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An environmental and economic impact comparison of renovation concepts for Dutch residential buildings

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Luc Dijkstra

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List of abbreviations

CED	Cumulative Energy Demand
CHP	Combined Heat and Power
CO_2	Carbon dioxide
C1	Renovation concept 1
C2	Renovation concept 2
C3	Renovation concept 3
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Coefficient
EI	Energy Index
EOL	End of life
EPS	Expanded polystyrene
EU	European Union
Eq.	Equivalent
FU	Functional unit
GHG	Greenhouse gas
GFA	Gross floor area
HCL	Hydrochloric acid
HHV	Higher Heating Value
J	Joule
kJ	Kilojoule (10^3 Joule)
MJ	Megajoule (10^6 Joule)
GJ	Gigajoule (10^9 Joule)
TJ	Terrajoule (10^{12} Joule)
PJ	Petajoule (10^{15} Joule)
kWh	Kilowatt hour (is equivalent to 3.6 MJ)
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LHV	Lower Heating Value
OSB	Oriented straight board
PAH	polycyclic aromatic hydrocarbons
PIR	Polyisocyanurate
PUR	Polyurethane
PVC	Polyvinyl Chloride
MCDA	Multi-criteria decision analysis
NaOH	Sodium hydroxide
NEN	Nederlandse Norm (Dutch standard)
NPC	Net Present Cost
NPV	Net Present Value
RD	Reference dwelling
SWH	Solar water heating
UF	Urea formaldehyde
UFA	Usable floor area or net internal area
VAT	Value added tax

Abbreviations used in equations

C	is the cost in year *n*
d	is the expected real discount rate per annum
K	Kelvin
m	meter
$\Delta MC_{CO_2-eq.}$	is the difference in CO_2 equivalent GHG-emissions between the baseline and renovation concept [kg CO_2-equivalent/m^2/year]
MC_{co2}	is the CO_2 equivalent mitigation costs in respect to baseline [EUR per kg avoided CO_2 –equivalent in respect to baseline]
n	is the number of years between the base date and the occurrence of the cost
NPC_{rc}	is the Net Present Cost of the renovation concept in [EUR/m^2/year]
$NPC_{baseline}$	is the Net Present Cost of the baseline in [EUR/ m^2/year]
p	is the period of the analysis
U	is the overall heat transfer coefficient [W/(m^2·K)]
R_c	is thermal resistance of a construction [m^2·K/W]
W	Watt

Abstract

In order to reduce the annual Dutch greenhouse gas emissions much can be gained by reducing the primary energy use of the Dutch residential building stock. The current average energy consumption of Dutch dwellings makes it difficult for the Dutch government to meet (inter) national agreements. A solution to this issue can be the renewal or renovation of the Dutch residential building stock. Since there are considerable more existing dwellings than newly built dwellings, and approximately 75% of the current Dutch residential building stock will still exist in 2050, this study focuses on renovation rather than renewal.

To show the differences between current policies and high ambition potential, a distinction is made between a low ambition renovation concept (inline with current policies) and high ambition renovation concepts. Based on the ambition levels three renovation concepts, named low ambition renovation concept, high ambition renovation concept and high ambition rebuilding concept, were defined. The three renovation concepts are compared with one another and with the current situation, and are evaluated on the four key performance indicators shadow cost, GHG-emissions, mineral resource depletion and net present cost. The key performance indicators are based on Life Cycle Assessment and Life Cycle Costing methods.

The overall conclusion of this study is that there is no single best solution in order to reduce the greenhouse emissions of the Dutch residential building stock. Because the best renovation solution depends on the stakeholders' environmental and economic point of view, desired lifetime extension, the current dwellings quality and the willingness of the inhabitants. From an environmental point of view a dwelling should always be renovated, with a preference for high ambition renovation. When the economic and cost-efficient greenhouse gas mitigation is more important, low ambition renovation is the best option.

In this study mainly the technical part of dwelling renovation is addressed. To implement dwelling renovation on a large scale in the Dutch residential building stock, social aspects of renovation also play an important role and need to be investigated. In order to achieve that the high ambition renovation concept is not solely interesting from and environmental point of view, as well as from an economic point of view, possible economic improvements on the cost of the renovation concept require further investigation.

1 Introduction

1.1 Background

The depletion of fossil fuels and the contribution they have on climate change when being combusted, compel us to a more sustainable society. The European Union (EU) has developed the “Europe 2020” growth strategy, in which climate change and energy sustainability both play a crucial role as one of the five main targets (European Commission, 2013). The EU has stated in “Europe 2020” the following ambition targets for climate change and energy sustainability:

- Greenhouse gas (GHG) emissions 20% lower in 2020 than 1990,
- 20% of energy from renewables, and
- 20% increase in energy efficiency.

From these EU ambitions targets, the GHG emissions 20% lower in 2020 than 1990 and 14% energy from renewables in 2020 have both become a policy measure in the Netherlands (Verhagen, 2012).

To reduce the Dutch CO_2-emissions[1], a major part can be gained by reducing the primary energy (fossil fuels) use of existing buildings (see figure 1). In particular the primary energy use for spatial heating as this was 660 PJ_{prim} in 2006 (for both utility and dwellings), which is 20% of the total primary energy consumption in the Netherlands (Menkveld & Beurskens, 2009).

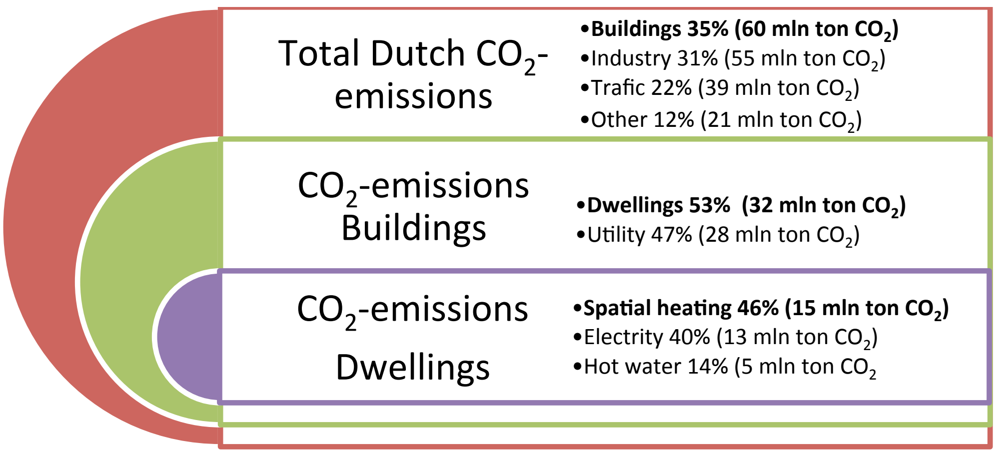

figure 1: Origin of Dutch annual CO_2-emission breakdown from national level, to building level and to dwellings level. Source: (Ecofys, 2005)

The energy consumption of buildings is not only significant in the Netherlands, but accounts for 40% of the total energy consumption in the European Union (European Commission, 2010). The European commission has therefore set energy performance guidelines in the Energy Performance of Buildings Directive (EPBD) for its member states. In the EPBD inter alia, the minimum energy performance

[1] CO_2 is one of the primary GHG emissions and is produced by combusting Carbon based fuels like natural gas, coal, oil and wood (IPCC, 2007).

requirement for new buildings is given and the building energy labelling scheme is introduced (European Commission, 2010).

To increase the energy performance and reduce the GHG-emissions of the existing Dutch residential building stock, the Dutch government defined in cooperation with different stakeholders the covenants “Meer met minder” and “Huurconvenant” (Rijksoverheid, Minister Spies: 'Vanaf 2020 nieuwbouw energieneutraal', 2012). These covenants make use of the EPBD labelling scheme to increase the energy performance of the dwellings.

“Meer met minder”
In the covenant “Meer met Minder” the Dutch government agreed with the construction-, energy suppliers- and building services unions upon two goals. To renovate at least 300,000 existing dwellings or other building types per year while increasing their energy label by at least two steps until 2020. They also try to stimulate investors in choosing sustainable energy measures.

“Huurconvenant”
In the covenant “Huurconvenant” the Dutch government agreed with the Dutch union of social housing corporations, the union of renting households and the union of private property investors upon two goals; In 2020 the total housing stock of social housing corporation should have an energy label B or higher (energy index[2] ≤ 1.25) and in 2020 at least 80% of the privately rented dwellings should have an energy label C or higher.

The covenants “Meer met Minder” and “Huurconvenant” will have two overlapping impacts on the current Dutch housing stock. First of all 2,400,000 existing dwellings or other buildings in the Netherlands will have to undergo a renovation and energy label increase of two steps before 2020. The total Dutch social housing stock, which is 32%[3] of the total Dutch dwelling stock, should have at least an energy index ≤ 1.25 in 2020.

These two covenants together with the “Lente-akkoord”[4] are part of the overall covenant “koepelconvenant energiebesparing gebouwde omgeving”. The goal of this overall covenant is to reduce the maximum energy use of both utility and residential buildings from 617 PJ in 2008 to 507 PJ in 2020 (Spies, et al., 2012).

[2] The energy index (EI) shows the energy performance of existing buildings as the energy performance coefficient (EPC) gives the energy performance of new buildings. It is a part of the building-labelling scheme. A low energy index score means a high-How lower the EI is how better the energy performance. Of the dwelling is. More information about the EI can be found in the report ISSO (2011).
[3] The Dutch social housing corperations owned 32% of the total Dutch residential building stock was 32% in 2011 source: (Rijksoverheid, Ontwikkeling woningvoorraad).
[4] The “lente-akkoord” convenant is for new buildings and “Meer met Minder” and “Huurconvenant” for existing buildings.

To increase the energy performance of the current Dutch housing stock is important, as approximately 75 per cent will probably still be a part of the Dutch housing stock in 2050 (PBL & ECN, 2011). Also the current average energy consumption of Dutch dwellings is too high to meet the existing climate targets (VROM-raad & Energieraad, 2004). Renovation can be a one of the solution for a more sustainable Dutch residential building stock.

1.2 Problem definition

Renewal of the current Dutch housing stock is needed in order to comply with (inter) national environmental agreements. Renovating these dwellings can be faster, less energy and GHG-emission intensive option than replacing them with the current available technologies (Pasztor, Rovers, & Vos-Effting, 2012). It is often unclear which renovation concepts (and materials) can best be used from an environmental and economic point of view. Therefore a comparison should be made between different existing renovation concepts, to find out how they score on different key performance indicators. This will give an insight in the current renovation concept bottlenecks and an idea how they can be further improved.

1.3 Research question

The main question arising from the need to reduce GHG-emissions in the Dutch housing stock by means of renovation, reads as follows:

“Which renovation concept(s) can best be used, from an environmental and economic point of view, when an Dutch dwelling is going to be renovated?”

To answer the main question, the following six separate sub-questions are formulated:

- *What type of dwelling would be a good representative of the Dutch residential building stock in need of renovation, to reduce the most (spatial heating related) GHG-emissions in the Dutch residential building stock? (See chapter 3)*
- *Which construction method and materials were used in the reference dwelling? (See chapter 3)*
- *What are the important key performance indicators to compare the renovation concepts upon? (See chapter 2)*
- *Which energy performance ambitions levels are interesting to be met by the renovation concepts? (See chapter 4)*
- *Which renovation concepts can best be used for the renovation of the reference building at the different ambitions levels? (See chapter 4)*
- *How do the different renovation concepts preform on the key performance indicators and what are the options for improvement? (See chapter 5 and 6)*

1.4 Research goal

The goal of this research is to get an insight in what kind of renovation concept for Dutch dwellings can best be pursed from an environmental and cost effective point of view, to meet (inter) national environmental agreements.

1.5 Reading guide

In chapter 2 the methodological approach is explained that is used to answer the research question. In this chapter the four key performance indicators that are used for the renovation concept comparisons are described, together with the used Life Cycle Assessment and Life Cycle Costing method. In chapter 3 an historical analysis of the Dutch residential building stock, the reference dwelling selection and reference dwelling description are described. The baseline scenario that is used to show the current situation during the comparison of the different renovation concepts is also described in chapter 3. In chapter 4 the three renovation concepts are described with their energy performance and environmental impact. In chapter 5 the three renovation concepts and the baseline scenario are compared with one another on the in chapter 2 defined key performance indicators. The improvement options of the renovation concepts are described in chapter 6. In chapter 7 the overall conclusion and recommendations are given.

2 Methodology

In this chapter the methodological approach that is used is explained in order to answer the research question. To designate a representative reference dwelling from the Dutch residential building stock a Multi Criteria Decision Analysis (MCDA) is performed (see section 2.1.1). The criteria defined for the MCDA are aimed at finding the most relevant reference dwelling for this study, which can be used to compare the different renovation concepts upon. The renovation concepts are compared (in chapter 5) with one another on the in this chapter defined key performance indicators (KPI's). The three defined environmental KPI's are based on the life cycle assessment method (see section 2.3), as the defined economic KPI is based on the life cycle costing method (see section 2.4).

2.1 Reference dwelling selection

In this study one reference dwelling was used to compare the different renovation concepts upon. To select a reference dwelling the in 2011 published report "Voorbeeld woningen 2011 bestaande bouw" (existing representative dwellings) was used. In this report 30 representative dwellings are defined[5], that represent the Dutch residential building stock.

In this section the MCDA methodology is described. The MCDA scoring and results are further elaborated in section 3.3.

2.1.1 Multi-criteria decision analysis

The MCDA method was used to select a reference dwelling that is most relevant in reducing the GHG-emissions of the Dutch residential building stock. The MCDA consists of five steps, as shown in figure 2.

figure 2: Summery five steps of a MCDA (multi-criteria decision analysis)

The five steps of an MCDA are further elaborated in the next paragraphs.

Step 1: Defining the criteria

In this step the criteria are defined on which the 30 representative dwellings of "Voorbeeld woningen 2011 bestaande bouw" are subjected to. The criteria need to have enough discriminatory power in order to create a distinction between the different representative dwellings.

[5] In appendix B the different representative dwellings and data are given from the report "voorbeeld woningen 2011 bestaande bouw".

Step 2: Defining the scores per criteria
The scores that the representative dwelling can obtain are listed per criteria. Per criteria there are five possibilities, which is an uneven number and therefore makes an average score possible.

Step 3: Defining weight factors
Not every criteria has the same importance, it is therefore necessary to distinguish between the different criteria by means of a weight factor. The weight factor is then multiplied with the score to get the weighted score per criteria.

Step 3: Assigning the scores
In step 3 the scores from step 2 are assigned per representative dwelling. When the scores are assigned per representative dwelling objectivity is important.

Step 4: Forming results
The scores of the representative dwelling per criteria are summed up to form a total score per representative dwelling.

2.2 Key performance Indicators

In chapter 5 the three different renovation concepts are compered on their environmental and economic performance. This comparison was based on the four key performance indicators (KPI's) described in this section.

The renovation concepts do not only have an impact on the environmental and economic performance during the use phase, but also during the construction and end of life phase. The KPI's should therefore be able to cope with the entire life cycle (construction phase, use phase and end of life phase) of the renovation concepts.

To evaluate the environmental impacts of a products from its "cradle", were raw materials are extracted from natural resources, through the production phase, use phase until its disposal, named "grave", the Life Cycle Assessment (LCA) is an accepted method (Bauman & Tillman, 2009). In the building sector Life Cycle Costing (LCC) is used to calculate the total cost over the entire lifecycle of a building (ISO, 2008). The LCA method is further elaborated in section 2.3 and the LCC in section 2.4.

Subsequently, the KPI's are selected from the LCA and LCC methods outputs. Not all possible LCA and LCC are relevant for this study. The outputs used as KPI's should be relevant and accepted in the building construction sector and useful for political decision-making. The KPI's should also be easily understandable for the relevant stakeholders; this will make the communication of the results easier. The four selected KPI's used for the comparison of the renovation concepts are shown in table 1. The KPI's are further elaborated in sections 2.2.1 until section 2.2.3.

table 1: Key performance indicators

Environmental comparison	**Unit**
- Shadow cost	[EUR]
- GHG-emissions	[kg CO_2-equivalent/kg emissions][6]
- Mineral resource depletion	[kg Sb-equivalent] and [US$]
Economic comparison	**Unit**
- Net present cost	[EUR]

The main environmental KPI used in this study was the shadow cost (see section 2.2.1), as this is the standard environmental indicator for Dutch buildings (Stichting bouwkwaliteit, 2011). The shadow cost also contains 13 different environmental impact categories under one single denominator. The other two environmental indicators, GHG-emissions (see section 2.2.2) and mineral resource depletion (see section 2.2.3), are part of the 13 different environmental impact categories used in the shadow cost. GHG-emission was selected as KPI because it is used in political decision-making on climate change. The depletion of mineral resources increases the price of building material. This can be an interesting indicator for construction companies to avoid using a lot of certain building materials to keep the future price of buildings down.

2.2.1 *Shadow cost*

In the Netherlands the environmental impact that a building has is measured in shadow cost, in accordance to the Stichting Bouwkwaliteit (2011) method. This method is developed for a uniformed environmental impact assessment of a buildings entire lifecycle. This is why the shadow cost is chosen as KPI for the environmental impact of the different renovation concepts.

The shadow cost incorporates 13 environmental impact categories (from the CML 2000 baseline[7] impact assessment method) under a single denominator (TNO & BECO, 2009). This single score represents the highest permissible environmental (prevention) cost level for the government per unit environmental damage that the government is still prepared to bear (TNO & BECO, 2009). The weighting factors, in shadow price [EUR/kg-eq.], used in the LCA per environmental impact can be found in the report Stichting Bouwkwaliteit (2011).

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[6] The Global warming potential in 100 years (GWP100) from the IPCC report (IPCC, 2007) is used to convert the GHG-emissions to CO_2-emissions in the LCA impact assessment method.
[7] The CML 2000 baseline is developed by the Institute of Environmental Sciences from Leiden University

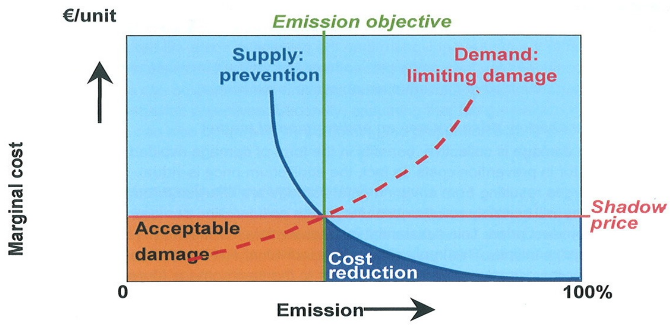

figure 3: Demand for limitation and supply of emission prevention on the virtual environmental market from an equilibrium price. If a government objective crosses the equilibrium point of demand and supply, the shadow price will under this objective be the same as the equilibrium price. Source: (TNO & BECO, 2009)

The thought behind the shadow price is the following:
"The cost of the environmental burden depends on the price that society is willing to pay for a clean environment and is related to the situation and moment. Generally speaking, the heavier the environmental burden, the greater the willingness to pay a higher price to limit environmental damage. In this way, a demand curve is created towards limiting environmental damage (see figure 3). A virtual environmental market. In addition to demand for emission restriction, there is a supply of emission prevention opportunities, which also has a particular price for each level of prevention. Generally speaking, the price increases the greater the reduction demanded. If there were to be a market for the environment, demand and supply would form an equilibrium price at the intersection of the curves of marginal damage limitation and marginal prevention cost." (TNO & BECO, 2009)

2.2.2 *GHG-emissions*

GHG-emission (climate change) is one of the environmental impact categories that is also incorporated in the shadow cost score. The weighting factor used to incorporate the GHG-emissions can be found in Stichting bouwkwaliteit (2011). The GHG-emissions, as shown in chapter 1, play a crucial role in (inter) national agreements and thus in political decision-making. Both "Meer met Minder" and "Huurconvenant" are based on these (inter) national GHG-emissions agreements. The effect that the different renovation concepts have on GHG-emissions is thus an important indicator for policy makers.

The GHG-emissions will also show the ratio between emissions produced by the renovation materials needed for the renovation concepts and the emissions that are avoided because of it. This will give an insight in the effectiveness of the renovation concepts in reducing GHG-emissions.

2.2.3 *Mineral resource depletion (excl. energy carriers)*

Mineral resource depletion is like GHG-emissions also part of the shadow cost score. The depletion of minerals is getting a more emerging debate. In some cases mineral depletion and limitations to the production capacity are driving up prices of raw materials (Steen, 2006). Resource depletion and shifts in material demand will have an impact on market prices. This often means that prices will go up, which could also negatively affect the ability to maintain and expend the man-made environment (Heijungs, et al., 2009)

The increase in mineral and thus material costs could be an interesting indicator for the construction sector. The construction sector has to pay a higher price for materials because of mineral resource depletion, while they also have an influence on the materials that they use. The construction companies can chose to avoid certain materials and only use them when they are needed, for example for important structural parts of the building.

The mineral depletion is shown in two different units [kg Sb-eq.] and [US$]. The general LCA impact assessment method used for this study (CML 2000 baseline) gives the mineral depletion in abiotic depletion [kg Sb-eq.]. This unit is not common for communication with the construction companies. That is why also a second impact assessment method (ReCiPe 2008[8]) was used, to express metal depletion in US dollars.

2.2.4 Net Present Cost

The capital investment required for the renovation and its cost reduction can be an important factor for an investor. The willingness to invest in a renovation usually depends on the benefits that the owner receives from it. The net present cost (NPC) will give an indication on which renovation is more economically beneficial over a certain time period. The costs that are incorporated in the NPC for this study can be found in section 2.4.

2.3 Life cycle assessment

The LCA (Life Cycle Assessment) is a quantitative method designed to evaluate the environmental impacts of a product from its “cradle” where raw materials are extracted from natural resources, through production and use phase, until its disposal named “grave” (Bauman & Tillman, 2009).

In the Netherlands an LCA determination method has been developed (based on the NEN 8006) to assess buildings and structures on their environmental performance. This way the LCA end results of Dutch buildings are based on the same methodological background. The guidelines of this method are shown in the report Stichting Bouwkwaliteit (2011).

In this study the determination method from Stichting Bouwkwaliteit (2011) was used for LCA, as this is the Dutch standard for LCA of buildings. For the LCA calculation the program SimaPro 7 was used. Both TNO and Utrecht University use SimaPro for their LCA calculations.

In accordance to the report Stichting Bouwkwaliteit (2011) the use of the CML 2000 baseline impact assessment method was required. For mineral depletion also the impact assessment method Recipe 2008 was used, as described in section 2.2.3. Recipe 2008 shows the metal depletion in US dollars instead of kg Sb-eq. as in CML 2000 baseline.

[8] ReCiPe 2008 impact assessment method is devolved by the consortium of RIVM (National Institute for Public Health and the Environment), CML (Institute of Environmental Sciences, Leiden University), Pré Concultants and Radboud University Nijmegen

2.3.1 *Functional unit and system boundaries*

The functional unit must allow quantifying the service given by the dwellings renovation in order to use it as a basis for comparison. The functional unit chosen for this study was the following one:

"Renovation concept that increases the energy performance and lifetime extension of a residential dwelling in the Netherlands expressed per m^2 usable floor area and per year of the total dwelling's lifespan."

The functional unit was chosen in such a way that it allows for possible future comparison with different Dutch dwellings and renovation concepts. To account for the different sizes of dwellings the functional unit is expressed in 1 m^2 of usable floor area. The lifespan of the dwelling is expressed per year, because the renovation concepts have different lifetime expectancies.

For the functional unit the materials are divided by the actual years that they were used during the total lifetime of the dwelling[9]. For example, if the façade of the reference dwelling is demolished during the renovation concept, it was only used for 55 years (current age reference dwelling). When the façade remains part of the dwelling after the renovation, it is used for 55 years + the lifetime extension of the renovation concept (5, 15 or 50 years). In figure 4 a graphical illustration is shown.

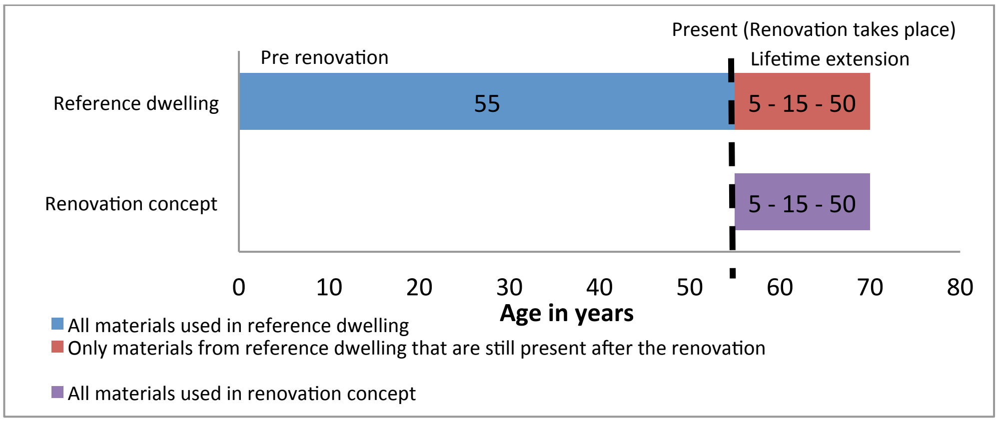

figure 4: Graphical illustration of how the years of the reference dwelling and renovation concepts are used in the functional unit. The lifetime extension of the baseline scenario and renovation concepts differs between 5, 15 and 50 years.

The system boundary of the LCA was cradle to grave. This includes the production, use and end of life (EOL) phase of the dwellings lifetime. In table 2 the process considered are mentioned.

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[9] Only the transport contributions of the concrete roof tiles in renovation concept 3 and limestone's used for the facade in renovation concept 2 are divided by the age of the reference dwelling and not reference dwelling + lifetime extensions. This was not possible because of how the renovation concepts where modelled in SimaPro.

table 2: LCA phase, processes considered and source used

Description	Process considered	Source(s)
Production (and renovation) phase	Extraction, processing and transportation and construction of materials.	Ecoinvent v2.2 database
Use phase	Spatial heating and auxiliary electricity use (for ventilation and boiler).	Ecoinvent v2.2 database and Energy use calculations from the program Vabi EPA-W
End of life	Deconstruction and sorting, Transportation of materials and Recycling, incineration or/of disposal of materials.	Ecoinvent v2.2 database, Stiching bouwkwaliteit (2011) and NEN 8006

The different processes that interact with the environment are accounted for in the LCA and can be found in the process tree in figure 5. The system boundaries are also shown.

