20,170</td>
<td>17,285</td>
<td>48,963</td>
<td>30,429</td>
</tr>
<tr>
<td><strong>Maintenance &amp; Replacement (30y)</strong></td>
<td>7,345</td>
<td>10,013</td>
<td>13,326</td>
<td>4,594</td>
<td>8,063</td>
</tr>
<tr>
<td><strong>Net Present Value</strong></td>
<td>166,555</td>
<td>163,809</td>
<td>169,152</td>
<td>178,321</td>
<td>170,227</td>
</tr>
<tr>
<td><strong>Financial incentives</strong></td>
<td>16,753</td>
<td>18,785</td>
<td>18,185</td>
<td>16,153</td>
<td>18,185</td>
</tr>
<tr>
<td><strong>Netto NPV</strong></td>
<td>149,801</td>
<td>145,024</td>
<td>150,967</td>
<td>162,168</td>
<td>152,042</td>
</tr>
</tbody>
</table>

Table 16 - Life cycle costs of different PH alternatives

The investment costs for the envelope are the same in all alternatives. The costs for installations differ however. From the table it is clear that the alternative using a more expensive pellet stove and a (larger) solar boiler results in a higher investment cost compared to the alternative with a solar boiler and a gas installation (+5000 €). The gain from the lower energy consumption cost (due to the lower unit price of pellets compared to gas) is lost in the extra costs for maintenance and replacement (more expensive investment results in higher maintenance cost and replacement cost) of the pellet stove.

The electric alternatives are cheaper in investment and maintenance+replacement costs compared to the PH-Gas alternatives, but due to the much higher unit cost for electricity compared to gas, the energy consumption cost is a lot more elevated, resulting in an overall negative result.

Without taking into account the financial incentives, the order of the considered alternatives in terms of cost efficiency is:

1. PH-GasSun
2. PH-Gas
3. PH-PelletSun
4. PH-ElectSun
5. PH-Elekt

The same order is valid when considering primes. The results however, lie in the same order of magnitude (the differences are small). Sensitivity analysis should check the results for robustness.

![Graph showing life cycle costs of different PH alternatives](image)

**Figure 31 - Life cycle costs of different PH alternatives**

### 5.4 Life Cycle Costs of All Scenarios

**Overview of results**

![Graph showing life cycle cost, incl. financial incentives of all alternatives considered](image)

**Figure 32 - Life cycle cost, incl. financial incentives of all alternatives considered**
The graphs show that the order of cost efficiency changes when financial stimuli are taken into account. Without primes and fiscal deductions, the LE-GasSun alternative scores best. With financial stimuli included, the PH-alternatives become more interesting, with PH-GasSun as best option.

The graphs also show that the NPV of the most alternatives lies in the same rather small range of ± 10000 €.

Therefore, more detailed analysis is carried out, showing the relations between investment cost and total cost.

**Investing in cost efficiency**

1) Investment cost and life cycle cost without financial stimuli
The optimal curve of investment vs. total cost is shown and formed by the alternatives having the lowest combination of the 2 indicators (pareto-principle).

Without taking financial stimuli into account, the ideal curve goes from SR-Gas over LE-Gas to LE-GasSun. This alternative shows the lowest total cost. Higher investments, towards VLE or PH-alternatives do not show additional benefit on life cycle costs and thus are not efficient.

The VLE-alternatives are competitive to the PH-alternatives, when fiscal deductions are not taken into account. It is possible that there is an alternative LE/VLE-optimum further than LE-SunGas, before the curve goes up again towards PH-alternatives, but this option was not identified.

The solar alternatives score better than the alternatives without solar system (for LE, VLE and PH, Gas & Elect): more investment leads to a better cost efficiency.
2) Investment cost and life cycle cost with financial stimuli

Figure 35 - Investment cost vs. Total Present Value, with financial grants
When considering the net costs (investment & total cost with inclusion of financial grants) the optimum lies further on the investment curve: PH-GasSun becomes the most interesting alternative in terms of cost efficiency. However, to achieve this point, an extra net investment of 15000 € is needed for an additional cost efficiency of 5000€, compared to the LE-GasSun alternative.

In this context, the VLE-alternatives are suboptimal. The investment compared to the energy savings is too high, due to the lower fiscal deductions compared to the PH-alternatives.