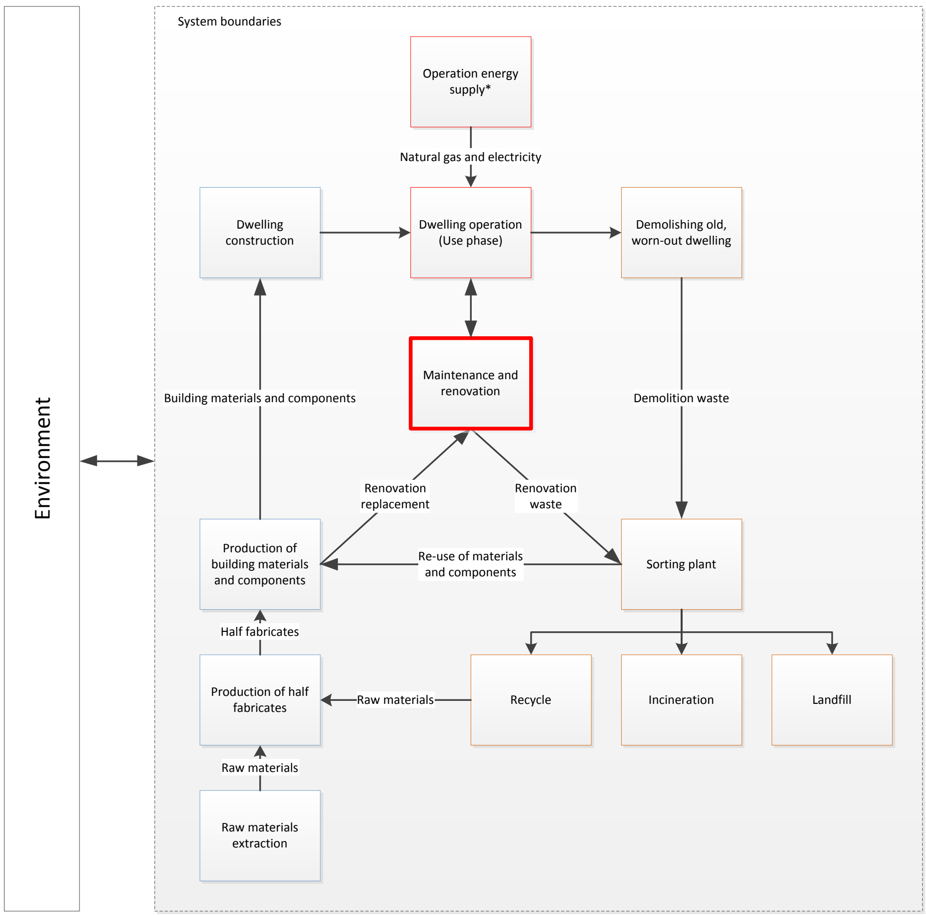

figure 5: Process tree renovation concepts. *In the operation energy supply only the spatial heating energy and electric auxiliary energy are taken into account. The building phase is in blue, the use phase in red and the EOL phase in brown. Own adaptation of (Nieuwlaar, 2012)

2.3.2 *Data and assumptions*

The data that were used for the building materials of the reference dwelling and different renovation concepts come from literature research and supplier information. Further information about these data and assumptions can be found in appendix D.

The energy use during the operational phase was calculated per renovation concept by the program Vabi EPA-W. This program will give an independent and constant end result based on the same parameters. The parameters used and the results from Vabi EPA-W are given in appendix D and E.

The end of life disposal was based on the NEN 8006. In this report the Dutch EOL disposal standards are shown for building materials.

In SimaPro the database ecoinvent v2.2 was used. The data in ecoinvent v2.2 are from the Swiss centre for life cycle inventories. The disadvantage of the ecoinvent database is that it is often based on Swiss or German production standards and it can be out-dated in some cases. Despite these disadvantages it is a widely accepted database in the LCA field for the Swiss and Western European situation. More information on the ecoinvent buildings products can be found in the report Kellenberg et al. (2007).

2.4 Life Cycle Costing

The life cycle costing (LCC) was based on the ISO (2008) report. In this report the international standard guidelines are given for LCC. The cost made in the past and the current value of the reference dwelling, have not been taken into account.

The results of the LCC method are given in the NPC (Net Present Cost) value. The NPC gives the sum of the discounted costs over the period of interest per renovation concept. The NPC was chosen because a renovation is often an investment to reduce the annual costs, while these are still costs and not benefits. The NPC was calculated by means of equation 1. For a social housing corporation the NPV (Net Present Value) could be preferred over NPC, because rent is a benefit and not a cost.

$$NPC = \sum_{n=1}^{p} \frac{Cn}{(1+d)^n}$$

Equation 1 Source: (ISO, 2008)

With:

- C is the cost in year *n*,
- *d* is the expected real discount rate per annum,
- *n* is the number of years between the base date and the occurrence of the cost, and
- *p* is the period of the analysis.

In line with ISO (2008) the real costs were used for the NPC calculation. This means that inflation and deflation were not taken into account and that current known values were used. The costs that had been taken into account were investment cost, replacement cost, energy cost and demolishing cost (see appendix F). The maintenance costs were not accounted for, as these data were not found during this study.

The discount rate used for LCC of buildings and constructions should be between 0% and 4% (ISO, 2008). In this study a discount rate of 3% was used. The same interest rate was provided by the Rabobank in the “033 energie” project in Amersfoort (Schotman, 2013), the social housing corporation Hestia also required 3% profitability for their renovation project “de bestaande wijk van morgen” (Rovers, 2012).

It was assumed that the increasing energy price trend from the past decade would continue in the future, due to fossil resources depletion (van Cann, 2011). The values used during the LCC method for natural gas and electricity are shown in table 3.

table 3: natural gas and electricity values used during LCC.

Description	Unit	Value	Source
Natural gas price	[EUR/m^3]	0.697	(CBS, 2013)
Electricity price	[EUR/kWh]	0.188	(CBS, 2013)
Annual price increase of natural gas	[%/year]	6.3	(van Cann, 2011)
Annual price increase of electricity	[%/year]	3.9	(van Cann, 2011)

The investment data used during the LCC came from literature research and supplier information. More information about the investment cost can be found in appendix F.

To calculate the NPC the different renovation concepts had been modelled in Microsoft excel. The end results are also shown in the same function unit as the LCA results (see section 2.3.1).

3 Reference dwelling

In this chapter the Dutch residential building stock is analysed. From this analysis one building type (from a certain time period) is selected as reference dwelling. The reference dwelling characteristics are described in this chapter together with the baseline scenario. The baseline scenario is used in chapter 5 during the comparison of the defined renovation concept to show the current situation.

3.1 Historical analysis of the Dutch residential building stock

The Dutch residential building stock consists of about 7.2 million dwellings in 2011 (Rijksoverheid, Volkshuisvesting Informatie Systeem, 2012). In figure 6 the Dutch residential building stock is divided into different characteristics[10]. The characteristics used in figure 6 give a general indication of how the Dutch residential building stock looks like.

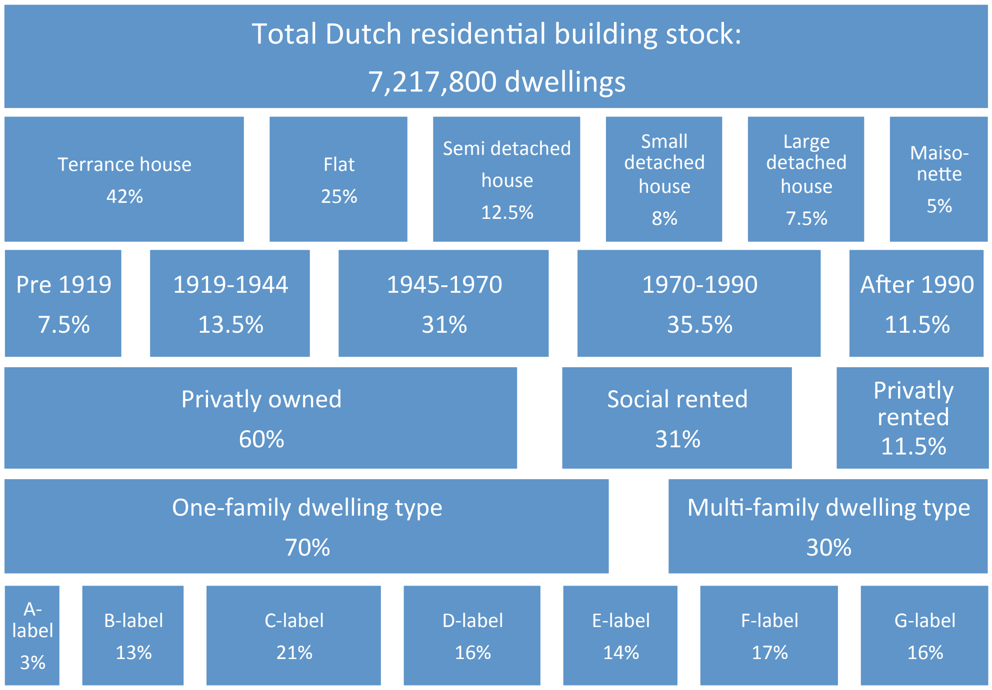

figure 6: Division of the total Dutch residential building stock in the following characteristics; building type, year, ownership, one or multi-family house and Energy-label. Sources: (W/E-adviseurs & PRC, 2011) (Rijksoverheid, Volkshuisvesting Informatie Systeem, 2012) (Rijksoverheid, Ontwikkeling woningvoorraad) (PRC Bouwcentrum & E/W adviseurs, 2006).

During the post war housing shortage the construction industry used standardization and scale to meet the at that time high housing demand (Bone A. , 2009). This resulted in the construction of many terrace houses and flats to house as many households as possible. During this period quantity was more important than the quality of the dwellings (Schouten, 2004).

[10] Dwelling type, building period, ownership, one- or multi-family dwelling and Energy label

After 1970 until 1987 the total amount of households grew rapidly in the Netherlands, with an increase of 49% (Boelhouwer, van der Heijden, & Papa, 1991). The reasons for this increase in households were the individualization process[11] of the Dutch society and a population increase of 14% during that time period (Boelhouwer, van der Heijden, & Papa, 1991). To cope with this increase in households (and thus housing demand) the Dutch residential building stock grew almost as rapidly as the amount of households (Boelhouwer, van der Heijden, & Papa, 1991).

In 1975 the first legislative requirements where made for roof and wall insulation during building construction (Bone A. , 2009). This was initiated by the Ministry of Economic affairs after the 1970s oil crisis's[12] (de Jong, Weeda, Westerwoudt, & Correlje, 2005). The legislative thermal insulation demands were changed almost every five years after 1975[13]. This eventually led to the current legislative thermal insulation demands in the "Bouwbesluit 2012" (building decree) (Knowmax & BRIS, n.d.).

From 1990 until 2007 there has been an increase of 1.4 million privately owned dwellings and a decrease of 200,000 rental dwellings (van Ewijk & ter Rele, 2008). This can be attributed to the privatization of Dutch social housing corporations[14] and the governmental promotion of home ownership (Schouten, 2004). The percentage of homeowners has since grown from 45% in 1990 to 60% in 2011 (Schouten, 2004).

In 1992 the first "Bouwbesluit" was introduced in the Netherlands. Through the "Bouwbesluit" the Dutch government is actively involved in the health, safety, usability, energy and environment requirements of buildings (unknown, Bouwbesluit, 2012). The Energy Performance Coefficient (EPC) for dwellings was in 1995 introduced in the "Bouwbesluit" (Bone A. , 2007). The EPC of dwellings is gradually lowered over time until it reaches zero. The EPC lowering instrument helps with the Governmental ambition of only building energy neutral dwellings in 2020 (Rijksoverheid, Energiebesparing, n.d.).

The energy performance of the current Dutch residential building stock can be roughly divided into three equally large sections. About one third has an Energy label A, B or C, one third has D or E and one third has F or G (PRC Bouwcentrum &

[11] The individualization process let to an increase of single households. This can be attributed to young adults whom leave their elderly homes quicker (and single), divorces and an aging society (Schnabel, n.d.).

[12] In the 1970's two oil crises occurred. The first oil cries in 1973 was caused by the OPEC oil export embargo because of the Yom Kippur war. The Iranian Revolution caused the second oil crisis in 1979. Source: (unknown, Energy crisis, 2013)

[13] In 1980; Floor $R_c \geq 1,3$ $m^2 \cdot K/W$, wall $R_c \geq 2.0$ $m^2 \cdot K/W$, roof $R_c \geq 2.0$ $m^2 \cdot K/W$ and double glass for living room and kitchen. In 1985; Floor $R_c \geq 1,3$ $m^2 \cdot K/W$, wall $R_c \geq 1.3$ $m^2 \cdot K/W$, roof $R_c \geq 1.3$ $m^2 \cdot K/W$ and double glass for living room and kitchen. In 1988; Floor $R_c \geq 1,3$ $m^2 \cdot K/W$, wall $R_c \geq 2.5$ $m^2 \cdot K/W$, roof $R_c \geq 2.5$ $m^2 \cdot K/W$ and double glass for all rooms. Source: (Bone A. , 2009)

[14] The secretary of state Heerma drafted in 1989 a note about the privatization of the Dutch social housing corporation in the 1990s. This note was as policy accepted in 1994 by the Dutch government. In order to keep economically viable in the long term the corporations built less new social houses, sell social rented houses, built more homes for homeownership, demolish social rented houses for more viable rentable houses, increase rent and participate in commercial projects. Source: (Schouten, 2004)

E/W adviseurs, 2006). Almost 70% of the pre-war dwellings and 50% of the dwellings built between 1946 and 1979 has currently an energy label F or G (PRC Bouwcentrum & E/W adviseurs, 2006).

Future developments in households

In the next 35 years the number of households will grow more rapidly than the population (Koenen, 2012). The increase in households is mainly caused by the increase in one-person households as shown in figure 7. The aging of the Dutch society mainly causes this increase in one-person household, but young singles and smaller families also influence this (Koenen, 2012).

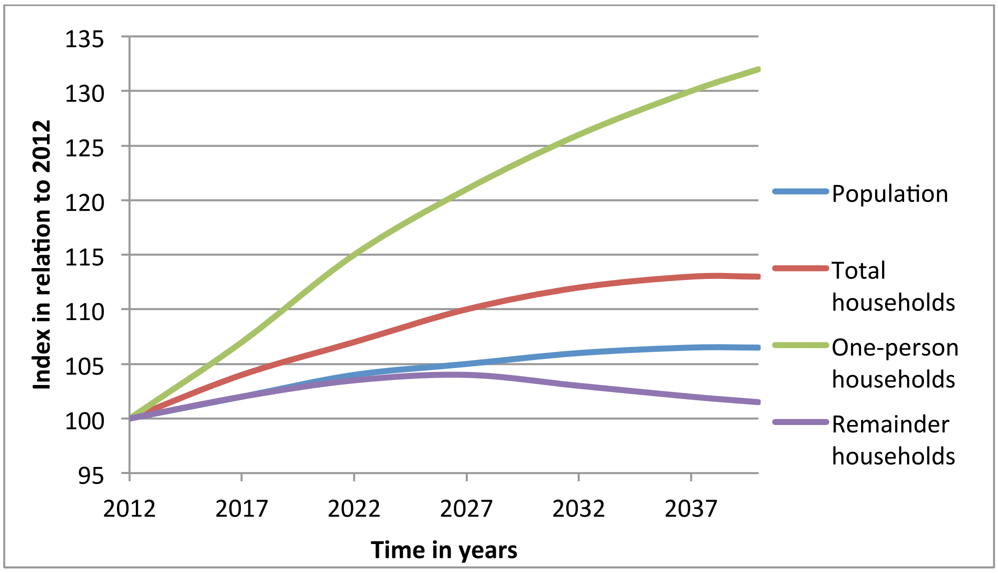

figure 7: Households and population development between 2012 and 2040 (index 2012=100) source: (Koenen, 2012)

Household's energy use for domestic heating

The changes and transitions that have occurred in Dutch dwelling stock, as mentioned before, also had an impact on the energy use for domestic heating. In figure 8 the energy use for domestic heating is shown per inhabitant from 1950 onwards.

The NAM (Nederlandse Aardolie Maadschappij) found in 1959 the large natural gas field "Slochteren" in the province Groningen. This led to the development of a large national gas grid in the Netherland, where almost all Dutch dwellings are connected on. Before the national gas grid mainly coal and gas stoves in the living room were used for spatial heating. The national gas grid enabled the large-scale deployment of central heating systems[15] for dwellings in the Netherlands. The gas boiler used for the central heating system gradually replaced the coal stoves, which caused a decline in the amount of coal used for domestic heating (see figure 8).

[15] The heat generated for the central heating system comes from (in the Netherlands) a gas boiler and is exchanged with a closed water system. The closed water system brings the hot water to radiators, placed throughout the dwelling, were the radiators heat up the room that they are in.

The implementation of the central heating systems in dwellings did led to an increase in energy use for domestic heating. Instead of only heating up the living room with a stove, the whole interior of a dwelling is heated up, which is more energy intensive.

Due to energy reduction measures (legislation, insulation and higher boiler efficiencies) the natural gas use per household has since 1980 dropped with 25 per cent (CBS, PBL & Wageningen UR , 2012).

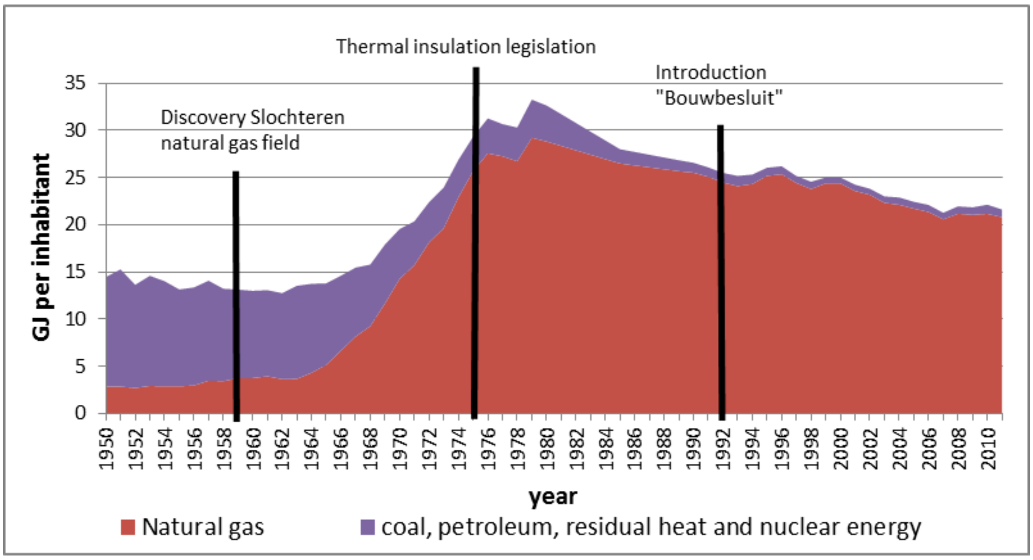

figure 8: Energy use for domestic heating per inhabitant of natural gas and coal (petroleum, residual heat and nuclear energy) in GJ. Source: (CBS, PBL & Wageningen UR , 2012)

3.2 Previous research

There has already been research done on renovating the Dutch residential building stock. In appendix A some of these studies are further elaborated. In this section only the conclusions of appendix A are mentioned.

In previous studies the main focus was on the terrace houses from the time period 1946 until 1965 and 1966 until 1975. They were mainly used as reference dwelling because of:

- A large amount has been built in the Netherlands,
- They are poorly insulated,
- A large portion is owned by the Dutch social housing corporation, and
- They all have almost the same structural appearance, which makes interchange ability and up scaling easier.

It was also concluded in the report Ecofys (2005) that the biggest CO_2-emissions reduction could be achieved in privately owned pre 1966 dwellings and post-war (rented) terrace houses pre 1980.

3.3 Selecting reference dwelling

In 2011 Agentschap NL[16] published the report "Voorbeeld woningen 2011 bestaande bouw" (existing representative dwellings). In this report 30 representative dwellings are defined[17], which represent the Dutch residential building stock. To select a reference building, the 30 representative dwellings from Agentschap NL with their information are used.

During previous studies the terrace dwellings from the time period 1946 until 1965 and 1966 until 1975 were mainly used (see section 3.2). To find out which dwelling type best meets the criteria for this research a multi-criteria decision analysis (MCDA) method is used. The MCDA methodology is described in section 2.1.1. The MCDA prioritizes the 30 representative dwellings on how they score per defined criteria.

To reduce the annual GHG-emissions of the Dutch residential building stock the reference dwelling should have a low energy performance and been built in large quantities. Renovation is also a way to counter the depreciation of a dwelling that occurs over time. An exterior renovation is a large investment that will mainly occur after 45 years (Nunen & van Bergen, 2011). For the reference dwelling the following criteria are defined:

1. Energy performance,
2. Age,
3. Quantity, and
4. Up scaling possibility.

The defined criteria, scoring and weight factor are further elaborated in section 3.3.1 until section 3.3.4.

3.3.1 Energy performance

The EPBD labelling scheme psychological effect promotes the renovation of dwellings with a low energy label. In figure 9 it is shown that this is the best path, as renovating a dwellings with poor insulation has a higher effectiveness on the energy use reduction than renovating an average insulated dwelling.

[16] Agentschap NL is an agency of the Ministry of Economic Affairs, which carries out governmental policies about innovation, energy, environment and international entrepreneurship.
[17] In appendix B the different reference dwellings are shown including their characteristics from the report "Voorbeeld woningen 2011 bestaande bouw".

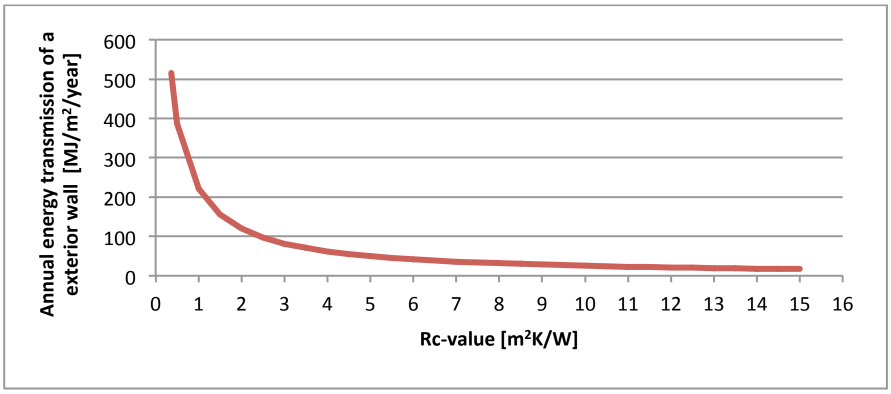

figure 9: Influence of R_c value on heat transmission of an exterior wall. Source: (Duijve, 2012)

The scores are based on the energy labels of the EPDB labelling scheme. These are also used in “Voorbeeld woningen 2011 bestaande bouw”. How lower the energy performance of the dwelling type is, the higher the score gets. The score per energy label is given in table 4. This criterion receives a weight factor 4 out of 4.

table 4: Categories description with score for the energy performance criteria

Name	Description	Score
Very high energy performance	Energy label A	1
High energy performance	Energy label B	2
Average Energy performance	Energy label C and D	3
Poor energy performance	Energy label E	4
Very poor energy performance	Energy label F and G	5

3.3.2 *Age*

Large renovations mainly occur to older dwellings that do not meet the current safety standards and inhabitants demands (the functional lifetime has ended). To increase the functional and technical lifetime of the dwelling a large capital investment is needed for renovation.

During the average 120-year lifetime of a Dutch dwelling it has on average a form of renovation every 15 years (Nunen & van Bergen, 2011). After the first 15 years the central heating boiler is replaced, after 30 years the toilet, restroom and kitchen and after 45 years the building’s exterior envelope is upgraded (Nunen & van Bergen, 2011). This means that mainly buildings older than 45 years will receive the necessary capital injection for a big renovation needed for the renovation concept in this study.

The need of renovation and the willingness to invest is higher for older dwellings than for new ones, thus how older how higher the score. For the scores the 15-year cycles are used from the report Nunen & van Bergen (2011) (see table 5). This criterion receives a weight factor 3 out of 4.

table 5: Categories description and score of the age criteria

Name	Description	Score
Minor maintenance	On average every 5 years	1
Replacing installations	On average every 15 years	2
Indoor renovation (toilet, bathroom, kitchen etc.)	On average every 30 years	3
High quality renovation (upgrading building's exterior envelope)	On average every 45 years	4
End of lifetime (demolishing or conservation)	On average at 120 years	5

3.3.3 *Quantity*

To make a real impact on GHG-emission reduction, not only a poor energy performance plays a role, but also the quantity. The reference dwelling should cover a large part of the Dutch residential building stock in order to have an big impact.

The scores are given for the amount of representative dwellings that have been built in the Netherlands. The score gets higher as more of the same dwelling type exists in the Dutch residential building stock (see table 6). This criteria receives a weight factor 2 out of 4

table 6: Categories description and score of the quantity criteria

Description	Score
< 150,000 houses	1
150,000 - 300,000 houses	2
300,000 - 450,000 houses	3
450,000 - 600,000 houses	4
> 600,000 houses	5

3.3.4 *Up scaling*

The possibility to upscale a renovation program in a district will cut the renovation costs down and could improve the participation within a district. It also ensures that a large part of the same dwellings are renovated in a short time period and not dispersed over a long time period. The scoring and description are shown in table 7. This criterion receives a weight factor 1 out of 4

table 7: Categories description and score of the up scaling criteria

Name	Description	Score
Very low	-Monument -Unique dwelling type (shapes)	1
Low	-Low density of the same dwelling type when build in an district -Not attached	2
Average	- Average density of the same dwelling type when build in an district	3
High	- High/average density of the same dwelling type when build in an district - Attached to neighbouring dwelling of the same type	4
Very high	-Very high density of the same dwelling type when build in an district -Attached to neighbouring dwellings of the same type	5

3.3.5 *MCDA results and reference dwelling selection*

The results from the MCDA are shown in figure 10. In appendix C the score given per representative dwelling is shown. The terrace house from 1946 until 1964 and terrace house pre 1946 both score the best on the defined criteria. They are closely followed by the terrace house from 1965 until 1974 and the detached house pre 1964.