The alternatives on electricity are not competitive, with/without subsidies, because of the higher energy costs over 30 years.

**Sensitivity analysis: alternative economic scenarios**

The results above are calculated with the following parameters: Discount rate 5% ; Energy prices raising 4%/year ; Analysis period 30 year.

Sensitivity of the results was checked using sensitivity analysis. The input parameters were varied and the influence on the results was investigated.

**Energy price raise**

![Figure 36 - Ranking of alternatives (from 1-10) for Net NPV (incl. Primes etc)](image)

The LE-alternatives get worse in the ranking with higher energy price raises (Rank 1 = best option, Rank 10 = worst)
Figure 37 - Net NPV in function of the yearly energy price rise for 5 alternatives

The LE-alternatives are more interesting with lower energy price raises, the PH-alternatives become the best options from 3%/year increase. The Pellet-alternative rises less fast than the alternatives on gas, due to the lower unit price for pellets compared to gas.

Period of analysis
Also the influence of the considered analysis period was analysed. The alternative options investigated are 20 and 40 years, for different price increase scenarios.

Figure 38 - Ranking of alternatives using different analysis periods

In high-rise scenarios for energy, the ranking of the alternatives is independent of the analysed period (right figure).
The other two ranking-figures (2%/y and 4%/y) show that the ranking of the LE options gets worse and that of the PH-Gas & -Pellet alternatives gets better, due to the higher influence of energy costs when a larger period of analysis is considered.

**Sensitivity analysis: other aspects**

**Energy consumption (cost)**

As already mentioned, the calculations for energy consumption were executed using the Flemish EPB-software. This software is used to obtain a characteristic primary energy consumption level. The method implies some simplifications and assumptions, which results in a energy consumption that is not the same as the actual consumption measured in real houses. However, no clear evidence or better figures exist in how to correct the calculated consumption to a more realistic energy use. Therefore, it was decided to do no sensitivity analysis on this part.

**Rest value**

For information, the calculated discounted rest value of the replaced elements (installations) over 30 years is given in the table below, compared to the net NPV. The order of the scenarios’ cost efficiency hardly change. Only the PH-Gas alternative becomes less interesting than LE-GasSun & PH-PelletSun due to the rest value of the (renewed) solar boiler after 30 years.

<table>
<thead>
<tr>
<th></th>
<th>SR-Gas</th>
<th>LE-Gas</th>
<th>VLE-Gas</th>
<th>PH-Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net NPV</td>
<td>184,898</td>
<td>154,975</td>
<td>158,225</td>
<td>149,801</td>
</tr>
<tr>
<td>RV Replaced</td>
<td>0.0</td>
<td>865</td>
<td>732</td>
<td>732.3</td>
</tr>
<tr>
<td>elements</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>184,898</td>
<td>154,110</td>
<td>157,493</td>
<td>149,069</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>LE-</th>
<th>VLE-</th>
<th>PH-</th>
<th>PH-</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GasSun</td>
<td>GasSun</td>
<td>PelletSun</td>
<td>ElektSun</td>
</tr>
<tr>
<td>Net NPV</td>
<td>150,068</td>
<td>153,448</td>
<td>145,024</td>
<td>150,967</td>
</tr>
<tr>
<td>RV Replaced</td>
<td>2,518</td>
<td>2,430</td>
<td>2,430</td>
<td>3,013</td>
</tr>
<tr>
<td>elements</td>
<td></td>
<td></td>
<td></td>
<td>780</td>
</tr>
<tr>
<td></td>
<td>147,550</td>
<td>151,018</td>
<td>142,594</td>
<td>147,954</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>161,388</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>149,564</td>
</tr>
</tbody>
</table>

Table 17 - Overview of rest value of different scenarios

6. **COMBINING COSTS AND ENVIRONMENTAL IMPACT FOR OPTIMAL DECISION MAKING**

6.1 **INVESTING IN A LOWER ENVIRONMENTAL IMPACT**

When we consider the global environmental impact (Eco-indicator 99 score) over 30 years for the analysed alternatives and compare this to the investment cost, the curve shows that investing in more energy savings and renewable energy is beneficial for the environment.
Figure 39 - Environmental impact vs total investment for considered alternatives

Without subsidies, only the PH-Gas and the PH-GasSun are not on the pareto-front. This is due to the lower investment cost and lower global environmental impact of the PH-alternatives on electricity.