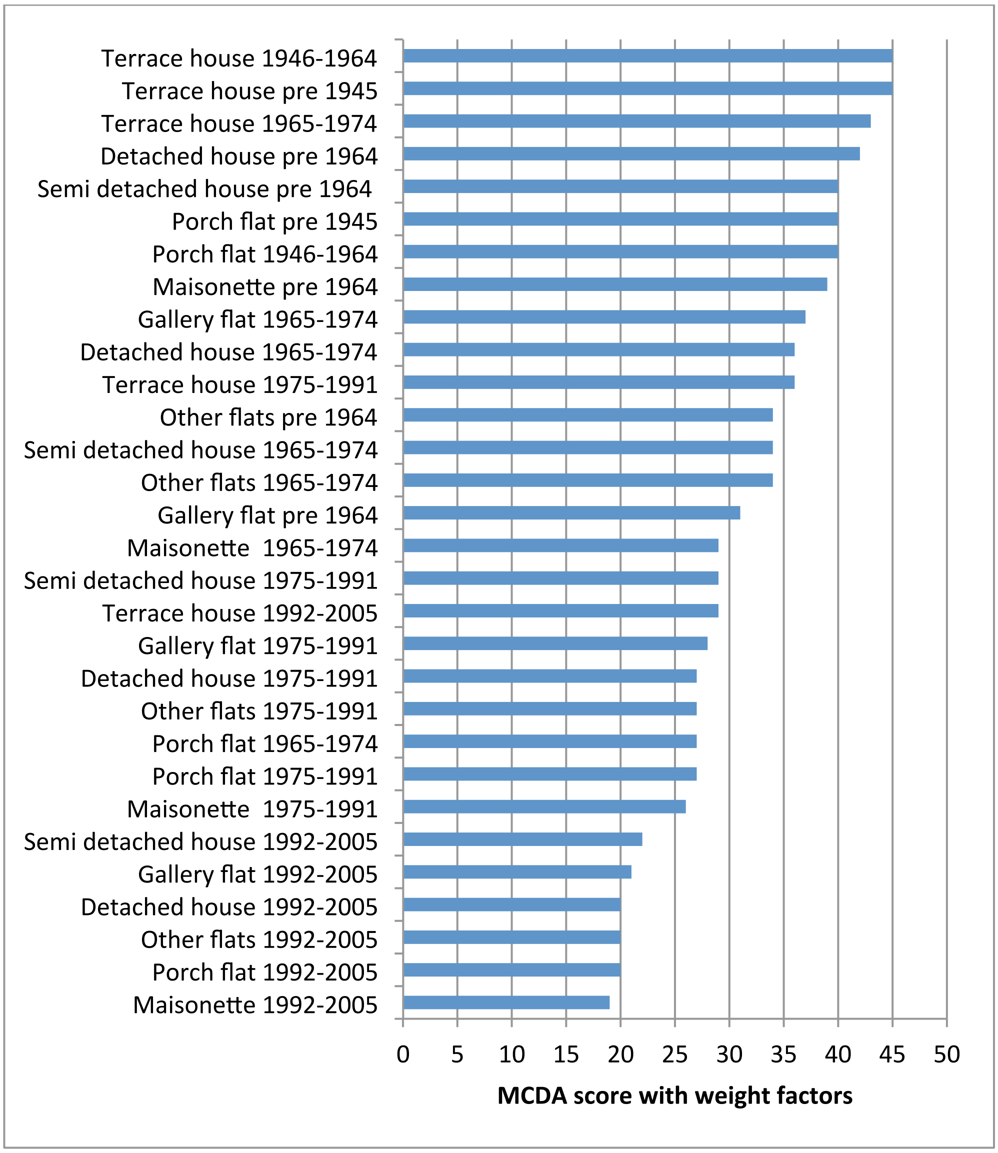

figure 10: Scores from the MCDA with weighting factor of representative dwellings (see appendix C)

The MCDA results do not point out one reference dwelling, but point in the direction of the terrace houses pre 1974. It is not desired to generalise the three terrace houses into one reference dwelling. The terrace houses are already generalised per time period in “Voorbeeld woningen 2010”. Therefore one of the three terrace houses from a specific time period is chosen as reference dwelling.

The three representative terrace houses pre 1974 have in general a lot in common, but do differ in specifics. The general appearance is the same; they all have a poor energy performance and were built in large quantities. In that same period the building construction method changed from a traditional to a more modular construction method, its dimensions changed and there was a small increase in energy performance. The main differences of the three terrace houses are shown in table 7.

table 7: General description characteristics of terrace houses in the building periods pre 1945, 1946-1964 and 1965-1974. Source: (W/E-adviseurs & PRC, 2011)

Description	Pre 1945	1946-1964	1965-1974
Impression			
Building method	Traditional building method used. The ground floor is made from wood.	During this period a switch from traditional to modular building method occurs. Decrease in wooden floors.	Mainly modular construction method is used. Concrete floors and sandwich filled frame panels.
Current energy-label and index[18]	G (EI = 3.18)	F (EI = 2.49)	E (EI = 2.08)
Usable floor area	102 [m^2]	87 [m^2]	106 [m^2]
Current Gas use	3,337 [m^3/year]	2,246 [m^3/year]	2,030 [m^3/year]
Amount	523,000	478,000	606,000

The terrace house from the time period 1946 until 1964 is chosen as reference dwelling for this research. This terrace house has the most in common with both the terrace houses from the time period's pre 1945 and 1965 until 1974. The building method and energy performance is in-between the other two terrace houses. The renovation concepts can most likely be more easily adapted to the other two terrace houses.

[18] Most dwellings were upgraded (double glass and condensing boiler for example) and currently have a higher energy label/index then when they were built.

3.4 Reference dwelling

The reference dwelling chosen in section 3.3.5 (terrace house from 1946 until 1964) is further described in this section. When there is referred to the reference dwelling in this report, the in this section descript dwelling is meant.

3.4.1 *Description*

In the time period 1946 until 1965 around 478,000 terrace dwellings were built (W/E-adviseurs & PRC, 2011). These terrace dwellings are owned for 57% by social housing cooperation, 40% is privately owned and 3% is privately rented.

The terrace houses from 1946 until 1965 are built in large post war neighbourhoods near the city centre, with a lot of space and greenery (Hoogers, et al., 2004). During the post war housing shortage the construction industry used standardization and scale to meet the at that time high housing demand (Bone A. , 2009). This led to a shift from traditional dwelling construction[19] to a faster modular construction method[20]. The downside from this is a dull and poorly differentiated neighbourhood.

Figure 11: Panoramic photo of a street with 1960s terrace dwellings. Source: (Nunen & van Bergen, 2011)

During the construction of the terrace houses in that period no insulation was used, the windows where made out of single glass and the internal heating was provide by a coal or gas stove on the ground floor (W/E-adviseurs & PRC, 2011). Most of the terrace houses have had a renovation in which most of them received a central heating system and double-glazing on the ground floor. Some terrace dwellings had also their walls insulated (27%), ground floor (7%) or roof (16%) (W/E-adviseurs & PRC, 2011). The energy performance of the terrace house has thus increased during its lifetime, but is still poor (see table 7).

The biggest problems with these terrace houses is that there noisy, damp[21] and drafty (Hoogers, et al., 2004). The dwellings also don't meet the current demands in living space surface area. Was this in the year 1947 still 21 m^2 per person in 2000 it is 50 m^2 per person (Dijkmans & Jonkers, 2011). This means that mainly the kitchen, bathroom and bedrooms are too small and don't meet the current demands of the inhabitants (Hoogers, et al., 2004).

[19] A labour intensive building method were missionary brickwork and wooden floors are used.
[20] The use of prefab construction elements and concrete increased the building construction speed
[21] Moisture passes through the porous ground floor (in case of a hollow brick floor or timber floor), causing mold problems. The bathroom shows mold spores, because of poor ventilation capabilities (Hoogers, et al., 2004)

3.4.2 *Technical properties*

The terrace house from 1958 is built on a masonry foundation of bricks with or without piles depending on its location in the Netherlands (Bone A. , 2007). The ground floor is made from wood and has a crawl space of 600 mm underneath (Sanjee, 2007). The exterior walls are non-insulated cavity walls with a 50 mm air cavity and constructed from (clay and limestone) bricks (Weijers, 2010). On top of the dwelling sits a slightly sloped roof with concrete tiles (Vringer & Blok, 1993). The windows on the ground floor are fitted with double glass and on the first floor with single glass (W/E-adviseurs & PRC, 2011).

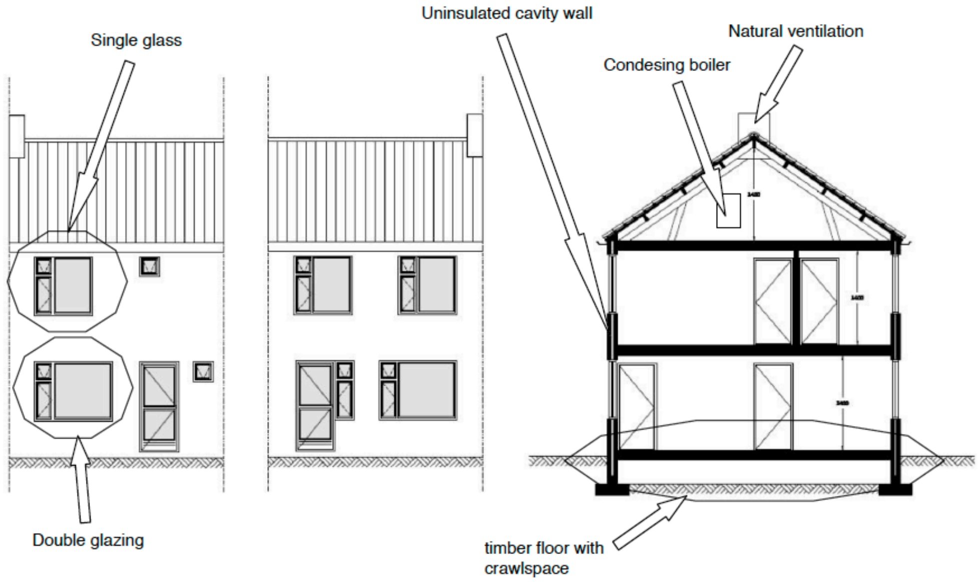

figure 12: Schematics of the front façade, back façade and cross-section of a terrace dwelling source: (Weijers, 2010)

The average usable floor area of the terrace house is 87 m^2 and its dimensions are 5.50 x 8 meters (inside measurements are 5.25 x 7.75 meter) (Hoogers, et al., 2004). The terrace dwelling is divided into three floors: ground floor, 1ste floor and attic. On the ground floor there is the living room, kitchen and toilet. On the 1st floor the bedrooms and bathroom. The attic can be accessed by means of an open staircase and can be used as bedroom, study or storage.

When the terrace house was build a coal or gas stove on the ground floor was used for space heating. In the 1980s a lot of the coal or gas stoves were replaced by a central heating system with a conventional gas boiler (Hoogers, et al., 2004). The average lifetime expectancy of a boiler is around 15 years (Nunen & van Bergen, 2011), thus the specific boiler type will vary per dwelling. The estimations of terrace houses from 1946 until 1964 are that (W/E-adviseurs & PRC, 2011):

- 31% has a HR107 condensing boiler,
- 23% has a HR100 condensing boiler,
- 25% has an increased efficiency boiler,
- 8% has a conventional boiler, and
- 13% has another form of heating.

It is assumed that the reference dwelling currently has a HR100 condensing boiler which replaced the in the 1980s fitted conventional boiler.

The technical properties of the terrace house (1946-1964) are shown in table 8. In appendix D the materials used in the reference dwelling are further descript.

table 8: The average technical properties of the reference dwelling (terrace house 1946-1964) source: (W/E-adviseurs & PRC, 2011)

Technical properties reference dwelling			
Description	Surface area [m^2]	R_c value [$m^2 \cdot K/W$]	U-factor [$W/m^2 \cdot K$]
Total ground floor area	47	0.32	1.72
Sloping roof	57,3	0.39	1.54
Front façade	21,15	0.36	1.61
Back façade	21,15	0.36	1.61
Single glazing	6.5	-	5.2
Double glazing	15	-	2.9
UFA (Usable floor area)	87 m^2		
Boiler type	HR100 Condensing boiler		
Ventilation	Naturel ventilation		
Age reference dwelling	Assumed to be 55 years		

3.5 Baseline scenario

To compare the renovation concept to the current situation a baseline scenario is used. In the baseline scenario it is assumed that the reference dwelling is used for an additional 5 years and is then demolished.

The baseline scenario is adapted to the functional unit in order to compare it to the renovation concepts in chapter 5. The baseline scenario does not meet the requirements for the functional unit. The functional unit is meant to compare the renovation concepts and not the baseline scenario. The baseline scenario is used to show the difference between the current and new situation and is only therefore adapted to the functional unit.

3.5.1 Investment cost

The current value of the reference dwelling depends on the region that it is build, district, quality and the economic principle of supply and demand (Liebregts & Verheij, 2010). It is estimated that the current value of the reference dwelling lies somewhere between 120,000 EUR and 240,000 EUR (Liebregts & Verheij, 2010).

The current value of the reference is not used for the baseline scenario or the renovation concepts. The uncertainty is high and does not give added value to the renovation concept comparison, the goal of this study. For the baseline scenario only the annual operational energy cost and end of life demolishing cost are accounted for (see appendix F).

3.5.2 *Energy performance*

The energy performance of the reference dwelling from the W/E-adviseurs & PRC (2010) report is not used. The energy performance of the reference dwelling is recalculated with the program Vabi EPA-W (see appendix E). This is done to keep the comparison in chapter 5 standardized as descripted in section 2.3.

When the energy performance is recalculated the energy index of the reference dwelling is 2.57, resulting in an energy F label. The total annual primary energy use is 99,319 MJ_{Prim}[22]. In figure 13 a breakdown is shown of the total annual primary energy use. Spatial heating accounts for 80% of the primary energy consumption. Thus by insulating the reference dwelling exterior, the biggest energy reduction can be gained.

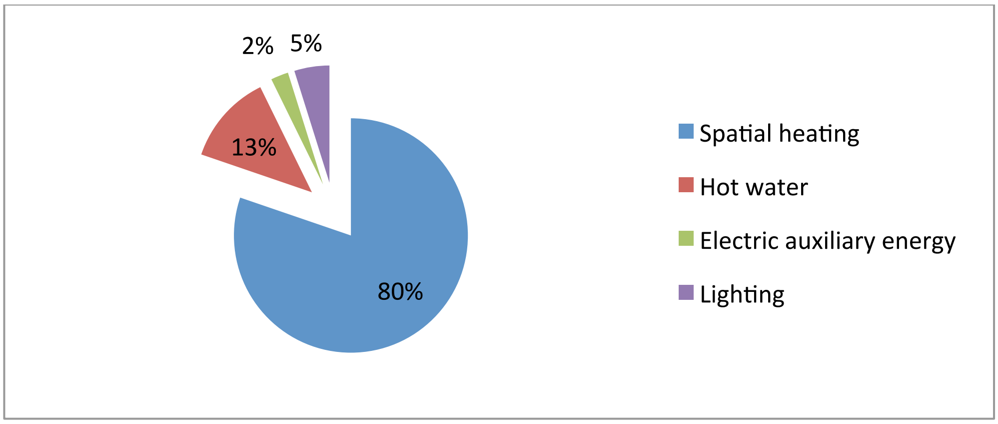

figure 13: Breakdown of the 99,319 MJ_{Prim}[23] total annual energy use of the reference dwelling. The breakdown shows the results from Vabi EPA-W. For more information see appendix E.

3.5.3 *Environmental performance*

For the baseline scenario no additional materials are added. It is assumed that the current boiler will last the additional 5 years. The additional 5 years are accounted for in the environmental impact of the materials that are used for reference dwelling.

The environmental impact in functional unit (see section 2.3.1) of the baseline scenario is shown in figure 14. The total shadow cost of the baseline scenario is 6.1 EUR/m^2/year. The environmental impact of the energy use is about 15 times higher than that of the materials used for the reference dwelling. This difference is so large because the environmental impact of the building materials is depreciated over a time period of 55 (current age) + 5 years (lifetime extension baseline) and a high annual operational energy use.

[22] This is the expected theoretical primary energy use calculated by the program Vabi EPA-W. The energy use is very depended on the inhabitants' behaviour and will thus differ per household. Additional electricity use form electronic devices (TV, PC, etcetera) are not included.
[23] See footnote 22

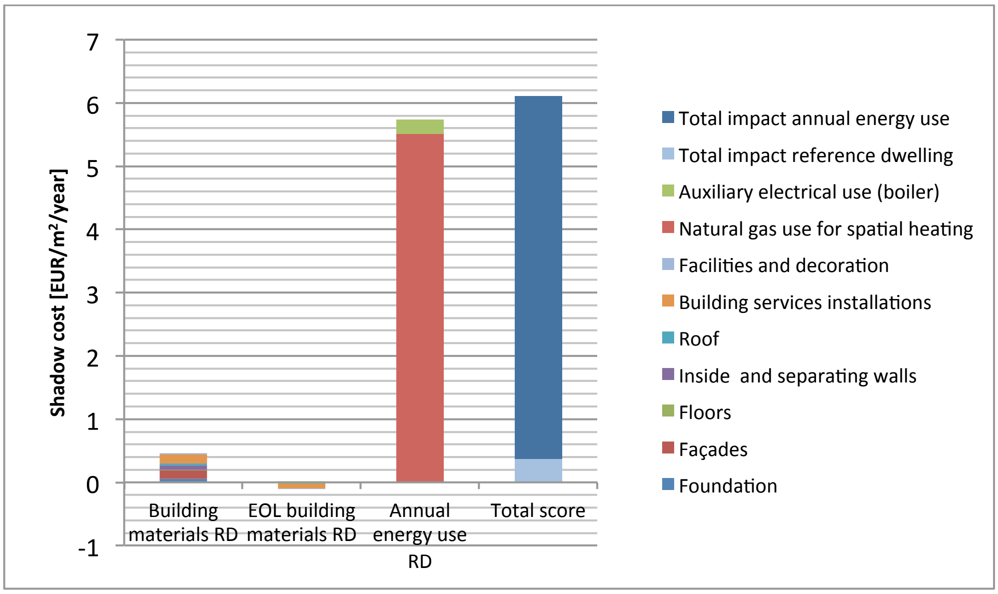

figure 14: Shadow cost of baseline scenario [5 years] shown as functional unit.

3.6 Conclusions and discussion

3.6.1 Conclusion

The conclusions from chapter 3 are the following:

- In order to meet the post war housing demand the construction companies built terrace houses and flats to standardize and scale up their dwelling production output.
- Dwellings built before 1975 are from origin not insulated.
- The amount of privately owned houses increased during the last decades by the privatization of the Dutch social housing corporations and governmental promotion.
- The maximum acceptable energy performance of newly built dwellings is regulated in the “Bouwbesluit” from 1995 onwards.
- The Dutch residential building stock can almost be divided into three equally large energetic performance sections. One third of dwellings has an energy label A, B or C, one third D or E and one third F or G.
- Almost 70% of the pre-war dwellings and 50% of the dwellings built between 1946 and 1979 has currently an energy label F or G
- In the next 35 years, the number of households is expected to grow more rapidly than population increase and is mainly caused by the aging of the Dutch society.
- The natural gas use per household has dropped with 25 per cent since 1980, due to ambitious energy policy measures.
- In previous studies the main focus was on the terrace houses from the time period 1946 until 1965 and 1966 until 1975
- The terrace houses pre 1974 are the most interesting representative dwellings to renovate within the Dutch residential dwelling stock to reduce the most GHG-emissions emitted by Dutch residential building stock.
- The environmental burden of the annual operational energy use of the reference dwelling is 15 times higher than that of the used building materials (over a deprecation period of 60 years).

3.6.2 *Discussion*

The reference dwelling was selected from 30 representative dwellings of the Dutch residential building stock by using a MCDA. From the MCDA it was concluded that the reference dwelling should be selected from the terrace houses pre 1974, based on the defined criteria to reduce the GHG-emissions in the Dutch residential building stock. This was also concluded in previous studies. In figure 6 is shown that only 42% of the Dutch residential building stock is terrace houses, this excludes thus 58% of the Dutch residential building stock. From an exterior and structural point of view terrace houses do have a lot in common with semidetached and detached houses. The renovation concepts elements as floors, façade, roof, and building services installations could easily be adapted to semidetached and detached houses; only the amount of material and total cost would change. These one-family dwellings (terrace houses, semidetached houses and detached houses) form 70% of the Dutch residential building stock. The conclusions from this report are thus relevant for 42%-70% of the Dutch residential building stock.

The data used for MCDA came from the reports “Voorbeeldwoningen bestaande bouw 2011” and “Kernpublicatie WoOn energie 2006”. Both reports are based on data from the governmental initiated residential research “WoOn 2006”. The research methodology that was conducted to collect the data in “WoOn 2006” was a survey sampling method. The results in “WoOn 2006” about the household energy use are based on the response of 4,800 Dutch households, and will therefore only give an indication of what the energy performance could be of the total 7,2 million households in the Netherlands (see figure 6). This data uncertainty will mainly affect the energy use and performance data in the “Voorbeeldwoningen bestaande bouw 2011” report. The energy performance criterion has a weighting factor of 4 out of 4 and will have a big influence on the outcome of the MCDA. As the reference dwelling was built before 1975, when the first legislative requirements for insulation were issued (see section 3.1), the energy performance will be poor and the data uncertainty will probably not really affect the MCDA outcome.

The material data used for the LCA of the reference dwelling comes from literature research. The data found were comprehensive and the main report used from Vringer & Blok (1993) has a data uncertainty of 6.5%. The bigger uncertainty lies in structural changes that could have been made during the lifetime of the reference dwelling. In section 3.4.1 was shown that the usable floor area of the reference dwelling does not meet the current household demands. Therefore a dormer could have been added to the roof and an expansion on the ground floor could have taken place. These structural changes have not been taken into account and will affect the current amount of materials used. These structural changes can differ from dwelling to dwelling in the same street, which makes it difficult to incorporate in the results. These changes will also affect the renovation concepts on the amount of material use and the applicability of the renovation concept, and can make a uniform large-scale renovation difficult.

The annual operational energy use of the reference dwelling is an important factor for the LCA and LCC during the user phase. The annual operational energy use is dependent on the inhabitants’ behaviour, technical properties and orientation of the dwelling. In the report of Sanjee (2007) the maximum deviation per dwelling of the annual natural gas use was 1,500 m^3 per year, for terrace dwellings in the same block. The inhabitants’ behaviour will thus directly influence the environmental impact and total cost of the reference dwelling (this also applies to the renovation concepts). In this study theoretical energy calculations for the annual operational energy use were performed with Vabi EPA-W. This program uses averages to incorporate the inhabitants' behaviour. As no household is the same this will create a high uncertainty in the annual operational energy use of the reference dwelling and renovation concept, which will differ per household. However, it is not feasible to calculate the environmental impact and total cost effect per single household in the Netherlands; therefore the average annual operational energy use from Vabi EPA-W was used. This problem could also be solved by determining a realistic deviation in the annual operational energy use and define a high energy using household and low energy using household to show the difference.

4 Renovation concepts

In this chapter the renovation ambition levels are explained for the reference dwelling of chapter 3. Based on the renovation ambition level three renovation concepts are defined. The renovation concepts characteristics, energy performance and environmental impact are then further elaborated.

4.1 Ambition levels

In this study a distinction is made between a low ambition renovation and a high ambition renovation. Low ambition renovation uses traditional renovation techniques to gain an energy performance increase of two labels or energy label B. This is in line with current Dutch policies (see section 1.1). The high ambition renovation uses more innovative techniques to reach at least an energy A label or higher. The distinction between low and high ambition renovation is made in this study to see how the environmental and economic impact between the two relates. In other words, is the current policy focus on low ambition renovation indeed the best option, or should the focus lie on the more innovative and not that common high ambition renovation. The specifications per ambition level are described in the next two sections.

4.1.1 Low ambition level

The low ambition level renovation is based on the “Meer met Minder” and “Huurconvenant” covenants. The “Huurconvenant” states that the entire Dutch housing corporations housing stock should at least have an energy index of 1.25 (energy B label) or lower in 2020. The same energy index requirement of ≤1.25 is used for the low ambition level renovation. Besides an energy performance increase the renovation should also extend the functional lifetime of the dwelling with 15 years.

4.1.2 High ambition level

The high ambition renovation is based on two innovative terrace house renovation projects in the Netherlands called “de Kroeven” and “de bestaande wijk van Morgen”. The requirements for both projects were at least an energy A label or higher and a functional lifetime extension of approximately 50 years. Renovating the dwelling to energy A label or higher also has the following advantages:

- When the entire Dutch residential building stock is renovated to an energy A label in the next 40-50 years, the current annual cumulative GHG-emissions in the Dutch residential building stock are reduced with one third (Pasztor, Rovers, & Vos-Effting, 2012), and
- The actual lifetime expectancy of an average Dutch dwelling is 120 years (Nunen & van Bergen, 2011). It is thus not realistic that the now 55-year-old reference dwelling, with a low ambition level renovation, is demolished after 15 years. A long-term renovation vision should thus be preferred.

4.2 Renovation concepts

Based on the two ambition levels set in section 4.1 three different renovation concepts are defined. The renovation concepts are the following:

- renovation concept 1; low ambition renovation concept,
- renovation concept 2; high ambition renovation concept, and
- renovation concept 3; high ambition rebuilding concept.

For the low ambition level renovation only one renovation concept is defined. To reach the low ambition level no drastic measures are needed (see W/E-adviseurs & PRC, 2011). The main deviation among low ambition renovation concepts would be the difference in insulation material used (EPS pearls instead of glass wool for example). As the insulation method and total weight will probably stay the same, it is expected that this will not have a large impact on the KPI's. Also the environmental and cost performances of insulation materials have already been studied in the report of Duijve (2012). Therefore only one low ambition renovation concept is defined.

There are two renovation concepts defined for the high ambition level renovation. The high ambition renovation leaves most of the structure intact, only the façade and roof are replaced. For the high ambition rebuilding concept most of the dwelling is demolished and is then rebuild. It is expected that this will reflect in the environmental impact.

The renovation concepts are further described in section 4.3 until section 4.6. The characteristics of the three different renovation concepts descript in these sections are summarised in table 9.

table 9: Summary of the renovation concepts characteristics, which are further elaborated in section 4.3 until section 4.6. The baseline scenario (section 3.5) is also shown.

Description	Baseline	Concept 1	Concept 2	Concept 3
Energy performance	F-label	B-label	A^{+}-label	A-label
Lifetime extension	5 years	15 years	50 years	50 years
Investment costs	-	Low/Average	High	High
Impact on inhabitants	Low	Low	High	Very high
Comfort level	Low	Average	High	High

4.3 Renovation concept 1: the low ambition renovation concept

The aim of the low ambition renovation concept is an energy index score of at least 1.25 or lower and a lifetime extension increase of 15 years. This is done by using conventional renovation methods and frequently used renovation materials.