Figure 40 - Environmental impact vs net investment for considered alternatives

With subsidies, the VLE-alternatives are not on the pareto front, due to the higher net investment cost compared to the more energy efficient PH-alternatives.

6.2 THE OPTIMAL SOLUTION FOR COST EFFICIENCY AND ENVIRONMENTAL IMPACT

A last balance in decision making can be made between cost efficiency (life cycle cost) and environmental impact. Therefore, the life cycle costs are compared to the global environmental impact over 30 years.

1) Without financial stimuli
Three points are ‘not-dominated’: PH-PelletSun (lowest environmental impact), LE-GasSun (lowest Total Present Cost) and in between the PH-GasSun alternative. There is no unique optimum. However, the cost efficiency for the most alternatives is comparable, while the difference in environmental impact (Eco-indicator 99 score) is larger. This becomes clear when the results are ‘normalised’ against the SR-Gas scenario which scores worst for both criteria (Total Present Value & EcoPoints). The lowest Total Present Value is 80% of the value of SR-Gas, while the lowest Environmental Impact is only 28% of the Impact of SR-Gas.

This is of course the case when environmental impact and cost efficiency are considered to be equally important.
Figure 42 - Normalised results of Cost efficiency vs. Environmental Impact
2) Net results with financial stimuli

This leads to similar results. The LE-GasSun alternative is no longer on the optimal curve, due to a shift in cost efficiency, caused by fiscal deductions for PH-alternatives.

Figure 43 - Net present value vs. Environmental impact of alternatives considered

The 3 decision criteria can be shown together in one graph with LCC and LCA-results on the Y-axes (costs left axis - red, ecopoints right axis - blue), in function of the investment cost (X-axis)
The graphs clearly indicate that from the point LE-GasSun on (full circle) the Total Costs don’t go down substantially anymore, when extra investing. When financial stimuli are taken into account, the PH-GasSun alternative has the lowest total cost.

The environmental impact, due to the lower energy consumption keeps going down when extra investments in energy savings and renewable energy take place. The Total cost over 30 years stays more or less the same for the more ambitious alternatives.
7. CONCLUSIONS FROM THE CASE STUDY

It is clear that the presented results are only valid for the considered case and methodological choices:

- Row house with South orientation.
- Price levels and economic scenarios considered
- Assumptions and simplifications (lay-out, energy calculation,...)
- ...

and that the results do not represent a general conclusion or indication for other projects.

From an environmental point of view, based on the aggregated eco-indicator 99 (H/A) score, it seems beneficial to ambition the passive house standard and to use renewable energies (solar system for hot water), as the additional impact from materials is quickly compensated by the savings in environmental impact resulting from the reduction in heat demand. This conclusion; however, is not valid for all impact categories, and may vary depending on the choice of LCIA method (mainly because of the negative effect of the electricity use for auxiliaries (e.g. mechanical ventilation system) on some environmental impact categories).

From an economic viewpoint, LowEnergy and PassiveHouse-alternatives show a similar cost efficiency. Without financial stimuli, the LE-GasSun (Low Energy, with Solar boiler) would be the best option. Taking into account financial stimuli (and especially the fiscal deductions for Passive Houses), the PH-GasSun alternative results as best alternative. However, most of the studied alternatives (LE – VLE – PH) score substantially better than the standard renovation (SR) and show a Total Present Value that lies in a rather small range, thus with a similar cost efficiency.

When combining costs and environmental impact, no single optimum can be identified: financially PH-GasSun is the best option but PH-PelletSun has the lowest eco-indicator99 score

For similar cost efficiency (LE & PH); however, large environmental benefits can be obtained, through more important energy savings (over 30 years). However, this implies an increase in initial investment which is not always easy to bear, even when additional financial incentives are present.
Conclusions

RESEARCH CONCLUSIONS
The literature review shows that a wide variety of methodological approaches exists when it comes to determining cost efficiency and environmental impacts of energetic retrofits of buildings. On the one hand, boundary conditions can be chosen to a certain degree (what is in- and excluded from the evaluation, which are the decision criteria, ...), on the other hand, data for evaluation is not always available, variable or is uncertain, especially when it comes to future forecasts. A clear and uniform methodology should be established in order to make results of different studies comparable.