There are many insulation materials on the market today that could be used for renovation concept 1. In a previous study different insulation materials for a cavity wall were compared with one another on their cost perspective and environmental impact. In this study from Duijve (2012) it was concluded that glass wool, EPS and rock wool can be considered the best materials available today for an renovation. In this study glass wool and EPS did score slightly better than rock wool.

Glass wool insulation is a common and conventional insulation material for renovation projects in the Netherlands (Bone A. , 2009). This is why glass wool is chosen over EPS as insulation material for renovation concept 1. The insulation methods used for renovation concept 1 are based on the methods descript in Bone (2009) for glass wool insulation.

4.3.1 *Renovation measures*

The exterior cavity walls are injected with loose glass wool insulation material. Filling the 50 mm cavity increases the R_c value of the exterior wall to 1.61 $m^2{\cdot}K/W$ (ISSO, 2011).

The ground floor is insulated with 120 mm thick glass wool sheets placed between the wooden floor joints (ISOVER, n.d.). By insulating the ground floor the R_c value is increased to 2.5 $m^2{\cdot}K/W$ (ISOVER, n.d.). To reduce the humidity and radon accumulation in the crawl space a PE film is placed on the bottom of the crawl space (Bone A. , 2009).

The roof is insulated with 100 mm thick glass wool sheets between the purlins (ISOVER, n.d.). The glass wool sheets have a white impact resistant and decorative finishing layer. Placing the insulation between the purlins increases the R_c value to 2.54 $m^2{\cdot}K/W$ (ISSO, 2012).

The current glazing is replaced by HR++ (high efficiency) double glazing in order to meet the energy index target. The current window frames are replaced by a PVC window frames to support the heavier HR++ double glazing.

The HR100 condensing boiler is replaced by a new HR107 condensing boiler to increase the heat generation efficiency. The HR107 condensing boiler is the new standard that is available on the market today. The air permeability of the dwelling is reduced by air proofing the dwelling. To insure that the dwelling can still be properly ventilated a central mechanical ventilation system is installed.

In appendix D more information can be found about of the materials used during the renovation. The materials and data shown in appendix D is used for LCA.

4.3.2 *Investment costs*

The average investments costs for renovation concept 1 were found by supplier information and literature research (see appendix F). The total average investment cost for concept 1 is 14,540 EUR (incl. VAT and labour). The uncertainty is high as the minimum investment cost was found to be 30 per cent lower and the maximum investment cost 20 per cent higher.

4.3.3 *Energy performance*

The energy index of the reference dwelling is 1.20 resulting in an energy B label (see appendix E). The total annual primary energy use is 46,461 MJ_{Prim}[24]. In figure 15 a breakdown is shown of the total annual primary energy use.

In comparison to the current energy performance, described in section 3.5.2, the total annual primary energy use is more than halved by renovation concept 1. Spatial heating still account for more than half of the primary energy consumption.

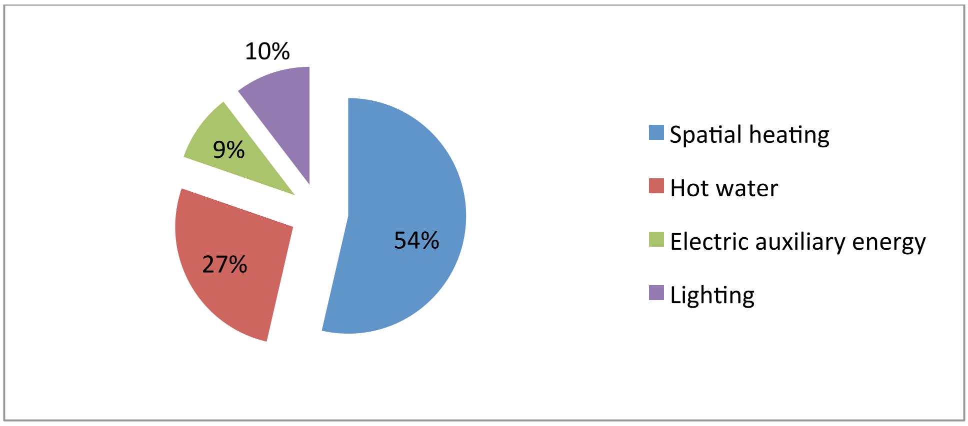

figure 15: Breakdown of 46,461 MJ_{Prim}[25] total annual energy use of the renovation concept 1. The breakdown shows the results from energy performance calculations. For more information see appendix E.

4.3.4 *Environmental impact*

The environmental impact of renovation concept 1, expressed in shadow cost, is 448 EUR. The environmental impact of the renovation concept 1, shown in figure 16, is divided into seven building elements (foundation, facades, floors, inside and separating walls, roof, building services installations and facilities and decorations). The materials used per element can be found in appendix D.

The main contributors to the shadow cost shown in figure 16, are the material production and end of life disposal. The contribution of transport is to small (+/- 2%[26]) compared to the materials to be of any interest for this study.

[24] This is the expected theoretical primary energy use calculated by the program Vabi EPA-W. The energy use is very depended on the inhabitants' behaviour and will thus differ per household. Additional electricity use form electronic devices (TV, PC, etcetera) are not included.
[25] See footnote 24
[26] Transport of materials to the building site and during the end of life scenario

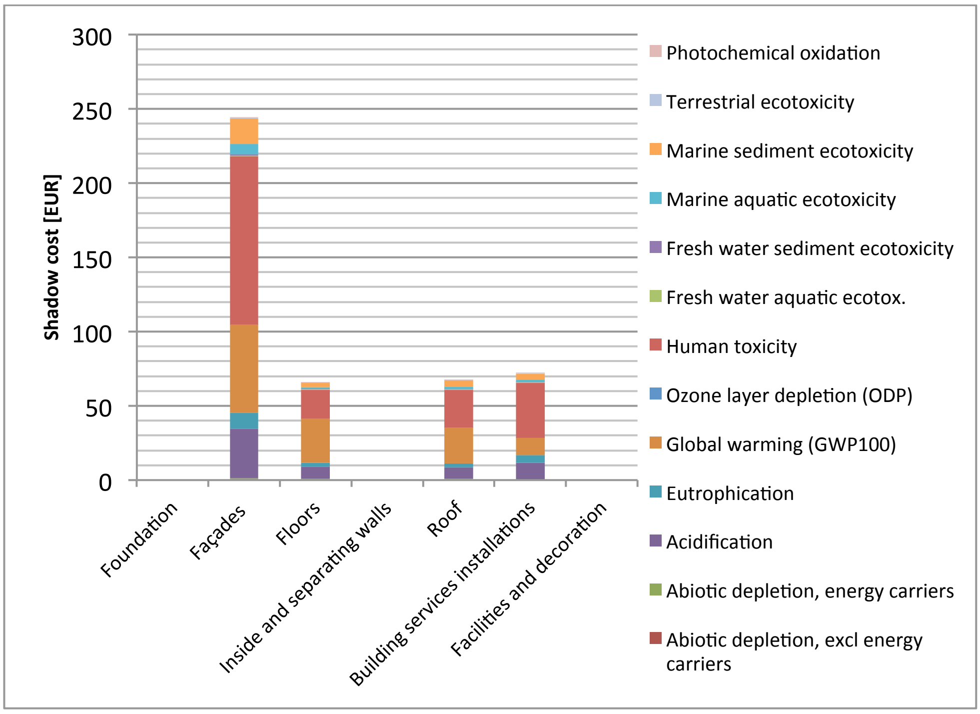

figure 16: Shadow cost from cradle to grave of the materials used for renovation concept 1.

The main contributor to the shadow cost of renovation concept 1 is the façades (245 EUR) as shown in figure 16. This is mainly caused by the PVC window frames (143 EUR excl. transport) that are used to replace the current wooden window frames. The glass wool insulation, which is used for the ground floor (44 EUR excl. transport) and roof (46 EUR excl. transport), has the largest contribution for both building elements. The environmental impacts of the mechanical ventilation (33 EUR excl. transport) and boiler (37 EUR excl. transport) have on the building services insulations is almost the same.

Environmental impact categories.

The human toxicity, global warming potential (GWP) and acidification contribute the most to the shadow cost from the 13 environmental categories (see figure 16).

The three emissions that mainly contribute to the total human toxicity of renovation concept 1 (in shadow cost) are the following:

- Chromium VI to air (81 EUR),
- Polycyclic aromatic hydrocarbons (PAH) to air (39 EUR), and
- Benzene to air and water (37 EUR).

The Chromium VI is released in the atmosphere by the production of Ferrochromium. Ferrochromium is one of the materials used to produce low alloy steel. The low alloy steel chart form ecoinvent was used for the LCA, but the actual composition of the low alloy steel used in the renovation concept can be different. Thus the human toxicity caused by Chromium VI is depended on the actual low alloy steel (composition) used in the renovation concepts. In renovation concept 1 low alloy steel is mainly used for the PVC window frames and HR107 condensing boiler. In renovation concept 1 the PAH emissions are mainly produced during the production of aluminium. PAH emissions are a by-product of carbon-containing fuel burning. Aluminium is mainly used for the double glazing, PVC window frame and condensing boiler. For the production of glass wool Phenol is used as binder.

During the production of Cumene, which is used to produce Phenol, Benzene emissions to air and water occur.

The GWP and acidification impacts are both mainly produced by burning fossil fuels for energy during material production. Acidification is mainly caused by the use of coal and oil, which emit sulphur dioxide (50% of total acidification) and nitrogen oxide (19% of total acidification) emissions. Another substance that causes acidification is Ammonia (31% of total acidification), which is not linked to GWP.

The most energy intensive materials in renovation concept 1 are:
- Façades; Double glazing and PVC window frame,
- Floors; glass wool and PE film vapour barrier,
- Roof; glass wool, and
- Building services installations; both condensing boiler and mechanical ventilation.

The ammonia emissions mainly occur during the production of zinc coating coils, which are used for the PVC window frames and zinc spiral air ducts.

Renovation concept 1 LCA

The environmental impact in functional unit (see section 2.3.1) of renovation concept 1 during its 15 year lifetime extension is shown in figure 17. The environmental impact of the annual energy use is still 3 times higher than the contribution of the building materials. The building materials from the reference dwelling have almost the same environmental impact as the materials added for renovation concept 1. This is because the building materials of renovation concept 1 are only used for 15 years, while those used in the reference dwelling are at least used for 55 years.

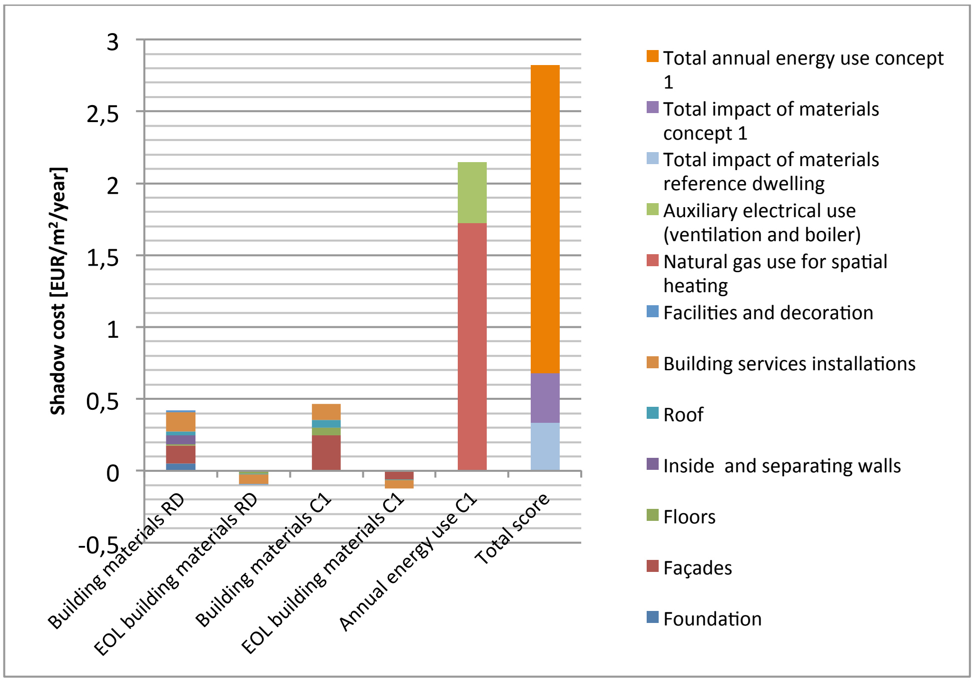

figure 17: Shadow cost of renovation concept 1 [15 years] shown in functional unit

4.3.5 Impact on inhabitants and comfort level

The impact on the inhabitants is low during the renovation according to renovation concept 1. The most inconvenience the inhabitants will have is when the windows are replaced. The comfort level is increased by the exterior insulation and the installation of central ventilation, but in comparison to renovation concept 2 and 3 this is still low.

4.4 Renovation concept 2: the high ambition renovation concept

In the Netherlands there have been two large scale, innovative and high ambition renovation projects carried out for terrace houses. These projects are “De Kroeven” in Roosendaal and “Bestaande wijk van morgen” in Kerkrade-West. The high ambition renovation concept in this study is based on “De Kroeven”, because of data availability.

The social housing corporation AlleeWonen commissioned the renovation of 246 dwellings to a passive house level[27]. The project was divided and appointed to two different architects and energy consultants. This resulted into two projects, with different designs and construction methods named:

- “505” (134 dwellings), and
- “506” (112 dwellings).

In this study the renovation concept is based on the project “505”. This renovation concept is chosen because it has a better air tightness, was slightly cheaper to build and the renovation process was faster than that of the renovation concept “506” (Boonstra, et al., 2011). It was later on also used as basis for new dwellings in the same district, because AlleeWonen found it the best construction method of the two projects (Renovatie in de Kroeven in Roosendaal , 2011). The end result of the renovated dwellings from project “505” is shown in figure 18.

figure 18: Renovated terrace dwelling from project 505 in district de Kroeven, Roosendaal. Source: Energiesprong

[27] Passive houses (energy A^{++} label) have a comfortable indoor climate all year round with minimal energy input. This concept was developed by Wolfgang Feist and Bo Adamson. The annual heating demand of a passive house may not exceed 15 kWh/(m^{2}a) for newly built dwelling and 25 kWh/(m^{2}a) for a renovated dwelling (International Passive House association, 2010).

The objectives set by AlleeWonen for the renovation project were:

- lifetime extension of 50 years,
- Energy A^{++} label, and
- the dwelling stays inhabited during the renovation (Brink, n.d.).

The total renovation, from the preparation in the garden until the final finishing's, takes place in a three-week period. To avoid too much disturbance for the inhabitants, the new roof and the two facades are placed within one day. The total investment cost is estimated at 100,000 EUR (incl. VAT and labour) per dwelling (see appendix F).

4.4.1 *Renovation description*

During the project "505" renovation the outer skin of the cavity wall was demolished. The next step was to excavate and insulate the outside of the foundation with EPS (Expended Polystyrene) insulation blocks. The prefab wooden-frame façade elements were then placed against the still standing inside skin of the wall. The prefab wooden-frame elements were made out of softwood and contain cellulose fibre insulation[28] (Boonstra, et al., 2011). The triple glazed windows with PVC frame were factory mounted in the prefab façade elements. Finally battens were mounted onsite, to allow for the installation of natural slate tiles while also providing a ventilated façade. Aluminium sheets were placed against the façade sides of window and door openings. The R_c value of the façade is 9.1 $m^2 \cdot K/W$ (Boonstra, et al., 2011).

The existing roof was removed and replaced by prefab wooden-frame roof elements. The prefab wooden-frame roof was also insulated with cellulose fibre (Boonstra, et al., 2011). The outside of the roof elements was covered with a PVC roofing material. The R_c value of the new roof is 10 $m^2 \cdot K/W$ (Boonstra, et al., 2011).

The timber ground floor and the sides of the foundation were insulated with PU (Polyurethane) foam spray[29] (Boonstra, et al., 2011). The PU foam spray and the EPS insulation on the outside of foundation allow an R_c value of 8 $m^2 \cdot K/W$ (Brink, n.d.).

The building services systems are not entirely based on "de Kroeven" but were an adaptation of "de Kroeven". This was done because of data availability. The HR100 condensing boiler was replaced by a new HR107 condensing boiler. The original radiator system was adjusted to a smaller heat demand (Boonstra, et al., 2011). Ventilation is provided by balance ventilation with heat recovery. The solar water heater was excluded in this research. The solar water heater would have had an impact on the energy performance of renovation concept 2, described in section 4.4.2. The energy performance is thus not the same as that of "de Kroeven".

[28] Cellulose insulating material is produced from recycled paper or wood fiber mass. The obtained cellulose fibers have a wool like structure. Boric acid and borax are added to make the cellulose fibers moisture and flame retardant. (Jelle, 2011)

[29] There is currently a debate over the negative health effects that PU foam spray insulation can have (a specially with a timber floor) (van der Parre, 2013). TNO is currently still researching the effects of PU foam spray insulation on human health. Renovation concept 2 is based on "de Kroeven" and therefore PU spray is used. This report will not further discuss the effects of PU spray on human health.

In appendix D more information can be found about of the materials used during the renovation. The materials and data shown in appendix D is used for LCA.

4.4.2 *Energy performance*

The energy index calculated with Vabi EPA-W of renovation concept 2 is 0.70 resulting in energy A^+ label. This is lower than the energy A^{++} label of “de Kroeven”, because the solar water heater used for “de Kroeven” is not accounted for in renovation concept 2 (see section 4.4.1). The total annual primary energy use is 27,083 MJ_{Prim}[30]. In figure 19 a breakdown is shown of the annual primary energy use.

The total primary energy of renovation concept 2 is 25% of the total primary energy use of the baseline scenario (see section 3.5.2). Spatial heating is no longer the biggest contributor to the annual energy use, but hot water use is.

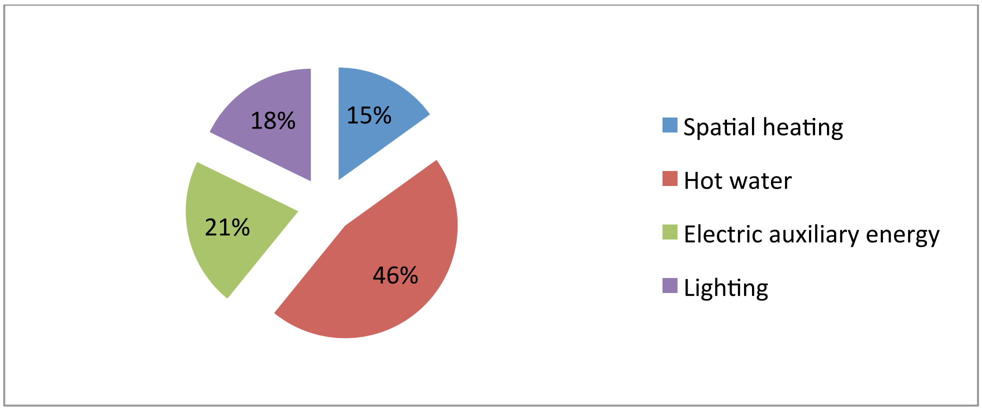

figure 19: Breakdown of the 27,084 MJ_{Prim}[31] total energy use of the renovation concept 2. The breakdown shows the results from energy performance calculations. For more information see appendix E

The primary energy needed for the electric auxiliary energy (ventilation and the boilers’ pump, electronics and ventilator) is higher than that of spatial heating. When a dwelling is insulated to this level, more attention should also be paid to the energy efficiency and consumption of auxiliary equipment.

4.4.3 *Environmental impact*

The environmental impact of renovation concept 2, expressed in shadow cost, is 1321 EUR. The environmental impact of renovation concept 2, shown in figure 20, is divided into seven building elements just as renovation concept 1. The materials used per element can be found in appendix D.

The main contributors to the shadow cost shown in figure 20, are the material production and end of life disposal. The contribution of transport is to small (+/- 3%[32]) compared to the materials to be of interest for this study.

[30] This is the expected theoretical primary energy use calculated by the program Vabi EPA-W. The energy use is very depended on the inhabitants’ behaviour and will thus differ per household. Additional electricity use form electronic devices (TV, PC, etcetera) are not included
[31] See footnote 30
[32] Transport of materials to the building site and during the end of life scenario

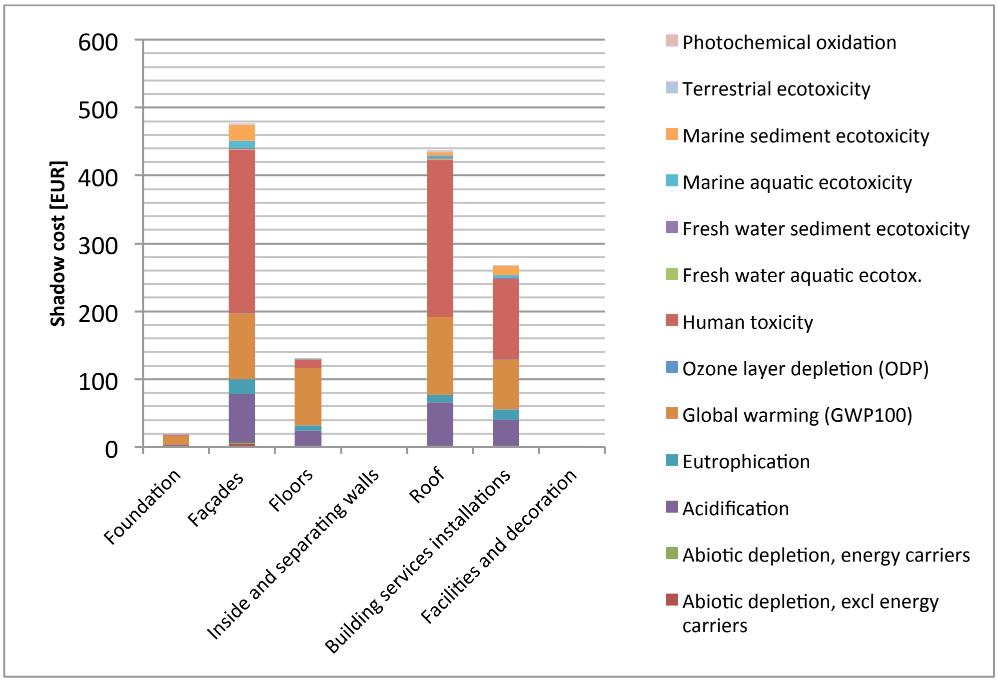

figure 20: Shadow price from cradle to grave of constructing renovation concept 2.

The main contributors to the shadow cost of renovation concept 2 are the facades (477 EUR) and roof (437 EUR) elements as shown in figure 20. The materials used in the facades that cause the high shadow cost are the PVC window frames (143 EUR excl. transport) and triple glazing (149 EUR excl. transport). The shadow cost of triple glazing is 1,5 times higher than that of HR++ double glazing used in concept 1 and 2. The higher shadow cost for triple glazing is caused by the extra glass sheet, but also by the use of Krypton gas (21 EUR excl. transport) instead of Argon gas. For the floor only PU spray is used and it thus the contributor to the shadow cost. The main contributor to the shadow cost of the roof is the PVC roofing material (223 EUR excl. transport). This is relative high compared to the shadow cost of concrete roof tiles (46 EUR excl. transport from the reference dwelling), while fulfilling the “same” function. The environmental impact of the mechanical ventilation (117 EUR) and boiler (138 EUR) on the building services insulations are almost the same. The building services installations is higher in comparison to renovation concept 1 because of the replacement that occurs every 15 year and the use of balance ventilation.

Environmental impact categories.

The human toxicity, global warming potential (GWP) and acidification contribute the most to the shadow cost (see figure 20), just as in renovation concept 1.

The three emissions that mainly contribute to the total human toxicity of renovation concept 2 are just as in renovation concept 1: PAH (175 EUR), Chromium VI (135 EUR) and Benzene (117 EUR). The additional emissions of PAH compared to renovation concept 1 is caused by the additional aluminium that is used in renovation concept 2 (aluminium façade ornaments and boiler replacements). The additional increase in chromium VI compared to renovation concept 1 is mainly caused by the replacement of the boiler every 15 years. For the prefab elements (façade and roof) a lot of OSB is used. As for glass wool Phenol is also used as binder for OSB, which causes the Benzene emissions increase.

The GWP and acidification impacts are both mainly produced by burning fossil fuels for energy during material production. Acidification is mainly caused by the use of coal and oil, which emit sulphur dioxide (63% of total acidification) and nitrogen oxide (23% of total acidification) emissions. Another substance that causes acidification is Ammonia (14% of total acidification), which is not linked to GWP.

The most energy intensive materials used in renovation concept 2 are:
- Foundation; EPS insulation blocks
- Façades; Triple glazing and PVC window frame,
- Floors; PU insulation spray,
- Roof; PVC roofing material, and
- Building services installations; both condensing boilers and mechanical ventilation.

The ammonia emissions mainly occur during the production of zinc coating coils, which are used for the PVC window frames and zinc spiral air ducts.

Renovation concept 2 in functional unit
The environmental impact in functional unit (see section 2.3.1) of renovation concept 2 during its 50 year lifetime extension is shown in figure 21. The environmental impact of the annual energy use is 1.4 times higher than the contribution of the used building materials. The environmental impact of building materials is thus gradually playing a more important role on the environmental impact, because of the energy use reduction compared to renovation concept 1.

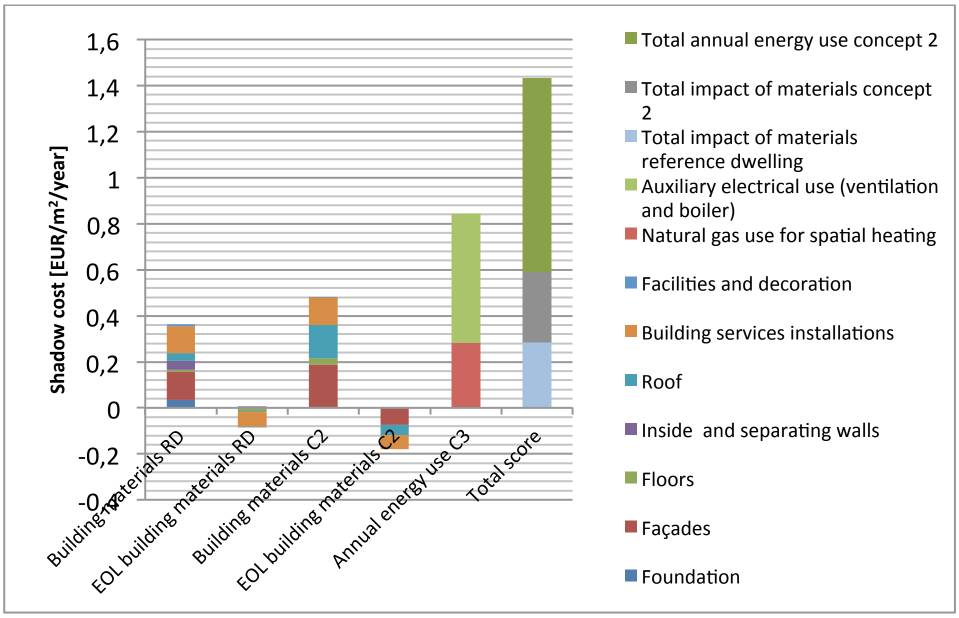

figure 21: Shadow cost of renovation concept 2 [50 years] in functional unit

4.4.4 Impact on inhabitants and comfort level

The impact on the inhabitants is relative high although the inhabitants do not have to move during this intensive renovation. When the entire roof and facades are replaced the inhabitants will encounter the most inconvenience. The comfort level is greatly improved by the high exterior insulation and balance ventilation.