Despite these varying methodological choices, some common conclusions can be drawn from the consulted studies:

- Energetic renovation measures are cost efficient. Applied measures result in cost savings in a rather short period (small pay-back time, good return on investment, annual savings)

- The optimal cost curve for individual insulation measures runs rather flat, which means that many solutions nearby the optimum have a similar cost efficiency, also going further than the optimum.

- The optimum U-value lies in many cases further than the legislative minimum requirement

- Depending on the methodology, data used and boundary conditions (costs included/excluded, eg. tax deductions; energy price scenarios) the optimum solution in terms of cost efficiency in projects is a ‘Low Energy’ renovation or even a Passive house renovation

- A recent Flemish study (3E, PHL, KUL, 2008) states that the most insulation measures have very low payback times (couple of years, max. 12.5 years), except window replacement. Optimal U-values for components are between 0.25 and 0.3 W/m²K for each opaque part of the envelope.

- From an environmental point of view, energetic renovation measures have a positive impact due to lower energy consumption during the use phase. However, this is not valid for all environmental impacts considered, especially not for measures implying a greater use of electricity (e.g. installation of a heat pump).

- Renovation is considered to be more efficient (for an environmental & financial point of view) than demolition and reconstruction, on condition that a thorough retrofit is technically possible (a good energy savings should be achievable).

The LCC-LCA analysis on the case study, although very specific (North-South oriented row house, experienced architect, expansion of living space) leads to similar conclusions.
Given the used boundary conditions and energy price levels, it is always interesting to renovate beyond standard practice. Indeed, from both the environmental and economical point of view, investing in advanced energy saving measures has a high potential in saving costs and environmental impact.

![Figure 46 - Cost efficiency of retrofit in function of energy savings (hypothetical graph)](image)

Which level of renovation (low energy, passive house standard,…) is economically most interesting depends on the boundary conditions of the conducted analysis:

- Costs included/excluded
- Scenarios assumed for energy prices, service lives, …
- Taking into account financial incentives or not
- Considering energy-relevant costs only or the total cost of renovation

For the studied row house, the cost efficiency between Low Energy, Very Low Energy and Passive House level were similar. A solar boiler proved to have a beneficial effect. Only the standard renovation scenario always scored worse (out of 10 scenarios considered).

Based on the results from the LCA study, it seems beneficial (for the given case) to strive to a lower heat demand level (passive house standard) and to use renewable energies (solar system for hot water and pellet furnace). However special care should be paid to the electricity consumption of auxiliaries (e.g. ventilation system, furnace, pumps) as the Belgian electricity supply mix has a negative effect on various impact categories which in some cases overrules the benefits of the reduced heat demand.

An optimisation of costs and environmental impact in one single scenario was not reached. The most environmentally friendly installations were less cost efficient. However, since the cost efficiency was similar for most alternatives considered, it could be interpreted that striving for a passive house standard renovation is better for the
environment at a similar cost efficiency. However, this requires a substantial extra initial investment (even when financial stimuli are taken into account).

**STEPS FORWARD**

This research has lead to an overview of existing knowledge on cost efficiency and environmental impact of energetic renovation, demonstrating its benefits and feasibility, also when striving for more ambitious levels like reaching passive house standard. Also in terms of methodology, further steps were taken in order to demonstrate differences and possibilities and evaluate the appropriateness of certain approaches.

The case studied has resulted in practical experiences with Life Cycle Costing and Life Cycle Analysis, using and developing tools and collecting data for the analysis. This has lead to some specific Belgian results in the field of cost efficiency and environmental impact of very ambitious retrofit projects. The work done should thus be considered as a first exploration in elaborating and applying a usable and sturdy methodology for cost efficiency analysis and environmental impact assessment on the building level.

The results are too limited to draw general conclusions. Therefore, further research could focus on obtaining additional results from other front running retrofit cases, to verify whether similar results are obtained and to identify most relevant parameters and choices that have an important influence on the final outcome.

The knowledge and experience on methodology will be used further in other projects where similar evaluations will be executed. An important follow-up aspect is the further harmonisation and standardisation of Life Cycle Costing and Life Cycle Analysis practice, in order to obtain comparable results in different projects.