4.5 Renovation Concept 3: High ambition rebuilding concept

The high ambition rebuilding concept is based on the “inschuifwoning” from Mulder Obdam[33]. By rebuilding the dwelling a lifetime extension of 50 years and energy A label are realised. In this concept the entire terrace dwelling was demolished except for its foundation, house separating walls and utility connections. Also other parts, depending on their condition, can be reused like the roof tiles, boiler and kitchen. On the foundation a dwelling with the same exterior appearance is rebuilt out of prefab elements. The renovation process took a total of 22 working days and is shown in table 10 (Mulder Obdam, n.d.).

table 10: Rebuilding process of the “inschuifwoning”. 1: current dwelling, 2: demolishing phase, 3: rebuilding phase, 4: renovated dwelling. Source: Mulder Obdam

[33] The “inschuifwoning” is a concept that is developed by the company Mulder Obdam. In 2010 the first “inschuifwoning” was realised in Ursem (Mulder Obdam, n.d.).

4.5.1 *Renovation description*

On the foundation a new floor from prefab sandwich floor-dek panels (made from sheet low alloy steel with PIR filling) was built. The R_c value of the ground floor by using the sandwich panels has increased to 4 $m^2 \cdot K/W$ (Kinspan, 2010). The prefab sandwich panels were also used for the first and attic floor.

The façade was built with prefab wooden-frame elements. The prefab elements have brick strips in the same colour as the adjacent dwellings and are. The HR++ double glazed windows with PVC frames were factory mounted in the prefab facade. The R_c value of the prefab façade elements is 3.5 $m^2 \cdot K/W$ (SBR, n.d.).

The roof was also built from prefab wooden-frame elements. The concrete roof tiles from the reference dwelling were reused. The R_c value of the prefab roof elements is 4.5 $m^2 \cdot K/W$ (Mulder Obdam, n.d.).

The HR100 condensing boiler was replaced by a new HR107 condensing boiler. The original radiator system was replaced and adjusted to the smaller heat demand. Instead of mechanical ventilation (used for the standard “inschuifwoning”), the optional balance ventilation system with heat recovery is used for renovation concept 3.

In appendix D more information can be found about of the materials used during the renovation. The materials and data shown in appendix D is used for LCA.

4.5.2 *Energy performance*

The energy index of renovation concept 3 is 0.86 resulting in energy A label. The total primary energy use is 33,225 MJ_{Prim}[34]. In figure 22 a breakdown is shown of the total primary energy use.

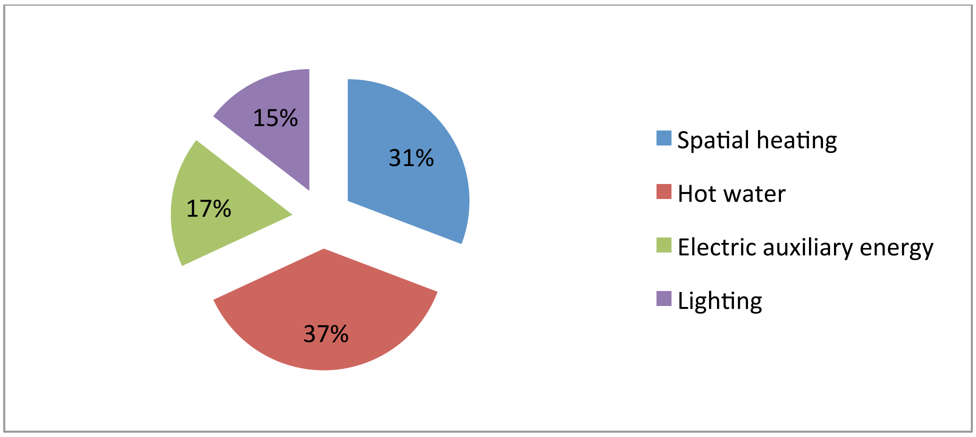

figure 22: Breakdown of the 33,225 MJ_{Prim}[35] total energy use of the renovation concept 3. The breakdown shows the results from energy performance calculations. For more information see appendix E

[34] This is the expected theoretical primary energy use calculated by the program Vabi EPA-W. The energy use is very depended on the inhabitants' behaviour and will thus differ per household. Additional electricity use form electronic devices (TV, PC, etcetera) are not included
[35] See footnote 34

The annual energy use for hot water is for renovation concept 3 a bit higher than that of spatial heating (see figure 22). It shows that reducing the energy use for hot water is getting more relevant and interesting for renovation concepts that have an exterior insulation level with a R_c value of 3.5 m^2·K/W or higher. In renovation concept 2 were the insulation level is even higher (R_c value of 8 until 10 m^2·K/W) than in renovation concept 3, reducing the energy use for hot water is more relevant than that of spatial heating (see figure 19).

4.5.3 *Environmental impact*

The environmental impact of renovation concept 3, expressed in shadow cost, is 2,914 EUR. The environmental impact of renovation concept 3, shown in figure 23, is divided into seven building elements just as renovation concept 1. The materials used per element can be found in appendix D.

The main contributors to the shadow cost shown in figure 23, are the material production and end of life disposal. The contribution of transport is to small (+/- 3.5%[36]) compared to the materials to be of interest for this study.

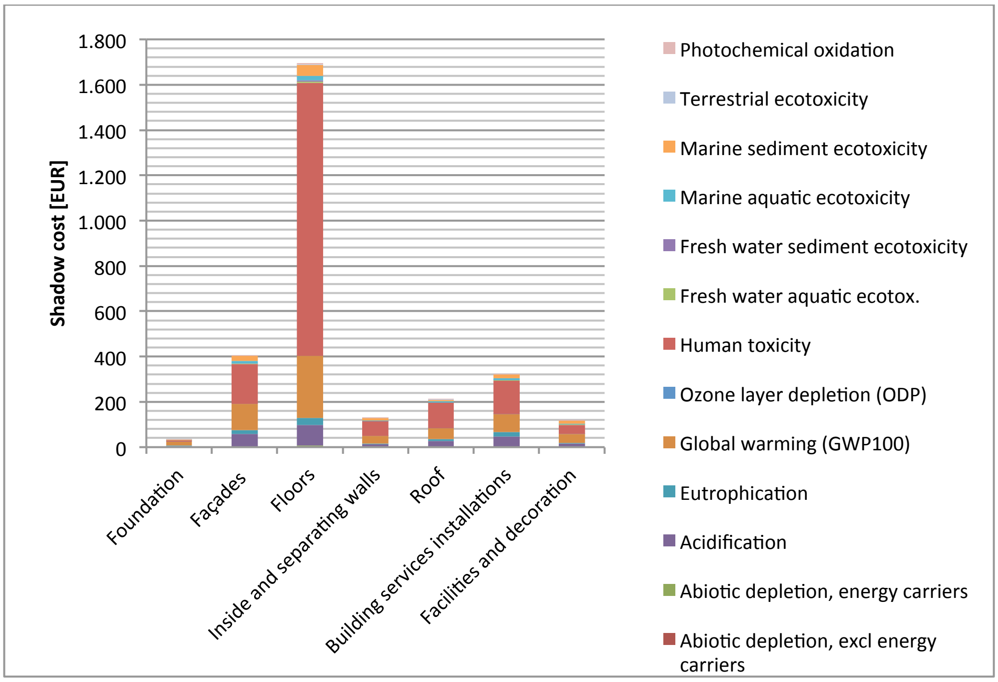

figure 23: Shadow cost of renovation concept 3 [50 years] in functional unit

The main contributors to the shadow cost of renovation concept 3 are the floors (1695 EUR) as shown in figure 23. The material used in the floors that causes the high shadow cost is the low alloy steel (1361 EUR excl. transport) used for the sandwich floor panels. The PVC window frames (143 EUR excl. transport) and double glazing (81 EUR excl. transport) contribute, like in concept 1, the most to the shadow cost of the façade. From the prefab elements used for the façade the fibre cement-facing tile (65 excl. transport) is the most contributing material. The main contributors to the roof elements are the glass wool insulation (93 EUR excl.

[36] Transport of materials to the building site and during the end of life scenario

transport) and OSB (42 EUR excl. transport). The boilers and radiators account for 139 EUR and the total ventilation for 117 EUR of the shadow cost.

Environmental impact categories

The human toxicity, global warming potential (GWP) and acidification contribute the most to the shadow cost (see figure 23), just as in renovation concept 1 and 2.

The emission that mainly contributes to the total human toxicity shadow cost of renovation concept 3 is Chromium VI (1,115 EUR). The other two main contributors are Benzene (211 EUR) and PAH (131 EUR). The high Chromium VI emission in comparison to renovation concept 1 and 2 is caused by the large amount of low alloy steel used for the sandwich floor-dek panels. The glass wool and OSB that are used for the prefab elements mainly cause the Benzene emissions. The increase in PAH emissions compared to renovation concept 1 is mainly caused by the Aluminium needed for the replacement of the boiler every 15 years.

The GWP and acidification impacts are both mainly produced by burning fossil fuels for energy during material production. Acidification is mainly caused by the use of coal and oil, which emit sulphur dioxide (57% of total acidification) and nitrogen oxide (30% of total acidification) emissions. Another substance that causes acidification is Ammonia (14% of total acidification), which is not linked to GWP.

The most energy intensive materials used in renovation concept 3 are:

- Foundation; concrete beam,
- Façades; PVC window frame,
- Floors; PIR insulation and low alloy steel used in the sandwich floor-dek panels,
- Roof; Glass wool insulation,
- Inside and separating wall; gypsum plaster board,
- Building services installations; both condensing boilers and mechanical ventilation, and
- Facilities and decoration; gypsum plasterboard ceiling

The ammonia emissions mainly occur during the production of zinc coating coils, which are used for the PVC window frames and zinc spiral air ducts.

Renovation concept 2 in functional unit

The environmental impact in functional unit (see section 2.3.1) of renovation concept 3 during its 50 year lifetime extension is shown in figure 24. The environmental impact of the annual energy use is 1.2 times higher than the contribution of the used building materials. The environmental impact of building materials is thus playing an increasingly more important role on the environmental impact.

The impact of renovation concept 3 is almost twice as high as the reference dwelling. The used sandwich floor-dek panels mainly cause this. The EOL bonus is high for renovation concept 3 because of the low alloy steel used in the sandwich floor-dek panels and building services installations.

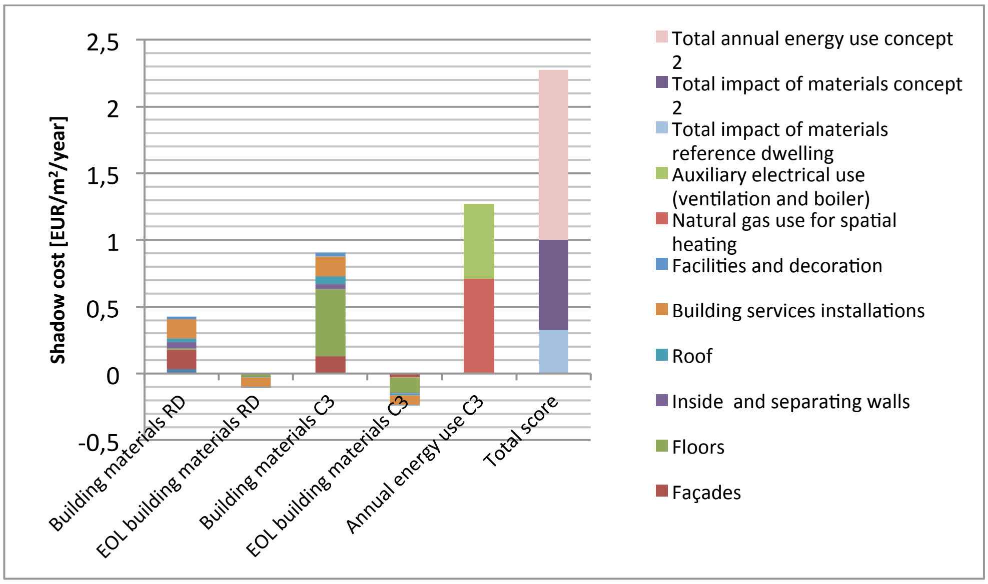

figure 24: Shadow cost of renovation concept 3 [50 years] in functional unit

4.5.4 *Impact on inhabitants and comfort level*

The impact on the inhabitants during renovation concept 3 is high, as the inhabitants will need to move to another dwelling for one month during the renovation. The comfort level is greatly improved by the high exterior insulation and balance ventilation. The replacement of the bathroom, kitchen, staircases and inside walls will give an additional impulse to the comfort level.

4.6 Sensitivity analysis of impact assessment method

The LCA impact assessment method used is CML 2000 baseline, with as endpoint indicator shadow cost, in accordance to the determination method from Stichting bouwkwaliteit (2011). This determination method is used for Dutch buildings and is not the standard for European buildings. In European projects different impact assessment methods can be used than CML 2000 baseline. Therefore the renovation concepts are also calculated with the impact assessment methods ReCiPe 2008 and Eco-indicator 99. The results of the different impact assessment methods, which have a different unit per method, are shown in figure 25. From figure 25 can be concluded that the environmental ranking of the renovation concepts will not change depending on the used impact assessment method. The single score of ReCiPe 2008 and eco-indicator 99 are a lot closer than that of CML 2000 baseline shadow cost.

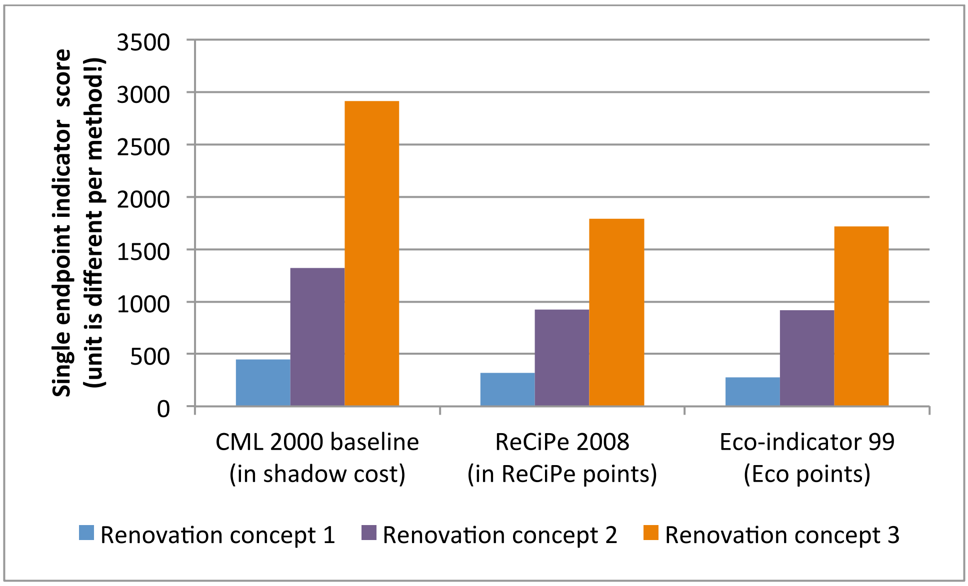

figure 25: Single endpoint score of the impact assessments methods (CML 2000 baseline in shadow cost, Recipe 2008 H in recipe points and Eco-indicator H in eco points).

4.7 Conclusions and discussion

4.7.1 Conclusions

The conclusions from chapter 4 are the following:

- The total building materials used for the high ambition renovation concepts are playing an increasingly more important role in the overall environmental impact of the dwelling. In the current situation the environmental impact of the annual operation energy use is 15 times higher than the building materials, as for renovation concept 2 it is 1.4 times and for renovation concept 3 it is 1.2 times higher.
- When the building exterior is insulated to a level of R_c 3.5 $m^2 \cdot K/W$ or higher, also the theoretical primary energy use of hot water is interesting to reduce besides just energy reduce on spatial heating.
- The following materials have a noticeable and interesting high environmental burden compared to the other materials used in the renovation concept:
  - PVC window frames (renovation concept 1, 2 and 3)
  - Krypton gas used for triple glazing (renovation concept 2)
  - Enamelled glazing parapets (renovation concept 2)
  - Aluminium ornaments (renovation concept 2)
  - PVC roofing material (renovation concept 2)
  - Sandwich panel Floor Dek elements (renovation concept 3)
- The renovation concepts mainly contribute to the following three categories of the 13 environmental impact categories incorporated in the shadow cost: human toxicity, global warming potential, and acidification.
  - Human toxicity is mainly caused by Chromium VI (released during low alloy steel production), PAH (released during aluminium production) and Benzene emissions (produced for Phenol production which is used for OSB and glass wool)

- The global warming potential and acidification are mainly energy related and mostly occur during electricity and heat production needed for the material production.

- Material transport from the manufacturer to the building site, and during the EOL phase just account for +/- 2 to 4% of the total environmental burden.

4.7.2 *Discussion*

In the ecoinvent database a cut off rule is used for recycling. This means that the benefits of recycling are not allocated to the materials that are recycled during their EOL phase (Frischknecht, et al., 2007). In this study the recycling benefits are allocated to the used materials as it was found to be a more justified method to show the environmental impact of the renovation concepts. There are no recycling charts available in the ecoinvent database, therefore the recycling charts are own adaptations based on ecoinvent reports (see appendix D). In the environmental performance sections the environmental impact of the EOL can be seen. For recycling the EOL has a positive impact on the environmental performance, which is mainly due to metal recycling, and therefore plays an important role during the environmental impact comparison of the renovation concepts and their used building materials.

The building material data used for the LCA of renovation concept 2 and 3 came from literature research, information from the supplier, and Mr S. Klerks (TNO expert). The information was not as comprehensive as that of the reference dwelling and can therefore differ from the real reference renovations ("de Kroeven" and " Inschuifwoning"). For the greater part the modelled renovation concepts are similar to the reference renovations, as will be the environmental impact. In some cases materials have a high environmental impact while only a small amount is used, which the case for the Krypton gas used for triple glazing in renovation concept 3 was. It could be that for the reference renovations materials were used in a low quantity that was not accounted for in the renovation concepts, while it has a large environmental contribution. This is due to the fact that the renovation concepts can only be modelled in detail when the specifications and drawings of the reference renovations are available. Therefore the designer of the reference renovations would need to support or be part of the study to deliver all necessary data in detail, which was not the case.

It is assumed that the boiler and heat recovery ventilation unit are replaced every +/- 15 years by the exact same units. This assumption is made as it is unsure what the standard will be in 15 or 30 years. The condensing boiler and ventilation heat recovery have been available on the market for several decades. They are currently in a fully/well-developed stage. The only new introductions on the market today are the combining of ventilation heat recovery with a condensing boiler and the CHP (combined heat power) boiler[37]. However, it is unlikely that a big efficiency leap of these devices will occur in the (near) future and will thus have a relatively low impact on the results. It is more likely that the condensing boiler will eventually be replaced by another heat source, for example a heat pump. Heat pumps have a different efficiency than condensing boilers and use electricity instead of natural

[37] Observed and concluded after visiting the bouwbeurs 2013 in the Jaarbeurs Utrecht, February 2013.

gas. This means that in the future the annual operational energy use might just consist of electricity and the use of natural gas will be completely replaced.

5 Comparison of renovation concepts

In this chapter the baseline and three renovation concepts are compared with one another. The renovation concepts are evaluated according to the in section 2.2 described key performance indicators (KPI's). The functional unit, described in section 2.3.1, is used as standardized unit for the comparison. The characteristics of the baseline and renovation concept scenarios can be found in table 9. In section 4.3 to section 4.5 a more detailed description of the renovation concepts is given. The baseline scenario as described in section 3.5 is used to show the current situation of the reference dwelling.

5.1 Environmental impact comparison

In this study there are three environmental KPI's defined. These environmental KPI's are:

- Shadow cost [EUR],
- GHG-emissions [kg CO_2-equivalent], and
- Mineral resource depletion [kg Sb-equivalent] and [US$].

More information on the environmental KPI's can be found in section 2.2.1 to section 2.2.3. In the next sections the renovation concepts are compared on how they performance per environmental KPI's.

5.1.1 Shadow cost

The shadow cost shows the environmental impact of the different renovation concepts, based on 13 different environmental impact categories under a single denominator (see section 2.2). The environmental performance of the renovation concepts in shadow cost is shown in in figure 26 and is standardized by the functional unit.

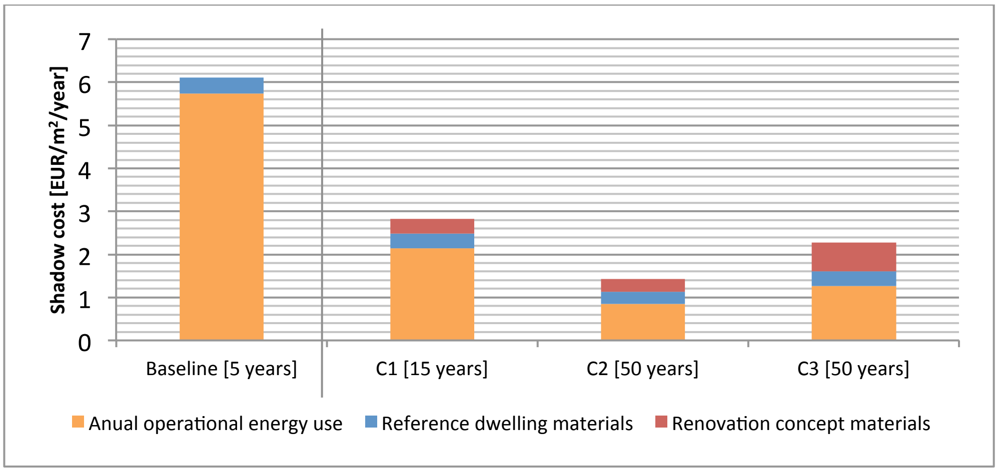

figure 26: Comparison of renovation concept 1, 2 and 3 on the shadow cost.

It can be concluded that from an environmental point of view renovating is always preferred over not renovating the reference dwelling. The amount of environmental damage from the materials used for the renovation is low compared to the induced reduction of the environmental damage of the annual operational energy use, when the baseline scenario is compared to the renovation concepts.

Renovation concept 2 is the best environmental option of the three considered renovation concepts. The difference in the amount of material added for concept 2 in comparison to concept 1 is minimal because of the longer period of time it is used in (50 years instead of 15 years), while the environmental reduction of the annual energy use is more than halved.

5.1.2 *GHG-emissions*

GHG-emissions are mainly produced when fossil fuels are burned to produce heat or electricity. The energy needed for the building materials is relatively low in comparison to the annual operational energy use, as is shown in figure 27. It can be concluded from figure 27 that the GHG-emissions mitigated by the renovation concepts (compared to the baseline) are significantly higher than the amount of GHG-emissions produced for the renovation concepts building materials.

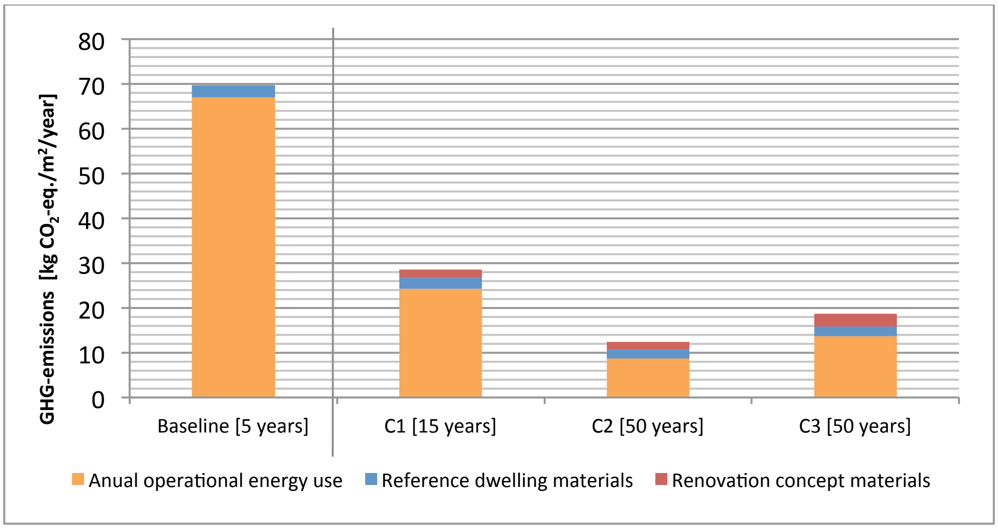

figure 27: Comparison of renovation concept 1, 2 and 3 on GHG-emissions

Mitigation of GHG-emission is the highest for renovation concept 2, which is on this subject the best option out of the three renovation concepts.

The ratio of GHG-emissions emitted by the annual operation energy use and building material is higher than that of the shadow cost. Therefore the building materials play an even less important role during the mitigation of GHG-emissions than during the reduction in annual operational energy use.

The maximum amount of possible GHG-emissions mitigation when the renovation concepts are implemented on the total amount of reference dwellings in the Dutch residential building stock can be calculated with information from table 7 and the GHG-emission deviation of the baseline and renovation concept in figure 27. The maximum amount of possible GHG-emissions mitigation per renovation concept is shown in table 11.

table 11: The possible GHG-emissions mitigation per renovation concept of the total amount of reference dwellings and total amount of terrace houses pre 1974.

Description	Possible GHG-emission mitigation [ton CO_2-eq/year]	
	Total reference dwelling	Total terrace houses pre 1974
Renovation concept 1	1,538,000	5,889,000
Renovation concept 2	2,328,000	8,913,000
Renovation concept 3	2,037,000	7,799,000

The Dutch residential building stock emits 32 million ton CO_2 per year (see section 1.1). The GHG-emissions breakdown of the Dutch residential building stock is shown in figure 1. By renovating all the terrace houses pre 1974 according to renovation concept 2 would avoid 28% of the current GHG-emissions produced by the Dutch residential building stock.