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12 Pre-normatief onderzoek: Levenscycluskostenanalyse (LCC) voor de beoordeling van de economische prestatie van duurzame gebouwen, 2009-2011
PUBLICATIONS

CONFERENCE PAPERS

OTHER PUBLICATIONS

LEHR PRESENTATIONS
Delem, L., Vrijders, J., *Economic and environmental impact of a renovation to passif house standard*, LEHR final workshop, 18 November 2009, Brussels

OTHER PRESENTATIONS (AVAILABLE ON REQUEST)


REFERENCES


3E, KULeuven, PHL. (2008). Studie naar de economische haalbaarheid van het verstrengen van de EPB-eisen bij residentiële gebouwen. VEA.


CWA. (2007). CWA 15963 - Saving lifetimes of energy efficiency improvements measures in bottom-up calculations.

De Jonghe, T. (n.d.). Ecokosten doorgerekend - Nieuw bouwen of renoveren?


Klunder, G. (n.d.). Search for the most eco-efficient strategy for sustainable housing transformation.


Power, A. (2008). Does demolition or refurbishment of old and inefficient homes help to increase our environmental, social and economic viability?.


ANNEX - SUMMARY OF REVIEWED STUDIES

A summary (scope, methodology, data, results, conclusions) of all revised studies and articles considered in the LEHR-research part on cost efficiency can be obtained by contacting the author (Jeroen.Vrijders@bbri.be).
### ANNEX – OVERVIEW OF RETROFIT SCENARIOS-MATERIALS

Table 18 - Overview of the main building elements and their corresponding composition in function of the defined heat demand level (materials present prior to renovation are not listed)

<table>
<thead>
<tr>
<th>Material Type</th>
<th>SR-Gas</th>
<th>LE-Gas</th>
<th>VLE-Gas</th>
<th>PH-Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Outerwall (E)</strong></td>
<td>mineral plaster</td>
<td>rockwool 10cm + mineral plaster</td>
<td>mineral plaster</td>
<td>mineral plaster</td>
</tr>
<tr>
<td>outside</td>
<td>gypsum plaster</td>
<td>gypsum plaster</td>
<td>14cm cellulose in wooden frame vapour barrier</td>
<td>24cm cellulose between FJI joists</td>
</tr>
<tr>
<td>inside</td>
<td></td>
<td></td>
<td>wooden lathwork+6cm wood wool</td>
<td>wooden lathwork+6cm wood wool</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>gypsum fibre board</td>
<td>gypsum fibre board</td>
</tr>
<tr>
<td><strong>Floor (E)</strong></td>
<td>floor covering*</td>
<td>floor covering*</td>
<td>floor covering*</td>
<td>floor covering*</td>
</tr>
<tr>
<td></td>
<td>OSB 18mm 10 cm rockwool between beams</td>
<td>OSB 18mm 15 cm rockwool between beams</td>
<td>cement fibre board</td>
<td>cement fibre board</td>
</tr>
<tr>
<td></td>
<td>gypsum fibre board</td>
<td>gypsum fibre board</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Common wall (E)</strong></td>
<td>gypsum plaster</td>
<td>gypsum plaster</td>
<td>wooden lathwork+6cm wood wool</td>
<td>9cm cellulose in wooden frame vapour barrier</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>gypsum fibre board</td>
<td>gypsum fibre board</td>
</tr>
<tr>
<td><strong>Inclined roof (E)</strong></td>
<td>zink</td>
<td>zink</td>
<td>zink</td>
<td>zink</td>
</tr>
<tr>
<td></td>
<td>water barrier</td>
<td>water barrier</td>
<td>water barrier</td>
<td>water barrier</td>
</tr>
<tr>
<td></td>
<td>wood panel 22mm</td>
<td>wood panel 22mm</td>
<td>wood panel 22mm</td>
<td>wood panel 22mm</td>
</tr>
<tr>
<td></td>
<td>bituminised soft fibreboard 22mm</td>
<td>bituminised soft fibreboard 22mm</td>
<td>bituminised soft fibreboard 22mm</td>
<td>bituminised soft fibreboard 22mm</td>
</tr>
<tr>
<td></td>
<td>wooden structure +14 cm rockwool</td>
<td>wooden structure +22 cm rockwool</td>
<td>wooden structure in FJI +30 cm cellulose</td>
<td>wooden structure in FJI +35 cm</td>
</tr>
<tr>
<td></td>
<td>vapour barrier</td>
<td>vapour barrier</td>
<td>vapour barrier</td>
<td>cellulose</td>
</tr>
<tr>
<td></td>
<td>gypsum plaster board</td>
<td>gypsum plaster board</td>
<td>gypsum plaster board</td>
<td>gypsum plaster board</td>
</tr>
<tr>
<td><strong>Outerwall (N)</strong></td>
<td>mineral plaster</td>
<td>mineral plaster</td>
<td>mineral plaster</td>
<td>mineral plaster</td>
</tr>
<tr>
<td></td>
<td>8 cm rockwool</td>
<td>14 cm rockwool</td>
<td>soft fibreboard 6cm</td>
<td>soft fibreboard 6cm</td>
</tr>
<tr>
<td></td>
<td>brick 14cm</td>
<td>brick 14cm</td>
<td>14cm cellulose between wooden frame</td>
<td>24cm cellulose between FJI joists</td>
</tr>
<tr>
<td></td>
<td>gypsum plaster board on lathwork</td>
<td>gypsum plaster board on lathwork</td>
<td>OSB 18mm 6cm</td>
<td>OSB 18mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6cm wood wool between lathwork</td>
<td>6cm wood wool between lathwork</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>gypsum fibre board</td>
<td>gypsum fibre board</td>
</tr>
<tr>
<td><strong>Floor (N)</strong></td>
<td>hard wood flooring+substructure</td>
<td>hard wood flooring+substructure</td>
<td>hard wood flooring+substructure</td>
<td>hard wood</td>
</tr>
<tr>
<td></td>
<td>4cm floor covering (cement binder)</td>
<td>4cm floor covering (cement binder)</td>
<td>4cm floor covering (cement binder)</td>
<td>flooring+substructure</td>
</tr>
<tr>
<td></td>
<td>6cm PUR</td>
<td>10cm PUR</td>
<td>10cm PUR</td>
<td>OSB 22mm</td>
</tr>
<tr>
<td></td>
<td>reinforced concrete slab 15cm</td>
<td>reinforced concrete slab 15cm</td>
<td>reinforced concrete slab 15cm</td>
<td>24cm cellulose between beams</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>cement fibre board 18mm</td>
</tr>
<tr>
<td><strong>Flat roof</strong></td>
<td>EPDM cover</td>
<td>EPDM cover</td>
<td>EPDM cover</td>
<td>EPDM cover</td>
</tr>
<tr>
<td></td>
<td>SR-Gas</td>
<td>LE-Gas</td>
<td>VLE-Gas</td>
<td>PH-Gas</td>
</tr>
<tr>
<td>-------------------</td>
<td>---------------------------------------------</td>
<td>---------------------------------------------</td>
<td>--------------------------------------------</td>
<td>-------------------------------------------</td>
</tr>
<tr>
<td></td>
<td>sloped rockwool panel (14cm average)</td>
<td>22mm wood panel</td>
<td>22mm wood panel</td>
<td>22mm wood panel</td>
</tr>
<tr>
<td></td>
<td>vapour barrier</td>
<td>sloping layer in wood</td>
<td>sloping layer in wood</td>
<td>sloping layer in wood</td>
</tr>
<tr>
<td></td>
<td>22mm wood panel</td>
<td>22cm rockwool between wooden beams</td>
<td>30cm cellulose between FJI joists</td>
<td>35cm cellulose between FJI joists</td>
</tr>
<tr>
<td></td>
<td>wooden beam structure</td>
<td>vapour barrier</td>
<td>vapour barrier</td>
<td>vapour barrier</td>
</tr>
<tr>
<td></td>
<td>gypsum board</td>
<td>gypsum board</td>
<td>gypsum board</td>
<td>gypsum board</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glazing</td>
<td>double glazing (U&lt;1.1W/mk)</td>
<td>double glazing (U&lt;1.1W/mk)</td>
<td>Double glazing (U&lt;1.1W/mk)</td>
<td>Triple glazing (U&lt;0.5 W/mk)</td>
</tr>
<tr>
<td>Insulation staircase to the cellar</td>
<td>/</td>
<td>9.8cm polyurethane foam boards</td>
<td>9.8cm polyurethane foam boards</td>
<td>9.8cm polyurethane foam boards</td>
</tr>
</tbody>
</table>

(E) existing part (North), (N) new extension (South)

* Ceramic tiles for the toilet, kitchen, income hall, and technical room. Hard wood flooring in the other rooms.