5.1.3 *Mineral resource depletion (excl. energy carriers)*

The mineral resource depletion is shown in two different units. This is done because the used impact assessment method based on stichting bouwkwaliteit (2011) (CML 2000 baseline) shows the mineral resource depletion in kg Sb-equivalent, which is a difficult unit to communicate. Therefore the impact assessment method Recipe 2008 is also used, which shows the metal depletion in US Dollars.

The comparison of the abiotic mineral resource depletion from CML 2000 baseline in kg Sb-equivelant is shown in figure 28. The comparison of metal depletion based on Recipe 2008 in US$ is shown in figure 29.

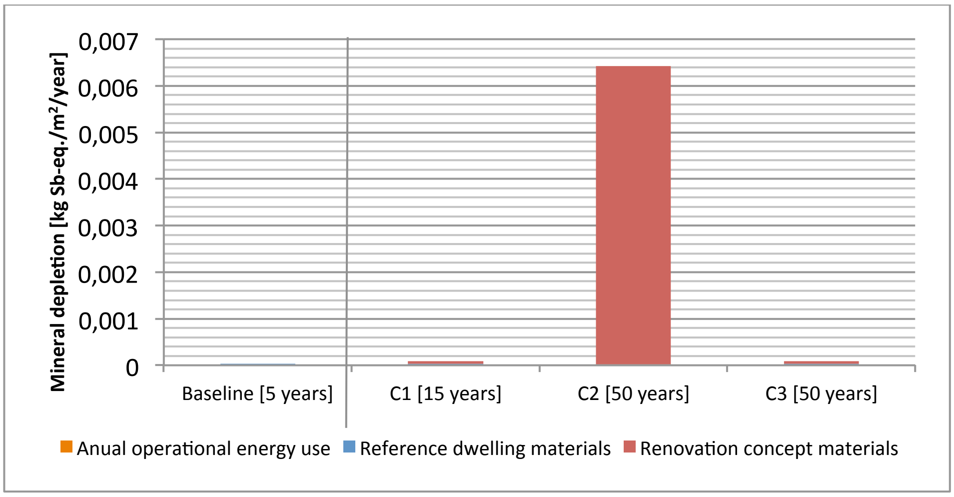

figure 28: Comparison of renovation concept 1, 2 and 3 on mineral depletion (CML 2000 baseline)

The abiotic depletion (excl. energy caries) of renovation concept 2 in figure 28 scores high compared to the other renovation concepts. This is caused by Krypton gas used for triple glazing in renovation concept 2.

The characterization factor used in CML 2000 baseline impact assessment method is 20.9 kg Sb-equivalent per kg krypton. Argon gas, used for double glazing, has a characterization factor of 4.71 x 10^{-7} kg Sb-equivalent per kg Argon. There is a large difference between the two characterization factors, while the difference in atmospheric concentrations (their extraction source) is not as large[38]. Background literature research of the CML 2000 baseline impact assessment did not answer which data were used to formulate the characterization factors. The results could not be compared to other impact assessment methods like Recipe and Eco-indicator 99, because krypton was not used in their characterization of mineral resource depletion.

When the used Krypton gas containing triple glazing is demolished, the Krypton gas can either be collected or will be released back into the atmosphere from which it was extracted. Therefore it is questionable whether the high mineral resource depletion of Krypton gas is justified. The environmental effect of the use of Krypton gas over Argon has is calculated in chapter 7.

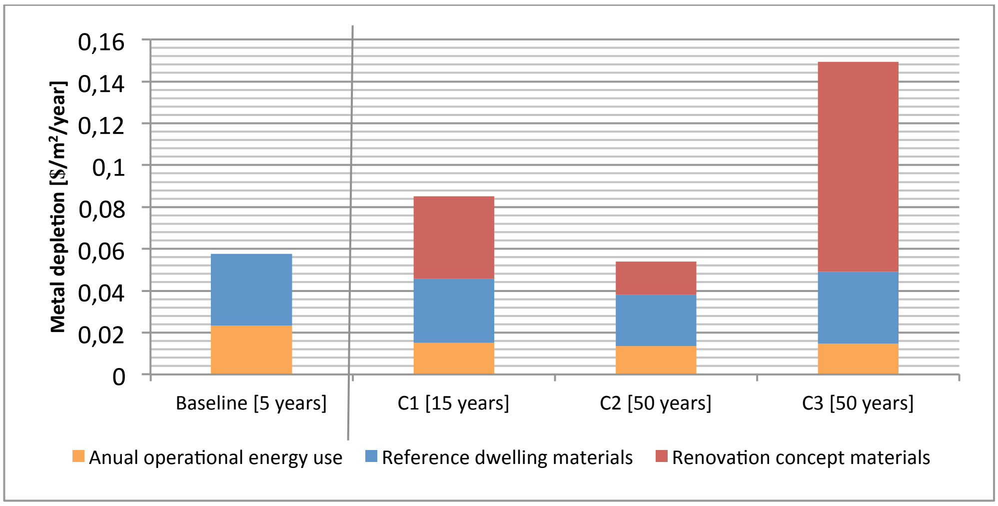

figure 29: Comparison of renovation concept 1, 2 and 3 on metal depletion (Recipe 2008)

The increase in metal depletion is at least when renovation concept 2 is used. The major difference between renovation concepts 1 and 2 is caused by the difference in lifetime extensions. The low alloy steel that is required for the sandwich panel Floor-Dek elements used in renovation concept 3 causes the main difference between renovation concepts 2 and 3.

The depletion of metals causes an increase in price, due to more effort that is required to extract metal from the environment. When all 478,000 reference dwellings (see table 7) are renovated according to renovation concept 3 (with a metal depletion effect of 0.1 US$/m^2/year), the total cost to society would then be 207 million US dollar.

5.1.4 *Sensitivity analysis*

The comparison of the three renovation concepts on the environmental KPI's (section 5.1.1 until section 5.1.3) is based on the thought that the renovation concepts are used until the end of their lifetime extension. This does not necessarily have to be the case. In figure 30 the shadow cost is shown for different lifetime extensions per renovation concept. It shows that for a lifetime of 3 till 7.5 years renovation concept 1 is the best environmental option, while after that period renovation concept 2 is the best option. Thus, if the dwelling is to be used for 3 to

[38] The atmospheric concentration of Argon is 9400 ppm and of Krypton 1 ppm (Wikipedia, 2013).

7.5 years light renovation is the best option, while if the dwelling is expected to be used longer than 7.5 years after its renovation, renovation concept 2 results in the lowest environmental impact. Renovation concept 3 does improve compared to the baseline scenario after 7.5 years (and after 35 years compared to renovation concept 1 projection), but will result in more environmental impact compared to renovation concept 2.

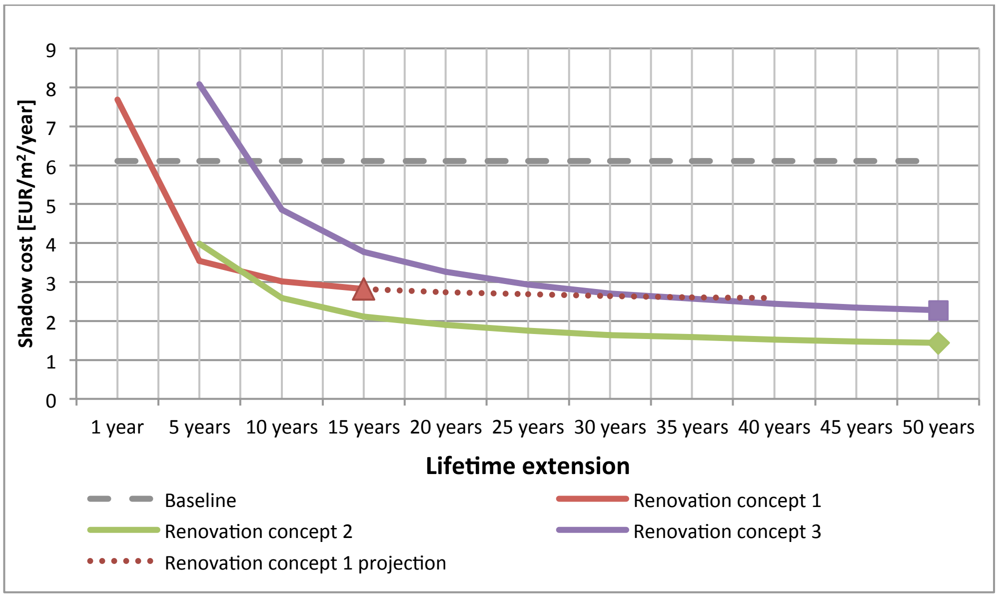

figure 30: Sensitivity of the shadow cost per renovation concept on lifetime extension

The sensitivity analysis graph for the GHG-emission and mineral resource depletion can be found in appendix G. The GHG-emission sensitivity analysis results in renovation concept 2 being the best option for all lifetime extensions. For mineral depletion the difference between renovation concept 1 and renovation concept 2 is very small.

5.2 Economic comparison

The economic comparison is based on the net present cost (NPC) as described in section 2.4. The results in the functional unit are shown in figure 31. For the uncertainty in the investment costs, error bars are shown for the minimum and maximum investment cost found per renovation concept. The annual operational energy costs consist of the natural gas and electric auxiliary energy cost. The data and calculation used are described in section 2.4 and appendix F.

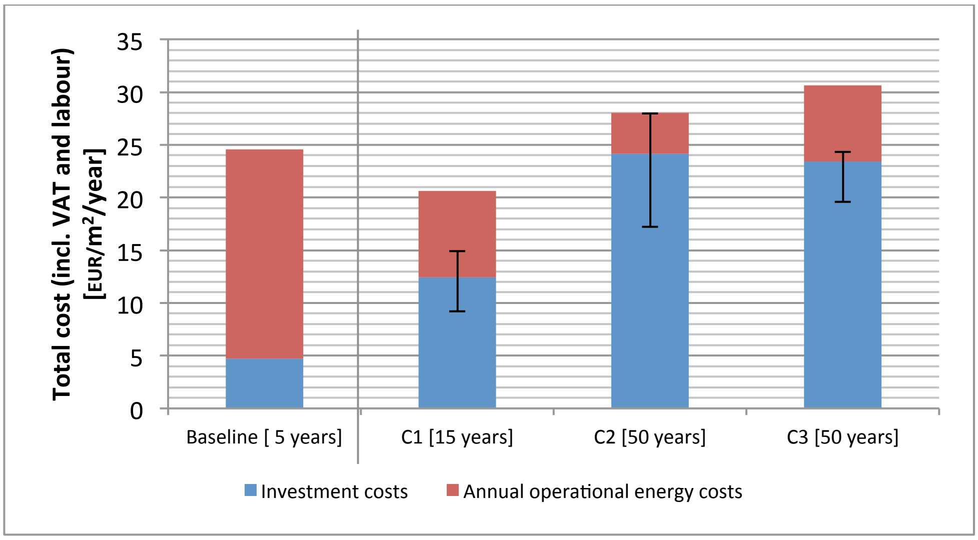

figure 31: The economic comparison given in the functional unit. The investment cost uncertainty is shown in the error bars.

From a cost point of view renovation concept 1 is more interesting, as it is the only renovation concept that is below the baseline. The initial investment cost for the high ambition renovation concepts 2 and 3 is currently too high compared to the cost saved by the reduction in annual operational energy use. The investments cost uncertainty bars do show that the NPC of the renovation concepts 2 and 3 can be equal or lower than the current (baseline) NPC.

To calculate the NPC several parameters were used. During literature research a value was obtained for each parameter (see section 2.4 and appendix F). These values are not fixed and can change depending on the situation and future scenario. To find the effect that these parameters can have on the end result a “what-if” analysis was incorporated in the excel investment model. The “what-if” analysis shows the effect that the parameters have on NPC by a per cent deviation of the used parameter value. If the NPC reaction is high to a small per cent deviation of the used parameter value, the NPC end result is sensitive to a change in that parameter. The sensitivity graphs and used deviation can be found in appendix F. In table 12 a summary is given of the sensitivity per parameter.

table 12: Sensitivity analysis per renovation concept of the NPC (see appendix F)

Description	C1	C2	C3
Initial investment cost	High	High	High
Discount rate	Average/high	Average	Average
Annual increase natural gas price	High	Average	High
Annual increase electricity price	Low	Low	Low

From the sensitivity analysis it can be concluded that the renovation concepts' NPCs are highly sensitive to a deviation in the initial investment cost and annual increase of the natural gas price.

The initial investment in the renovation concepts depends on the construction market. This means that it will no longer remain an uncertainty when the renovation concepts turn into a real project and receive offers from construction companies. The high sensitivity of the initial investment is also favourable for the renovation concepts. In figure 31 is shown that the NPC for renovation concepts 2 and 3 is higher than the baseline. When the investment cost is lowered because of up scaling or the learning effect it will have a high effect on the NPC. This effect could result in the NPC of renovation concepts 2 and 3 becoming below the baseline.

The level of the future gas price is highly uncertain. It is often assumed that prices will increase due to depletion of fossil fuel resources and the past trend (van Cann, 2011). Renovation concept 1 and 3 are more sensitive to appreciation of annual gas as gas usage by concepts 1 and 3s is higher compared to renovation concept 2. Their sensitivity to the annual increase of the electricity price is low, as the auxiliary electricity use (ventilation and boiler) is lower than the annual natural gas consumption.

The annual operational energy use is also uncertain, as that is depended on the inhabitants' behaviour, which is discussed in section 3.6.2.

5.3 GHG-emissions mitigation costs

To combine one environmental impact with the investment and operational costs, the GHG-emission mitigation costs are calculated per renovation concept. The mitigation cost can be interesting for policy makers if they want to use the cheapest measure to reduce GHG-emission.

The mitigation cost equation from Blok (2007) cannot be used, as the cost is not constant over the depreciation time period. Therefore and adaptation from Blok (2007) and Petersdorff, et all. (n.d.) is used instead (see equation 2).

$$MC_{CO_2-eq.} = \frac{NPC_{rc} - NPC_{baseline}}{\Delta M_{CO_2-eq,}} \qquad \text{Equation 2}$$

With:

$MC_{co2\text{-}eq}$	Specific CO_2 equivalent mitigation costs in respect to baseline [EUR per kg CO_2 –equivalent mitigated in respect to baseline].
NPC_{rc}	Net Present Cost of the renovation concept in [EUR/m^2/year].
$NPC_{baseline}$	Net Present Cost of the baseline in [EUR/ m^2/year].
$\Delta MC_{CO_2-eq.}$	The difference in CO_2 equivalent GHG-emissions between the baseline and renovation concept [kg CO_2-equivalent/ m^2/year] .

The CO_2-equivelant mitigation costs per renovation concept are shown in figure 32. The mitigation costs of the renovation concepts with their expected lifetime extension are shown in a bright colour. To show the sensitivity of the lifetime extensions the results are also given at different lifetime extension intervals.

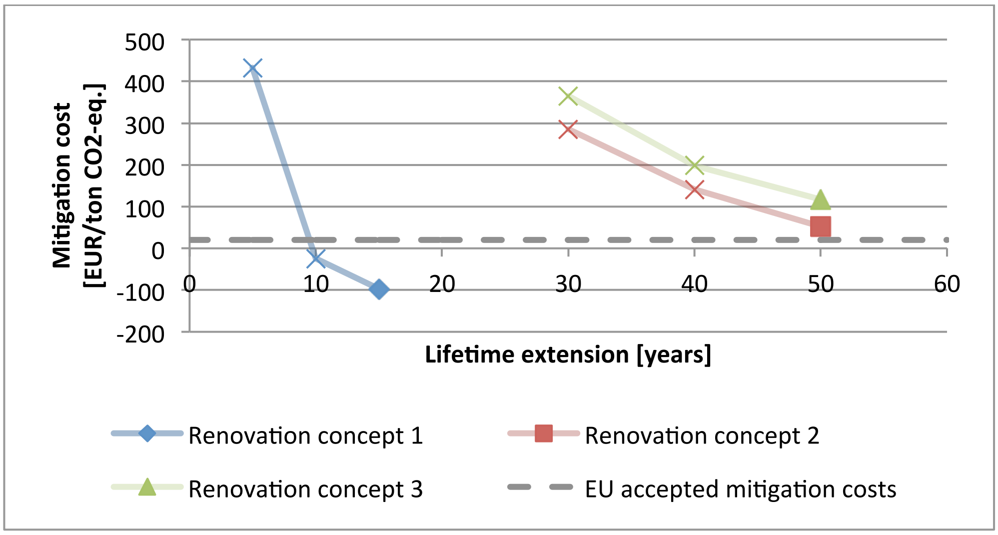

figure 32: Mitigation cost per renovation concept. With an indication of what the mitigation cost would be if the lifetime extension were not met.

Renovation concept 1 could be defined as a no-regret measure as the mitigation cost is negative and implementing this renovation concept would save money. To mitigate GHG-emissions with renovation concept 2 and 3 additional money is required to make the concepts viable.

In the EU member states 20 EUR_{2000}/ton CO_2-eq is widely accepted as an indicative limit of acceptable mitigation costs in the near term (Petersdorff, et al., n.d.). Even if inflation is accounted for both renovation concepts 2 and 3 are above the indicative limit of acceptable mitigation costs.

Concepts 2 and 3 will also remain below the EU carbon permits. The carbon permit price in 2008 was 30 EUR per ton and has currently dropped below 4 EUR per ton (Chaffin, 2013).

In the EU "roadmap for moving to a competitive low carbon economy in 2050" the ambition is set to reduce the GHG-emissions in 2050 with 80% in the EU-member states in respect to 1990 (European comission, 2011). Daniels et al. (2012) conducted a cost-effectiveness study on reaching this 80% emission reduction in 2050. In this study the mitigation costs of different measures required to reach this ambition lie between -150 until almost 400 EUR/ton CO_2-eq.[39] (Daniels, et al., 2012). This means that renovation concepts 2 and 3 are interesting energy saving options in order to reach the 80% reduction of the GHG-emissions in 2050.

[39] The uncertainty in this study is high because of the uncertainty in energy prices and technical costs (Daniels, et al., 2012).

5.4 Conclusions and discussion

5.4.1 Conclusions

The scores of the renovation concepts on the key performance indicator, impact on inhabitants and comfort level in comparison to one another is shown in table 13.

table 13: the score of the renovation concepts per KPI's, impact on inhabitants and comfort level (+ is best score, o is average score and – is worst score)

Description	Renovation concept 1	Renovation concept 2	Renovation concept 3
Shadow cost	-	+	o
GHG-emissions	-	+	o
Mineral depletion	+/o	-	+/o
Metal depletion	o	+	-
Total Cost	+	o	-
Impact on inhabitants	+	o	-
Comfort level[40]	-	o	+

From an environmental perspective the reference dwelling can best be renovated according to renovation concept 2 (high ambition level). When cost is more important than the environment impact renovation concept 1 (low ambition level) is the best option.

When all the terrace houses between 1946 and 1964 (reference dwelling) are renovated according to renovation concept 2 instead of renovation concept 1, around 790,000 ton CO_2 –eq. per year could be additionally mitigated. If it is enlarged to the all the terrace house pre 1974 a total of around 3,030,000 ton CO_2 –eq. per year is additionally mitigated.

Renovation concept 2 scores the best on environmental and cost performance from the two high ambition renovation concepts. The advantage of renovation concept 3 is that the entire interior is also rebuild, which could be preferred if it is in a poor condition.

When policy makers only have a certain amount of money available to spend on GHG-emissions mitigation, renovation concept 1 would be the best option out of the three renovation concepts. In order to reach the EU ambition of 80% emission reduction in 2050, the mitigation costs of renovation concepts 2 and 3 lie within the cost-effective measures mitigation costs.

The environmental score between the renovation concepts is not very sensitive to the lifetime extension of the dwelling (see section 5.1.4). Therefore there is no preference for one of the three concepts.

The net present value used for the total costs is very sensitive to the initial investment and the annual natural gas price increase. Both parameters have a high uncertainty (see section 5.2).

[40] Renovation concept 3 has the highest score over renovation concept 2 for comfort level. This is done as the entire inside (decoration and facilities) is also replaced and it is more or less a brand new dwelling.

Renovation concept 3 scores better on comfort level than renovation concept 2, as the entire interior (kitchen, bathroom, inside walls etc.) is also replaced. From the inhabitants' point of view renovation concept 1 is less intrusive than renovation concept 2 and especially in respect to renovation concept 3, which will not be inhabitable for one month.

5.4.2 Discussion

The answer to research question stated in the introduction depends on the stakeholder. When all the reference dwellings in the Dutch residential building stock are renovated according to renovation concept 2, GHG-emissions are mitigated highest, although at high cost. Despite the high cost, this option will mostly be preferred by environmental organisations. From a cost point of view renovation concept 1 is the best renovation concept. Most Dutch governmental subsidies and policies are aimed at mitigating GHG-emissions at the most cost-effective way. When renovation concept 1 is used, most GHG-emissions can be mitigated for a certain budget available for this. It can be concluded that it is the stakeholder's nature that decides what renovation concept is preferred.

In section 3.1 it is shown that the amount of households will increase in the Netherlands. It is thus unlikely that when the lifetime extension of the baseline scenario and renovation concept 1 has ended, the dwelling is demolished and no replacement will occur. In section 3.1 it is also described that it is unsure whether the same building type will replace the reference dwelling when demolished. The environmental and total cost impact of a new dwelling that will replace the current dwelling (and renovation concepts) has not been accounted for. This will have an impact on the comparison results. How this strongly depends on the materials used. When the building materials of the baseline scenario (60 years) are compared to environmental performance of building materials from renovation concept 2 (50 years) the difference is small in favour of renovation concept 2 (see figure 26). For renovation concept 3 (50 years) this is a lot bigger in favour of the reference dwelling, due to the sandwich panel floors (see figure 26). The environmental performance between renovation and replacement depends mainly on the materials used.

The annual operational energy behaviour (discussed in section 3.6) and the heat generation replacement (discussed in section 4.7.2) have a big influence on the natural gas use and cost. In section 5.2 it is shown that increase in natural gas price has a big influence on the NPC of the renovation concepts. The amount of natural gas used is uncertain but will also have a big impact on the NPC of the renovation concept.

The lifetime extension of the high ambition renovation concepts 2 and 3 is 50 years. In renovation concept 2 only the exterior is replaced and not the interior walls and floors, while in renovation concept 3 they are also replaced. For renovation concept 2 it is thus important that the current floors and inside walls are of such good quality so that they can last the 50 year lifetime extension. This could mean that renovation concept 2 is mainly interesting for dwellings with concrete floors and renovation concept 3 for dwellings with less quality floors, for example timber floors.

6 Renovation improvements

In chapter 4 the environmental performance of the renovation concepts is discussed. In this chapter improvement options per renovation concept are discussed for materials that scored high in chapter 4 on their environmental impact. This chapter is divided in building materials improvements (section 6.1) and energy generation improvements (section 6.2).

6.1 Building materials

In chapter 4 is shown that the environmental impact of building materials will play a more important role as the annual energy use is reduced. In the three renovation concepts materials were used with a high environmental impact that could be improved. The materials that can be improved and have a high environmental impact are shown in table 14.

table 14: materials with a high environmental impact that could be improved per renovation concept.

Description	Renovation concept
- PVC window frames	C1, C2 and C3
- Triple glazing	C2
- Enamelled glazing and aluminium ornaments	C2
- PVC roofing material	C2
- Sandwich panel floor-dek elements	C3

6.1.1 PVC window frame

The PVC window frames have in all renovation concepts a large contribution to the shadow cost of the façades. This is mainly caused by the PVC (58 kg per m^2), low alloy steel (30 kg per m^2), and aluminium (1.1 kg per m^2) materials used in PVC window frames (ecoinvent).

PVC window frames are not the only window frames available on the market today. Other widely used frames consist of aluminium, soft wood or hard wood. In the article of van Ewijk (n.d.) over the LCA of window frames the score of PVC frame is very dependent on its end of life (EOL). The EOL used are incineration, landfill or 90% recycling and 10% incineration. When the EOL is 90% recycling and 10% incineration, the PVC frame has the same low environmental score as aluminium and lower than that of wooden frames. If the EOL is incineration or landfill the environmental score is higher than that of aluminium and wooden frames.

In the report Vogtländer (2010) the PVC window frame has by far the worst environment score out of different (hardwood, softwood, PVC and aluminium) window frames. This is also caused by the method and EOL used in the research, which is also the case in the report Ewijk (n.d.).

The recycling of PVC window frames is the best EOL option in order to make PVC window frames environmental interesting. It is thus important that when PVC-window frames are used a good recycling scheme is in place. Incineration of PVC window frame should be avoided as this has a negative effect on the environment.

The incineration of plastics usually gives a positive environmental effect because of the high energy content of plastics[41], which can be converted into heat and electricity. This is not the case for PVC as Hydrochloric acid (HCL) emissions are produced during the incineration of PVC. To remove the HCL from the flue gas a scrubber is needed that uses 0.463 kg Sodium hydroxide (NaOH) per kg PVC (Ecoinvent v2.2), which causes an additional environmental burden.

The report Vogtländer (2010) also looked at a new material as window frame called Accoya wood. Accoya wood is softwood that is modified with acetic anhydride. This modification ensures a durability of 50 years above ground, swelling and shrinkage is reduced causing paints and varnishes to last 3 or 4 times longer and makes it indigestible to a wide range of insects (Accoya, n.d.). In the LCA of the report from Vogtländer (2010) the Accoya wood window frame has the best environmental score compared to the other window frames (from aluminium, PVC and hardwood).

The Accoya wood window frames with their 50 year durability could be a good replacement, from an environmental point of view, of the PVC window frames that are currently used for the renovation concepts.

6.1.2 Triple glazing

In renovation concept 3 triple glazing is used instead of HR++ double glazing which is used in renovation concept 1 and 2. The two air spaces in triple glazing are filled with krypton gas to reduce the thermal conductivity. The higher shadow cost of triple glazing is also caused by use of Krypton gas (1.22 EUR per m^2 triple glazing) and is high in comparison to that of Argon gas (0.000804 EUR per m^2 double glazing) used in HR++ double glazing.

The thermal conductivity of air is 0.024 W/(m·K), of Argon gas 0.016 W/(m·K) and of Krypton gas is 0.0095 W/(m·K)[42] (Kaye & Laby, n.d.). Argon gas has thus 67% the thermal conductivity of air and Krypton gas 40%. This means thus that Krypton gas insulates 27% better than Argon gas compared to air.

To reach the high glazing standards needed for a passive house level Krypton gas is used as filling for triple glazing (Homebuilding & renovating, 2011). To compensate for its higher environmental impact, Krypton gas in triple glazing should avoid at least the use of 14 m^3 natural gas per m^2 glazing during its lifetime compared to triple glazing with Argon gas filling (see section breakeven point). The total amount of glazing used for the reference dwelling is 21.5 m^2. The total amount of natural gas that Krypton gas needs to avoid compared to Argon gas is 300 m^3 during the lifetime extension of renovation concept 2. This equals 5% of the total natural gas used during the lifetime of renovation concept 2.

<u>Breakeven point</u>

Krypton gas avoids a part of the natural gas used for spatial heating and thus reduces the GHG-emissions. This compensates for its environmental impact during production. The environmental impact of Krypton gas is expressed in shadow cost. To calculate it to the amount of GHG-emissions equivalent the shadow price

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[41] Crude oil is one of the raw materials used for plastic. The use of oil gives plastics a high energy content.

[42] The thermal conductivity is based on a temperature of 273 Kelvin

weighting factor of GHG-emissions is used from Stichting bouwkwaliteit (2011) (see equation 3).

$$\frac{(1.22\ EUR\ shadow\ cost\ per\ m2 - 0.001608\ EUR\ shadow\ cost\ per\ m2^{43})}{0.05\ \frac{EUR\ shadow\ price}{kg\ CO2-eq.}^{44}} = 24.4\ kg\ CO2 - eq.per\ m2 \qquad \text{Equation 3}$$

To calculate the kg CO_2-emmisions to m^3 natural gas the factor from Milieucentraal (n.d.) is used (see equation 4).

$$\frac{24.4\ kg\ CO2 - eq\ per\ m2}{1.73\ \frac{kg\ CO2}{m3\ natural\ gas}^{45}} = 14\ m^3\ natural\ gas\ per\ m2 \qquad \text{Equation 4}$$

The Krypton gas used in triple glazing should thus avoid at least the use of 14 m^3 natural gas per m^2 glazing during its lifetime compared to triple glazing with Argon gas filling.

6.1.3 *Enamelled glazing and aluminium ornaments*

In renovation concept 2 enamelled glazing prefab elements are used as parapet between the floor and window frame. The enamelled glazing prefab elements have a total shadow cost of 68 EUR. The PVC window frame that holds the enamelled glazing and the glazing itself mainly contributes to this.

In the renovation concept “de wijk van Morgen” varnished wood is used instead of enamelled glazing as decorative finishing of the parapet. When 1 cm thick hardwood with varnish is used instead of the enamelled glazing and the rest of the parapet is based on the façade elements from renovation concept 3 the shadow cost is then 10 EUR instead of 68 EUR. This will reduce the shadow cost of renovation concept 2 with 4.5%

The Accoya wood, descript in section 6.1.1, could also be an interesting option for the outside of the parapet. Accoya wood can be used outside uncoated for 50 years, which makes it interesting material for to use for renovation concept 2. In renovation concept 2 also aluminium ornaments are used with a shadow cost of 40 EUR. Accoya wood could also be an interesting option to replace the aluminium ornaments with. More information can be found in Vogtländer (2010) about the LCA of Accoya as decking material.

6.1.4 *PVC roofing material*

The main contributor to the shadow cost of the roof is the PVC roofing material (223 EUR excl. transport). This is relative high compared to the shadow cost of concrete roof tiles (46 EUR excl. transport from the reference dwelling), while fulfilling the “same” function. Although with the PVC roofing material the zinc gutter (31 EUR excl. transport) is not needed. When standard roof tiles (87 EUR excl. transport) are used instead of concrete roof tiles the difference between PVC roofing material is still significant. When concrete tiles are used instead of PVC roofing material the shadow cost of renovation concept 2 will be reduced with 11% and with standard roof tiles it would be 8%.

[43] In triple glazing two air spaces are used instead of one in double glazing thus the shadow price of argon should be doubled
[44] (Stichting bouwkwaliteit, 2011)
[45] (Milieu centraal, n.d.)

6.1.5 Sandwich panel floors

The sandwich panel floor-dek elements used in renovation concept 3 contributed 1695 EUR to the shadow cost. To compare the shadow cost the sandwich panel floor-dek elements used for the first floor and attic floor are replaced by prefab timber elements (see appendix D). For the ground floor the sandwich panel floor-dek elements are still used, because of their insulation and construction characteristics. When the first and attic floor are made from prefab timber elements the shadow cost is 722 EUR instead of 1695 EUR. By using timber prefab floors for the first and attic floor the shadow cost of renovation concept 3 will be reduced with 33%.

6.2 Energy generation

In section 4.5.2 it is concluded that when the building exterior is insulation to a level of R_c 3.5 $m^2 \cdot K/W$ or higher, the theoretical primary energy use of hot water is getting also interesting to reduce besides that of spatial heating. The percentage used for hot water of the total energy used by the dwelling is 46% (see figure 19) for renovation concept 2 and 37% (see
figure 22) for renovation concept 3

To reduce the energy use needed for hot water a solar water heating system (SWH) and/or drain water heat recovery can be used. In “de Kroeven” (renovation concept 2) a solar water heater was used which is not accounted for in renovation concept 2. The 5 m^2 thermal solar collectors and 150 litre boiler saves 50% to 60% of the energy used for hot water (Boonstra, et al., 2011). Based on the Vabi EPA-W calculations this would save 170 m^3 until 210 m^3 of natural gas per year for hot water. This value will differ depending on the inhabitants’ behaviour. The payback period of the SWH lies within its technical lifetime (de Keizer & Alsema, 2008). For the SWH a lot of metals like copper and low alloy steel are needed. This means that the SWH will increase the environmental impact of the building services installations.

The drain water heat recovery can be an interesting option when the dwelling has a shower. The warm water that goes into the drain heats up to cold water that is used during the shower. To connect the drain water heat recovery to the existing drain and cold water piping in renovation concept 2 is difficult. It is a better option for renovation concept 3 where the piping is replaced. The natural gas needed for the hot water during a shower will be reduced with around 30%, depending on the inhabitants’ behaviour (Milieu centraal, n.d.). The payback period of the SWH lies within its technical lifetime (Milieu centraal, n.d.). The drain water recovery is made out of PVC and copper, which both will have an additional environmental impact on the building services installations.

7 Overall conclusions and recommendations

In this study an environmental and economic impact comparison of renovation concepts for Dutch residential buildings has been conducted. The following renovation concepts were defined in this study to be compared to one another:

- *Renovation concept 1:* low ambition (light) renovation, 15 year lifetime extension and energy B label (see section 4.3),
- *Renovation concept 2*: high ambition renovation, 50 year lifetime extension and energy A^{+} label (see section 4.4),
- *Renovation concept 3*: high ambition rebuilding, 50 year lifetime extension and energy A label (see section 4.5), and
- *Baseline scenario:* current situation, 5 year lifetime extension and energy F label (see section 3.5).

The renovation concepts are compared on four key performance indicators (see section 2.2), namely three environmental key performance indicators, shadow cost (main environmental indicator), GHG-emissions and mineral resource depletion, and one economic key performance indicator, net present cost. The environmental indicators were calculated by using the life cycle assessment method, and the economic indicator was calculated with the life cycle costing method (see sections 2.3 and 2.4).

Selecting representative reference dwelling

In this study one representative reference dwelling of the Dutch residential building stock was selected to compare the renovation concepts upon. The reference dwelling was selected by using a multi criteria decision analysis (MCDA). From the MCDA it was concluded that the terrace houses pre 1974 can be used best as reference dwelling in order to reduce the most GHG-emissions produced for spatial heating by the Dutch residential building stock. This conclusion still left three possible reference dwelling possibilities: terrace house pre 1945, terrace house from 1946-1964 and the terrace house from 1965-1974. The terrace house from 1946-1964 was selected as it has the most in common with the other two terrace houses. This will probably result in easy adaptable renovation concepts for the other two terrace houses. (See section 3.3)

The Dutch residential building stock consists for 42% of terrace houses. This would mean that by using the reference dwelling 58% of the Dutch residential building stock is excluded from this research. From an exterior and structural point of view (cavity walls, floors and roof) terrace houses do have a lot in common with the remaining types of the one-family dwellings in the Dutch residential building stock. One-family dwellings form 70% (including terrace house) of the Dutch residential building stock for which the conclusions of this report could also be of interest. (See section 3.1)

Recommended renovation concept

A recommendation on one renovation concept for the Dutch residential buildings is depended on the stakeholders' point of view, desired lifetime extension, dwelling quality and the willingness of the inhabitants. Therefore not one renovation concept can be pointed out as the best solution in every situation. The following conclusions will lead to the best renovation concept depending on specific situations.

Firstly, the renovation materials used for the renovation concepts have a high environmental impact in the first years of the lifetime extension. Renovation concept 1 surpasses the baseline scenario after a 3 year lifetime extension (see figure 30). From this point on the reference dwelling can better be renovated (by concept 1) than be left in its current state. The first 3 until 7.5 years renovation concept 1 is the best renovation option, after which renovation concept 2 becomes the best environmental option, till a lifetime extension of approximately 30 years. Renovation concept 3 does improve compared to the baseline after 7.5 years, but will result in a higher environmental impact compared to renovation concept 2. To conclude, when the dwelling is to be used for another 3 to 7.5 years renovation concept 1 will be the best option. When the dwelling is expected to be used longer than 7.5 years, renovation concept 2 results in the lowest environmental impact. (See section 5.1)

Secondly, also the economic perspective should be taken into account. When the economic perspective is more important than that of the environment, renovation concept 1 (NPC of 20.5 EUR/m^2/year) is the best option. The initial investment costs for the high ambition renovation concepts 2 (NPC of 28 EUR/m^2/year) and 3 (NPC of 30.5 EUR/m^2/year) are currently too high in comparison to the costs saved by the reduction in annual operational energy use. Between the two high ambition renovation concepts it is best to pursue renovation concept 2 from an economic point of view. (See section 5.2)

Subsequently, when one of the major environmental impact factors, GHG-emission, was combined to its investment and operational costs per renovation concept, it can be concluded that renovation concept 1 (-97 EUR/ton CO_2-eq. mitigated) is the most cost-effective way to mitigate the GHG-emission, compared to renovation concept 2 (52 EUR/ton CO_2-eq. mitigated) and renovation concept 3 (117 EUR/ton CO_2-eq. mitigated). This is of great importance for policy makers that have a certain budget available for on GHG-emissions mitigation; renovation concept 1 would be the best option out of the three renovation concepts. (See section 5.3).

Thirdly, there should also be paid attention to the lifetime expectancy of the dwellings. The average realistic lifetime expectancy of a Dutch dwelling is 120 years. The current age of the reference dwelling is 55 years, which implies that renovation concept 1 is a short-term solution compared to renovation concept 2 and 3. After the 15 year lifetime extension renovation concept 1 gets either a high ambition renovation or no action is taken. During that period the additional GHG-emissions cannot be mitigated, as they would have been by renovation concept 2. Additionally, when all terrace houses from 1946 until 1964 (reference dwelling) are renovated according to renovation concept 2 instead of renovation concept 1, around 790,000 ton CO_2–eq. could have been mitigated. If the scale is enlarged to the all terrace houses pre 1974, a total of approximately 3 million ton CO_2 –eq. per year could have been additionally mitigated of the total 32 million ton CO_2 –eq. produced per year by the total Dutch building stock. (See section 5.1.2)

Fourthly, the renovation concept will also have an impact on the inhabitants of the dwelling. The least intrusive concept on the inhabitants is renovation concept 1, followed at short distance by renovation concept 2, while for renovation concept 3 the inhabitants will have to move out of their dwelling for one month. This could be a decisive point for Dutch housing corporations that own 57% of the reference dwellings. In addition, the inhabitants also have an impact on the environmental and economic performance of the renovation concepts. The environmental and economic performances are both very sensitive to the inhabitants' behaviour, because they influence the annual operational energy use. The annual operational energy use on its turn has a major influence on the environmental impact and net present cost. This means that the conclusions on the renovation concepts can differ per dwelling due to the inhabitants' behaviour. (See sections 3.6.2, 4.2 and 5.4.2)

At last, the quality of the current building is also an important factor. To use renovation concept 1 and 2 the interior of the dwelling (inside walls, floors and foundation) should be of such a good quality that it can still be used for another 15 to 50 years. If this is not the case renovation concept 3 could be the only solution, although for renovation concept 3 the foundation also needs to last for another 50 years.

Recommendations for improvement

To make high ambition renovation more attractive than low ambition renovation, decreases in (material related) economic and environmental impact are important. In this study environmental improvement opportunities are provided that will lower the environmental impact and can therefore also lower the GHG mitigation costs (see section 6.1). There are also energy generation improvement opportunities provided that can reduce the net present cost of the renovation concepts (see section 6.2).

It is shown in chapter 4 that the environmental impact of building materials will play a more important role in high ambition renovations, due to the annual energy use reduction. This means that the choice of building materials used is increasingly more important. The following materials used in the renovation concepts could be improved (see section 6.1):

- PVC window frames used in renovation concept 1, 2 and 3,
- Krypton gas used in triple glazing for renovation concept 2,
- Enamelled glazed parapets and aluminium ornaments in renovation concept 2,
- PVC roofing materials used in renovation concept 2, and
- Sandwich floors-dek panels used in renovation concept 3.

It is concluded in section 4.5.2 that when the building exterior is insulation to a level with an R_c value of 3.5 $m^2 \cdot K/W$ or higher (the theoretical), reduction of primary energy use on hot water is of increasing interest, besides reducing energy use on spatial heating. Therefore reducing energy required for hot water in renovation concepts 2 and 3 is also important for the energy performance of the reference dwelling. The following technologies are interesting for the improvement of the two renovation concepts' hot water generation (see section 6.2):

- Solar water heater for renovation concepts 2 and 3, and
- Drain water heat recovery for renovation concept 3.

Further research

In this study the technical part of different renovations is addressed to reduce GHG-emissions in the Dutch residential building stock. In order to carry out a full-scale renovation project in the Dutch residential building stock a social research into what the stakeholders, the barriers and opportunities are needs to be conducted. The Dutch government already made renovation agreements with the Dutch social housing corporations, although not with private homeowners that own 60% of the Dutch residential building stock. During the renovation project “033 energie” in Amersfoort they had great difficulty in reaching the private homeowners. Only the so called “street ambassadors” scheme worked to convince private homeowners of renovation of their dwelling (Schotman, 2013). The question that needs to be answered is what the Dutch government needs to do in order to stimulate renovation among private homeowners.

The high ambition renovation concepts are interesting from an environmental point of view, however the initial investment costs are currently too high compared to the costs that could be saved. It should be investigated how these high ambition renovation concepts can be applied in a more cost-effective way. Could this be achieved by increasing standardisation and prefabbing, although a great part of this is already performed for example in the projects “de Kroeven” and “Bestaande wijk van morgen”, or could a new (GHG- mitigation) business model be a solution to make these high ambition renovation more economically attractive?

The Dutch society is aging, the amount of households is growing, there is a shortage of student rooms, there are regions in the Netherlands declining and growing in population. All these factors will influence the current and future Dutch residential building stock. What could be the role of renovation versus demolition and replacement for these (future) developments? A recent measure in the south of the province Limburg, which is a population decline region, is that a dwelling first needs to be demolished before it is allowed to build a new (Eigenhuis, 2013). It would be interesting to investigate whether and how renovation and/or replacement could take advantage of these different developing situations in the Dutch residential building stock.

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A Previous research

There has already been research done on analysis and renovation the Dutch residential building stock. A number of papers are named with their conclusion about a reference building for the Dutch residential building stock.

“PLUG-component” (Weijers, 2010)
The Dutch residential buildings from 1945 until 1975 don’t meet the modern quality demands because of their indoor surface area, poor comfort and bad indoor air quality. In this report a terrace building from 1945 until 1965 was chosen as the reference building to be renovated. This decision was based on; the amount built, the lack of insulation compared to 1965-1975 and the width of the façade.

“Kosteneffectieve energiebesparing en klimaatbescherming” (Ecofys, 2005)
In this paper among other things the CO_2-emission reduction potential for the Dutch residential housing stock is examined. In the paper it is concluded that the biggest CO_2-emission reduction can be achieved in privately owned pre 1966 dwellings and post-war (rented) terrace buildings pre 1980.

“Van E naar Beter” (Dijkmans & Jonkers, 2011)
The dwellings being built between 1945 until 1975 were not or poorly insulated. Afterwards insulating them occurred occasionally after the energy crisis in 1973. During the time period 1945-1975, terrace dwellings were the most constructed dwelling type. These buildings were built in neighbourhoods close to the city centre, schools and shops, which make them more attractive than newly build neighbourhoods. Most inhabitants

“Energiebesparing in bestaande woningvoorraad’ (Bogerd, 2009)
Dwellings that have been built between 1945 until 1966 have the worst insulation of the Dutch residential building stock, than buildings pre 1946 or post 1966. This does not apply to glass insulation, but for roof insulation, floor insulation and wall insulation. In this category the least post-isolation was also added pertaining to other building periods. It turns out that most dwellings built before 1976 still need to be isolated.

“Energiezuinige renovatie van naoorlogse woningbouw” (Sanjee, 2007)
In this research the terrace dwellings from 1950 until 1960 were examined. For this particular dwelling type was chosen because of the amount build, the poor insulation and the Dutch social housing corporations own a large part. In the past 25 years social housing corporations improved the thermal comfort by post isolation, frames with glazing and the boiler were replaced.

Conclusions about reference buildings from previous research:

- In previous research mainly terrace dwellings were used as reference buildings because of:
  - The amount of terrace dwellings being built
  - Poor insulation
  - A lot are owned by Dutch social housing corporations
  - They all look almost the same, thus a good interchange ability
- The biggest CO_2-emission reduction by dwellings can be done in:
  - Privately owned pre 1966 dwellings

  - Post-war (rented) terrace buildings pre 1980
- Renovations have taken place in dwellings owned by the socials housing corporations.

B Representative dwellings data

table B1: Representative dwellings with data. Source: (W/E-adviseurs & PRC, 2011)

Building type	Year	Amount	Per cent of building stock	Privately owned	Private rented	Social rented	Energy label
Large detached house	pre 1964	441,000	6,50%	91%	8%	1%	G
Large detached house	1965-1974	119,000	1,80%	95%	4%	1%	F
Large detached house	1975-1991	221,000	3,30%	96%	4%	0%	D
Large detached house	1992-2005	178,000	2,60%	98%	2%	0%	B
Semidetached house	pre 1964	285,000	4,20%	84%	6%	10%	F
Semidetached house	1965-1974	142,000	2,10%	84%	2%	14%	E
Semidetached house	1975-1991	224,000	3,30%	90%	6%	4%	C
Semidetached house	1992-2005	173,000	2,60%	95%	3%	2%	B
Terrace house	pre 1945	523,000	7,70%	71%	6%	23%	G
Terrace house	1946-1964	478,000	7,00%	40%	3%	57%	F
Terrace house	1965-1974	606,000	9,00%	47%	6%	47%	E
Terrace house	1975-1991	879,000	12,90%	61%	5%	34%	D
Terrace house	1992-2005	353,000	5,20%	78%	3%	19%	C
Maisonette	pre 1964	226,000	3,30%	29%	27%	44%	G
Maisonette	1965-1974	22,000	0,30%	17%	20%	63%	D
Maisonette	1975-1991	94,000	1,40%	21%	3%	76%	C
Maisonette	1992-2005	40,000	0,60%	39%	17%	44%	B
Gallery flat	pre 1964	69,000	1,00%	33%	11%	56%	D
Gallery flat	1965-1974	174,000	2,60%	16%	11%	73%	E
Gallery flat	1975-1991	109,000	1,60%	17%	17%	66%	C
Gallery flat	1992-2005	113,000	1,70%	34%	8%	58%	B
Porch flat	pre 1945	256,000	3,80%	23%	40%	37%	F
Porch flat	1946-1964	267,000	3,90%	17%	17%	66%	E
Porch flat	1965-1974	112,000	1,70%	17%	7%	76%	D
Porch flat	1975-1991	142,000	2,10%	14%	10%	76%	C
Porch flat	1992-2005	70,000	1,00%	33%	4%	62%	B
Other flats	pre 1964	99,000	1,50%	23%	17%	60%	E
Other flats	1965-1974	125,000	1,80%	13%	24%	63%	E
Other flats	1975-1991	125,000	1,80%	19%	16%	65%	C
Other flats	1992-2005	136,000	2,00%	47%	11%	42%	B

C Multi-criteria decision analysis

The score given to each representative dwelling and final score with and without weight factor are shown in table C1.

table C1: Results of the MCDA of the representative buildings from Agentschap NL with and without weight factors used.

Description	Energy performance	Age	Amount	Up scaling	Total score without weight factors	Total score with weight factors
Maisonette 1992-2005	2	2	1	3	8	**19**
Porch flat 1992-2005	2	2	1	4	9	**20**
Other flats 1992-2005	2	2	1	4	9	**20**
Detached house 1992-2005	2	2	2	2	8	**20**
Gallery flat 1992-2005	2	2	1	5	10	**21**
Semidetached house 1992-2005	2	2	2	4	10	**22**
Maisonette 1975-1991	3	3	1	3	10	**26**
Porch flat 1975-1991	3	3	1	4	11	**27**
Porch flat 1965-1974	3	3	1	4	11	**27**
Other flats 1975-1991	3	3	1	4	11	**27**
Detached house 1975-1991	3	3	2	2	10	**27**
Gallery flat 1975-1991	3	3	1	5	12	**28**
Terrace house 1992-2005	3	2	3	5	13	**29**
Semidetached house 1975-1991	3	3	2	4	12	**29**
Maisonette 1965-1974	3	4	1	3	11	**29**
Gallery flat pre 1964	3	4	1	5	13	**31**
Other flats 1965-1974	4	4	1	4	13	**34**
Semidetached house 1965-1974	4	4	1	4	13	**34**
Other flats pre 1964	4	4	1	4	13	**34**
Terrace house 1975-1991	3	3	5	5	16	**36**
Detached house 1965-1974	5	4	1	2	12	**36**
Gallery flat 1965-1974	4	4	2	5	15	**37**
Maisonette pre 1964	5	4	2	3	14	**39**
Porch flat 1946-1964	5	4	2	4	15	**40**
Porch flat pre 1945	5	4	2	4	15	**40**
Semidetached house pre 1964	5	4	2	4	15	**40**
Detached house pre 1964	5	4	4	2	15	**42**
Terrace house 1965-1974	4	4	5	5	18	**43**
Terrace house pre 1945	5	4	4	5	18	**45**
Terrace house 1946-1964	5	4	4	5	18	**45**

D Life Cycle Assessment data

In this appendix the used data and assumptions made during the LCA are given for the reference dwelling and three renovation concepts.

General material data

table D1: General material data

Description	Unit	value	Source
PVC	[kg/m^3]	1,400	(Vringer & Blok, 1993)
Sand	[kg/m^3]	1,350	(Vringer & Blok, 1993)
Steal/iron	[kg/m^3]	7,900	(Vringer & Blok, 1993)
Copper	[kg/m^3]	8,900	(Vringer & Blok, 1993)
Softwood and OSB	[kg/m^3]	580	(Vringer & Blok, 1993)
Gypsum	[kg/m^3]	957	(Vringer & Blok, 1993)
Plywood	[kg/m^3]	350	(Vringer & Blok, 1993)
Hardwood (Meranti)	[kg/m^3]	550	(Vringer & Blok, 1993)
Mortar	[m^3 mortar /m^3 bricks]	0.15	(Vringer & Blok, 1993)
Glass wool	[kg/m^3]	35	(Vringer & Blok, 1993) and ISOVER
Zinc	[kg/m^3]	6,900	(Vringer & Blok, 1993)
Limestone	[kg/m^3]	1,800	(Vringer & Blok, 1993)
Clay brick (Waalstenen)	[kg/m^3]	1,220	(Vringer & Blok, 1993)
High density clay brick (Gevelklinkers)	[kg/m^3]	2,100	(van Boxtel, 1995)
Concrete mortar	[kg/m^3]	1,900	(van Boxtel, 1995)
Stucco/plasterwork	[kg/m^3]	1,300	(van Boxtel, 1995)
EPS (Expended Polystrene)	[kg/m^3]	30	Ecoinvent v2.2 database
Single glazing	[kg/m^2]	10	Ecoinvent v2.2 database
Double glazing	[kg/m^2]	20	Ecoinvent v2.2 database
Triple glazing	[kg/m^2]	30	Ecoinvent v2.2 database
Natural stone	[kg/m^3]	2,275	Ecoinvent v2.2 database
Cellulose fibre	[kg/m^3]	50	Ecoinvent v2.2 database
PE LDPE	[kg/m^3]	920	Ecoinvent v2.2 database
PE HDPE	[kg/m^3]	950	Ecoinvent v2.2 database
PIR/PUR	[kg/m^3]	40	(Duijve, 2012) and (van Boxtel, 1995)
Aluminium	[kg/m^3]	2,700	(Wikipedia, 2013)
Cement fibre panel 8 mm	[kg/m^2]	15.4	(Eternit, n.d.)
Window frame	[m^2/ m^2 window]	0.21	(Kellenberger, Althaus, Kunniger, Lehmann, & Jungbluth, 2007)
Window glazing	[m^2/ m^2 window]	0.79	(Kellenberger, Althaus, Kunniger, Lehmann, & Jungbluth, 2007)

Recycling

The waste scenarios of the material are based on the NEN 8006:2004. The waste scenarios per material are divided in a percentage landfill, incineration, recycling and reuse. In Ecoinvent a cut-off rule is used for the recycling of materials in which the environmental impact is set to zero (Frischknecht, et al., 2007). As recycling avoids the input of (half) fabricates into the production process, it is assumed in this study, that recycling does have an environmental contribution. As no recycling charts are available in Econinvent, the following assumptions have been made for the recycling charts:

Aluminum

It is assumed that the produced "aluminum scrap, old" is recycled and produced in to "aluminum, secondary, from old scrap, at plant", which replaces the amount of "aluminum primary, at plant" needed for aluminum products[46]. A simplified overview of the aluminum production process can be found in Classen et al. (2007).

For the recycle chart 1 kg of aluminum scrap is processed into (1kg / 1,03 kg)[47] secondary aluminum. The chart "aluminum, secondary, from old scrap, at plant" chart is adapted to 1 kg of scrap input instead of the current 1,03 kg. The scrap preparation process is included in this chart. An overall efficiency of 90% is assumed from sorting plant to production process input. The avoided product is (1kg / 1,03 kg)*90% "aluminum primary, at plant".

Copper

It is assumed that the produced "Copper scrap, old/RER" is recycled and produced into "copper, secondary, at refinery/RER", which replaces the amount of "copper primary, at refinery/RER" used in copper products[48]. A simplified overview of the copper production process can be found in Classen et al. (2007).

For the recycle chart 1 kg of copper scrap is processed into (1kg / 1,31 kg)[49] secondary copper. The chart of "copper, secondary, at refinery" is used as recycle chart, which also includes the scrap preparation process[50]. The chart is adapted to 1 kg of scrap input instead of the current 1,31 kg. An overall efficiency of 90% is assumed from sorting plant to production process input. The avoided product is (1kg / 1,31 kg)*90% "copper primary, at refinery".

Steel

It is assumed that 1 kg "steel scrap", based on the simplified production process overview from Classen et al. (2007), can replace the use of "pig iron, at plant". An overall efficiency of 90% is assumed from sorting plant to production process input. The avoided product is 1kg*90% "pig iron, at plant".

[46] For the building materials of the renovation concepts "aluminum primary, at plant" is used.
[47] To produce 1 kg of secondary aluminium, 1.03 kg of aluminium scrap is needed (ecoinvent)
[48] For the building materials of the renovation concepts "copper primary, at plant" is used.
[49] To produce 1 kg of secondary copper, 1.31 kg of copper scrap is needed (ecoinvent)
[50] In ecoinvent iron scrap is used instead of copper because of the ecoinvent cut off rule, thus the origin does not play a role (Classen, et al., 2007)

Zinc

There is no secondary process for zinc in Ecoinvent. It is assumed "zinc concentrate, at beneficiation/GLO U" needed for "zinc primary, at regional storage/RER U" can be avoided by recycling zinc scrap. As scrap preparation process the chart "Iron scrap, at plant/RER U" is used[51]. An overall efficiency of 90% is assumed from sorting plant to production process input. The avoided product is (1/1.903)[52] kg*90% "zinc concentrate, at beneficiation/GLO U" per kg zinc scrap.

Brick

It is assumed that from 1 kg clay brick "Gravel, crushed, at mine/CH U" can be made with an efficiency of 90%. To account for the energy needed to crush the brick a TNO chart "vaste breker ex trans" is used.

Concrete

It is assumed that from 1 kg concrete "Gravel, crushed, at mine/CH U" can be made with an assumed efficiency of 90% from sorting plant to production process input. To account for the energy needed to crush the brick a TNO chart "vaste breker ex trans" is used.

Limestone

It is assumed that old limestone bricks can avoid "sand, at mine/CH U" input for new limestone bricks (Xella, n.d.). An overall assumed efficiency of 90% % is assumed from sorting plant to production process input. To account for the energy needed to crush the brick a TNO chart "vaste breker ex trans" is used.

Stucco/gypsum

It is assumed that from 1 kg stucco (1/1.16) kg "Gypsum, mineral, at mine/Ch U"[53] can be produced during recycling. An overall assumed efficiency of 90% is assumed from sorting plant to production process input. To account for the energy needed to crush the brick a TNO chart "vaste breker ex trans" is used.

Glass

The old flat glass is reused in the production process as substrate. It is assumed "limestone, milled, packed, at plant/CH U", "Silica sand, at plant/DE U" and "Soda, powder, at plant" are avoided with a ratio (1/1.208)[54]. An overall assumed efficiency of 90% is assumed from sorting plant to production process input. Possible contamination of the glass has not been taken into account.

Glass wool

The old glass wool is reused in the production process as substrate. It is assumed that "Glass cullets, sorted, at sorting plant/CH U", "Silica sand, at plant/DE U", "Soda, powder, at plant" and "Formaldehyde, production mix, at plant/RER U" can be avoided with a ratio (1/1.091)[55]. An overall assumed efficiency of 90% is

[51] In ecoinvent iron scrap is used instead of copper because of the ecoinvent cut off rule, thus the origin does not play a role (Classen, et al., 2007)
[52] To produce 1 kg of zinc, 1.93 kg of zinc concentrate is needed (ecoinvent)
[53] To produce 1 kg of stucco, 1.03 kg of gypsum mineral is needed (ecoinvent)
[54] To produce 1 kg of flat glass, 1.208 kg of materials are needed (ecoinvent)
[55] To produce 1 kg of glass wool, 1.091 kg of materials are needed (ecoinvent)

assumed from sorting plant to production process input. Possible contamination of the glass wool has not been accounted for.

<u>PE</u>
The main component in PE granulate is “oil,crude”. It is assumed that by recycling PE the oil input is avoided. Per 1 kg PE 0.84 kg crude oil is needed. It is assumed that by recycling process has a efficiency of 90%. Contamination and the times that the product can be recycled are not accounted for.

<u>PU</u>
The main components in PU rigid foam are “Methylene diphenyl diisocyanate, at plant/RER U” and “polyols”. It is assumed that by recycling PU these product are avoided with a ratio of (1/1.056). It is assumed that by recycling process has a efficiency of 90%. Contamination and the times that the product can be recycled are not accounted for.

<u>PVC</u>
The main components in “Polyvinylchloride, at regional storage/RER U” are “Polyvinylchloride, emulsion polymerized, at plant/RER U” and “Polyvinylchloride, suspension polymerized, at plant/RER U”. It is assumed that by recycling these products are avoided at a assumed efficiency of 90%. Contamination and the times that the product can be recycled are not accounted for.

<u>EPS</u>
The main component in “polystyrene, expandable, at plant/RER U” is “oil,crude”. It is assumed that by recycling EPS the oil input is avoided with a ratio (1kg/1.0429kg). It is assumed that the recycling process has a efficiency of 90%. Contamination and the times that the product can be recycled are not accounted for.

Reference dwelling

The reference dwelling materials are based on the report of Vringer & Blok (1993). The measurements and current state came from the report W/E adviseurs & PRC (2010) and Hoogers et al (2004). For additional constructional and material information the reports Sanjee (2007), Weijers (2010) and Bone (2008) were used.

Foundation
The terrace house is built on a masonry foundation. An assumption is made that there are no support piles needed. The masonry foundation has a pyramid shape as can be seen in figure B1. The cross section has an surface area of 0.3 m2 (Bone A. , 2007). The front and back foundations are 5.5 meter wide and the side foundations are 8 meter long (Hoogers, et al., 2004). The inside measurements of the dwelling are 5.25 x 7.75 meter and the outside measurements are 5.75 x 8.25 meter. Because the side foundation is used by two dwelling only half of it is accounted for in the LCA. There are also two brick footings placed to support a wooden beam for the ground floor (Sanjee, 2007). The footings

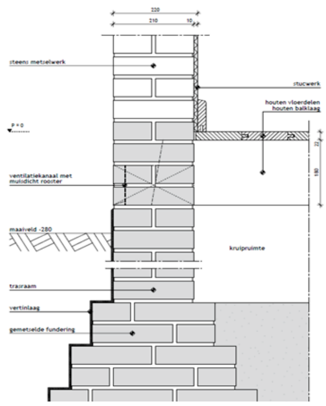

Figure D1: Example of foundation that was used are made from 0.1 m3 of bricks (Bone A. , 2007). During the foundation and footing construction Lime mortar is used (Bone A. , 2007). Stamped concrete could have been used as extra support of the foundation but is not accounted for (Sanjee, 2007). A “trasraam”, built from a denser brick, of 10 layers is used for the front and back façade against upcoming moisture (Sanjee, 2007). For the “trasraam” concrete mortar is used.

table D2: Data of materials used for the foundation RD

Description	Material	Unit	Value
Ground work	Sand	m^3	4.7
Masonry foundation	Clay bricks	Total kg	6950
Trasraam	Dense clay bricks	Total kg	2310
Lime mortar	Lime	Total kg	1680
Cement mortar	Cement	Total kg	314

Façades

The exterior wall is a non-insulated cavity wall with a 50 mm air cavity. The outer skin is made from 100 mm clay bricks and the inner wall from 100 mm limestone bricks (Weijers, 2010). The total closed surface area of one facade is 21.15 m^2 (W/E-adviseurs & PRC, 2011). From this the “ trasraam” surface area, from the foundation, is subtracted: 21.15 m^2 - 2.75 m^2 = 18.4 m^2. During construction the dwelling was fitted with a total of 21.5 m^2 single glazing with a wooden frame. During a past renovation the glazing on the ground floor was replaced by 15 m^2 double glazing (W/E-adviseurs & PRC, 2011). Assumed is that the double glazing was also placed with a new wooden frame. The dwelling is fitted with two outside doors from hardwood and glass (Vringer & Blok, 1993).

table D3: Data of materials used for the facades RD

Description	Material	Unit	Value
Brick	Clay	kg/m^2 façade	122
Limestone brick	Lime stone	kg/m^2 façade	320
Cement mortar	Cement	kg/m^2 façade	57
Door frame	Hardwood	m^3/door	0.102
Door	Hardwood	m^3/door	0.0373
Door glazing	Single glazing	m^2/door	1.02
Window frame	Wood frame	m^2/ m^2 window	0.21
Window glazing	Single glass	m^2/ m^2 window	0.79
Window frame	Wood frame	m^2/ m^2 window	0.21
Window glazing	Double glass	m^2/ m^2 window	0.79

Floors

The inside measurements of the dwelling are 5.25 x 7.75 meter (Hoogers, et al., 2004). The total inside floor area is thus 41 m^2. The dwelling has a total of three wooden floors. The floor finishing is from 18 mm softwood boards (Sanjee, 2007). Under the floorboards 65x140mm softwood joints are placed (Sanjee, 2007). Only under the ground floor an 80x180mm support beam is placed that rests on the two brick foundation footings (Sanjee, 2007). For the first and attic floor 2 m^2 per floor is subtracted for the staircases.

table D4: Data of materials used for the floors RD

Description	Material	Unit	Value
Ground floor	Softwood	m^3/ m^2 floor	0.0335
1^{st} and attic floor	Softwood	m^3/ m^2 floor	0.0344

Inside and separating walls

The dwelling separating walls are made out of 230 mm limestone blocks and cover a surface area of 55 m^2 (Vringer & Blok, 1993). In the LCA half of the separating wall is used, as two dwellings share it. The glue needed for the limestones is not accounted for (Vringer & Blok, 1993). The inside walls are made from gypsum blocks that are 70 mm thick and have a surface area of is 57 m^2 (Vringer & Blok, 1993). The dwelling has a total of 8 inside doors (Sanjee, 2007). The inside doors and doorframes are made from wood (Vringer & Blok, 1993).

table D5: Data of materials used for the floors RD

Description	Material	Unit	Value
Limestone blocks	Limestone	kg/m^2 wall	414
Gypsum blocks	Gypsum	kg/m^2 wall	67
Inside door	Plywood	m^3/door	0.0137
	Softwood	m^3/door	0.015
Inside door frame	Softwood	m^3/door	0.0473

Roof

The total surface area of the sloped roof is 57.3 m^2. The roof elements are made of plywood and are 1 cm thick (Vringer & Blok, 1993). For the batters (20 x 20 mm), the ridge-piece (63 x 163 mm) and the ceiling joint (63 x 163 mm) softwood is used (Vringer & Blok, 1993). The Purlins are not accounted for (Vringer & Blok, 1993). On the roof concrete roof tiles are placed (Vringer & Blok, 1993). The gutter has a total length of 11 meters and is made from 0.8 mm thin zinc plate and is 44 cm wide (Vringer & Blok, 1993). The drain is made from PVC with a total length of 8.8 meters, diameter of 100 mm and is 2 mm thick (Vringer & Blok, 1993).

table D6: Data of materials used for the roof RD

Description	Material	Unit	Value
Roof elements	Plywood	kg/ m^2 roof	3.5
Ceiling joints and ridge-piece	Softwood	kg/ m^2 roof	3.11
Concrete roof tiles	Concrete	kg/ m^2 roof	41.4
Gutter	Zinc	kg/ meter gutter	2.43
Drain	PVC	kg/ meter drain	1.74

Building services installations

The stove is not included in the LCA. The stove is replaced in 1980's by a conventional boiler and after 15 years replaced by a HR100 condensing boiler. The data from the report Vringer & Blok (1993) is used. For the radiators 20 m^2 powder coating is assumed to be used.

table D7: Data of materials used for the building services installation RD

Description	Material	Unit	Value
Boiler	Steel	kg	20.1
	Aluminium	kg	14
	Copper	kg	0.25
	Polystyrene	kg	0.44
Chimney	HDPE	kg	0.7
	Aluminium	kg	1
Piping central heating	Steel	kg	31
	Copper	kg	5
Radiators	Steel	kg	139
Natural gas piping	Copper	kg	8
Tap water piping	Copper	kg	21.6
Sewage	PVC	kg	20
Elektra	Copper wire	kg	1.86
	PVC	kg	2.6

Facilities and decoration
In the LCA one kitchen of 2,1 meter wide from particleboard and a steel worksheet is included (Vringer & Blok, 1993). There is one closed stairs to the first floor and one open stairs to the attic (Vringer & Blok, 1993). The surface area of both stairs cases is treated with paint and varnish. The dwelling has 22.1 m^2 of 5 mm thick plaster work, 68 meters of hardwood plinths, 170 m^2 of wallpaper, 8.4 m^2 floor tiles and 20.3 m^2 wall tiles (Vringer & Blok, 1993). Sanitary ceramics is included for the toilet and bathroom (Vringer & Blok, 1993). The facilities and decoration will have been replaced in the past 55 years, but have only been accounted for ones.

table D8: Data of materials used for the facilities and decoration RD

Description	Material	Unit	Value
Kitchen	Particle board	m^3	0.129
	Steel sheet	kg	34
Closed stairs	Softwood	m^3	0.21
	Hardwood	m^3	0.00836
	Alkyd paint	kg	0.00335
	Acrylic varnish	kg	0.00201
Open stairs	Softwood	m^3	0.19
	Hardwood	m^3	0.00836
	Alkyd paint	kg	0.00306
	Acrylic varnish	kg	0.00184
Plaster	Stucco	kg	144
Plinths	Hardwood	kg	0.0272
Wallpaper	Paper	kg	29.75
Floor tiles	Ceramic tiles	kg	20
	Base plaster	kg	4.8
Wall tiles	Ceramic tiles	kg	10
	Base plaster	kg	2.4
Sanitary	Sanitary ceramics	kg	24

<u>Assumptions made:</u>

- The EOL chart of mortar is based on Bricks EOL as there is none availed for mortar and it is probably disposed of in the same way
- It is assumed that the EOL of the sand for the groundwork has no environmental impact and will probably stay there after demolishing the dwelling
- Based on the report building products from Ecoinvent, the windows exist for 21% out of frame work and 79% out of glazing (Kellenberger, Althaus, Kunniger, Lehmann, & Jungbluth, 2007)
- There is no EOL for the disposal of zinc. Therefor the EOL disposal chart of aluminium has been adapted for zinc
- Sanitary is based only on sanitary ceramics and no other materials
- Wallpaper is based on (paper, wood-containing, LWC, at regional storage/ RER)
- Floor tiles EOL chart is based on Bricks as non-exist for ceramic tiles
- Zinc gutter sheet rolling is based on that of steel, as no chart is available for zinc.
- The process used for the aluminium in the boiler is sheet rolling because casting (which is properly done) is not available

Renovation concept 1

<u>Façade</u>

The external wall has a 50 mm thick empty cavity, between the inner and outer wall. The cavity is filled with blown glass mineral wool with a density of 35 m^3/kg. The windows are replaced by HR++ glazing with a PVC frame.

table D9: Data of materials used for the façade C1

Description	Material	Unit	Value
Insulation material	Glass wool	kg/ m^2 facade	1.75
Window frame	PVC frame	m^2/ m^2 window	0.21
Window glazing	HR++ double glazing	m^2/ m^2 window	0.79

<u>Floors</u>

First a 3 mm oriented strand board is placed against the floorboards to make it more airtight (ISOVER, n.d.). Than 120 mm glass wool sheets are placed between the joints on timber battens (the timber battens are not included in the LCA) (ISOVER, n.d.). On the soil a 2.3 mm PE film is placed as vapour barrier (Bone A. , 2009). It is assumed that PE film is 50 mm longer on both sides to partly cover and secure it to the foundation (47m2). The area covered by the insulation and OSB is 41 m^2 (floor surface area) - 4.3 m^2 (joints surface area) = 36.7 m^2.

table D10: Data of materials used for the floors C1

Description	Material	Unit	Value
OSB	OSB	m^3/m^2 floor	0.003
Insulation material	Glass wool	kg/m^2 floor	4.2
PE film	PE	kg/m^2	2.13

<u>Roof</u>

First a 3 mm tick oriented strand board is placed against the roof boards to make it more airtight (Bone A. , 2009). Than 100 mm glass wool insulation with a 1 mm plastic finish layer (assumed PE) is placed between the purlins (based on Isover sonestrong pro) (ISOVER, n.d.). The area covered by the insulation is 57 m^2 (roof surface area) – 2.4 m^2 (purlins surface area) = 54.6 m^2.

table D11: Data of materials used for the roof C1

Description	Material	Unit	Value
OSB	OSB	m^3/m^2 roof	0.003
Insulation material	Glass wool	kg/m^2 roof	3.5
PE film	Polyethylene	kg/ m^2 roof	0.92

Building services installations

The current HR100 condensing boiler is replaced by a new HR107 condensing boiler with higher energy efficiency. The data from the report Vringer & Blok (1993) is used for the boiler. The air permeability of the dwelling is reduced during the renovation. To insure that there is enough ventilation in the dwelling a central mechanical ventilation system is installed. For the ventilation an ITHO CVE ECO boxed ventilator is used (Itho Daalderop, n.d.). Additional ventilation material are assumed flex duct, spiral seam duct and wall air valve.

table D12: Data of materials used for the building services installations C1

Description	Material	Unit	Value
Boiler	Steel	kg	20.1
	Aluminium	kg	14
	Copper	kg	0.25
	Polystyrene	kg	0.44
Chimney	HDPE	kg	0.7
	Aluminium	kg	1
Mechanical ventilation	Polyamide	kg	1
	Polypropylene	kg	2.2
	Copper wiring	kg	0.05
	Electronics for control unit	kg	0.25
Flex duct	Aluminium	meter	6
Spiral seam duct	Steel	meter	12
Wall air valve	PVC	Piece	3

Assumption

- The 6.5% material uncertainty in the report Vringer & Blok (1993) has not been taken into account.
- Glass wool flocks for cavity wall are based on (glass wool mat, at plant/CH U) as shredded glass wool or glass wool flocks are not available. Also the high pressure insertion in the cavity wall have not been taken into account
- The density of glass wool in all cases is assumed as 35 kg/m^3 (Vringer & Blok, 1993)
- The mechanical ventilation box is based on the ITHO CVE ECO, as no corresponding ventilation box exists in ecoinvent (Itho Daalderop, n.d.). The weight of the ventilation box is 3,5 kg and the following amount of material used is assumed:
  - 1 kg Polyamide (ventilator)
  - 2.2 kg polypropylene (housing)
  - 0.05 kg copper wiring
  - 0.25 kg electronics for control unit (in ecoinvent)

  The forming process used for the plastic is injection moulding
- Mechanical ventilation also includes:

- 6 meter flex duct, aluminium (in ecoinvent)
- 12 meter spiral seam duct, steel (in ecoinvent) (accessories not included)
- 3x in wall air valve for houses (in ecoinvent)

- Based on the report building products from ecoinvent, the windows exist for 21% out of frame work and 79% out of glazing (Kellenberger, Althaus, Kunniger, Lehmann, & Jungbluth, 2007)
- For the floor insulation the wood mounting batters have been taken in to account.
- Roof insulation mounting has not been taken into account

Renovation concept 2

The materials used for renovation concept 2 came from the reports Boonstra et al. (2011) and Hogevorst, H. (2011). The details of the wooden prefab elements came from SBR (n.d.).

Foundation

The outside of the foundation is excavated and then insulated with 200 mm EPS blocks (Boonstra, et al., 2011). The height of the foundation is around 0.7 meter and 5,5 meter wide (Bone A. , 2007).

table D13: Data of materials used for the foundation C2

Description	Material	Unit	Value
EPS insulation	EPS	kg/m^2	6

Facade

The façade is made out of prefab elements. If a cross section were taken the façade elements would consist of (SBR reference detail 202.4.2.02 and Boonstra et al. (2011)):

- 19 mm thick natural tiles
- 28 mm thick empty cavity
- 20 mm thick water-resistant fibreboard
- 330 mm thick cellulose fibre
- 1 mm thick PE-film
- 12,5 mm thick Oriented strand board

To support the structure there is an I-beam placed every 50 cm. The I-beam consists of two softwood end bars (63 x 30 mm) and one inner OSB plate of (10x270 mm). Battens to mount the natural stone tiles are not accounted for. In the façade enamelled glass panels are incorporated. It is estimated that the glass panels consist of double glazing, PVC frame, 100 mm thick cellulose fibre and 12.5 mm OSB (Boonstra et al. 2011). The windows are made out of triple glazing with a PVC frame (Boonstra et al. 2011). To protect the façade element openings aluminium strips are placed against the opening sides (Boonstra et al. 2011). The aluminium sheets are 167 mm wide and 2 mm thick (SBR reference detail 202.4.2.02). The total length of the aluminium sheets is estimated at 32 meter. The solar screens are not included in the LCA. The new outside doors are insulated by PU foam and HR++ double glazing (From Kergo). The door from the reference dwelling is used as basis on which 50 mm PU foam is added and the glazing type is changed to HR++ double.

table D14: Data of materials used for the facades C2

Description	Material	Unit	Value
Façade element	Natural stone plates	kg/m^2 closed facade	22.8
	Fibreboard	m^3/m^2 closed facade	0.02
	Cellulose fibre	kg/m^2 closed facade	16.5
	PE film	kg/m^2 closed facade	0.92
	Oriented strand board	m^3/m^2 closed facade	0.0179
	Softwood	m^3/m^2 closed facade	0.0159
Façade glass panel	Double glazing	m^2/ m^2 glass panel	0.79
	PVC frame	m^2/ m^2 glass panel	0.21
	Cellulose fibre	kg/m^2 glass panel	5
	Oriented strand board	m^3/m^2 glass panel	0.0125
Aluminium sheet	Aluminium	kg (total)	28.9
Window	PVC frame	m^2/m^2 window	0.79
	Triple glazing	m^2/m^2 window	0.21
Insulated door with glass	Hardwood (frame)	m^3/door	0.102
	Hardwood (door)	m^3/door	0.0373
	Double glazing	m^2/door	0.77
	PU rigid foam	kg/door	2.6

Floors

The ground floor is insulated with 230 mm thick Polyurethane spray (ISSO 82.1 & Boonstra et al. 2011). During the spraying process also the sides of the foundations in the crawlspace are insulated with Polyurethane spray. It is assumed that the same thickness of PU is applied on the foundation as on the ground floor. The foundation in the crawlspace has a height of 600 mm – 230 mm of PU floor insulation. The total surface area of the foundation is than 9.6 m^2 and 41 m^2 for the floor area. The ground floor joints prevent 4.3 m^2 x 0.14 meter = 0.6 m^3 of PU being sprayed on the ground floor.

table D15: Data of materials used for the floors C2

Description	Material	Unit	Value
PU insulation	Polyurethane	kg/m^2 floor	6.54

Roof

The roof is made out of prefab elements. If an cross section is taken the façade elements would consist of (SBR reference detail 431.4.0.02 and Boonstra et al. (2011)):

- 4 mm PVC roofing material
- 12.5 mm Oriented strand board
- 335 mm cellulose fibre
- 1 mm PE-film
- 12,5 mm Oriented strand board

To support the structure there is an I-beam placed every 50 cm. The I-beam consists of two softwood end bars (63 x 30 mm) and one inner OSB plate of (10x275 mm). The prefab elements are supported by one ridge-piece (63 x 163 mm) and two purlins (63 x 163 mm) made from softwood (Vringer & Blok (1993) and Boonstra et al. (2011)). The PVC triangle battens on the roof for rainfall and window are excluded from the LCA. The drainage has a diameter of 70 mm and is made from 3 mm thick aluminium with a total length of 8.8 meter (Vringer & Blok (1993) and Boonstra et al. (2011)).

table D16: Data of materials used for the roof C2

Description	Material	Unit	Value
Façade element	PVC roofing	kg/m^2 closed facade	5.8
	Oriented strand board	m^3/m^2 closed facade	0.0304
	Cellulose fibre	kg/m^2 closed facade	16.5
	PE film	kg/m^2 closed facade	0.92
	Softwood	m^3/m^2 closed facade	0.00756
Ridge piece	Softwood	m^3/roof	0.0565
Purlins	Softwood	m^3/roof	0.113
Drain	Aluminium	kg/meter	3.49

Building services installations

The current HR100 condensing boiler is replaced by one HR107 condensing boiler. The data from the report Vringer & Blok (1993) is used for the boiler. The original radiator system has been adjusted to a smaller heat demand. The living room has one new radiator replacing two large ones (Boonstra, et al., 2011). The flow in the other radiators has been reduced and they are fitted with thermostatic valves (Boonstra, et al., 2011). The thermostatic valves are not accounted for. During its lifetime extension it is assumed that the condensing boiler + chimney is replaced twice. The renovated dwelling is fitted with heat recovering balance ventilation system. The heat recovering balance ventilation unit is replaced twice during its lifetime extension. The solar collector and boiler as used in the “de Kroeven” project is not used in this study.

table D17: Data of materials used for the building services installations C2

Description	Material	Unit	Value
Boiler	Steel	kg	20.1
	Aluminium	kg	14
	Copper	kg	0.25
	Polystyrene	kg	0.44
Chimney	HDPE	kg	0.7
	Aluminium	kg	1
Balance ventilation	Polystyrene, HIPS	kg	15
	Polyamide	kg	5
	(Expended) Polypropylene	kg	9
	Polycarbonate	kg	9
	Electronics for control unit	Piece	0.35
	Copper wiring	kg	0.3
Flexible duct	Aluminium	Meter	12
Spiral seam duct	Steel	Meter	24
Wall air valve	PVC	Piece	6
Silencer DN 125	Steel	Piece	2
Exhaust air outlet	Steel/ Aluminium	Piece	2
Radiator	Steel	kg	40
Radiator piping	Steel	kg	3.8

<u>Decoration and facilities</u>
Because only the outer skin of the dwelling is replaced the inside of the dwelling stays intact. An inside refurbishment of the toilet, bathroom and kitchen was optional and is not accounted for. The inside of the glass sandwich panel do need to be treated. For this 6 m^2 plaster work of 5 mm is accounted for.

table D18: Data of materials used for the building services installations C2

Description	Material	Unit	Value
Plaster	Stucco	kg	39

Assumptions

- For cellulose fibre the EOL charts newspaper (AVI and Landfill) are used, as none exist for cellulose fibre. Newspaper is chosen because cellulose fibre is usually made out of recycled newspaper (wiki). The borax powder (9% total mass) and Boric acid (0,8% total mass) that is also used to make cellulose fibre is not accounted for, as no EOL chart was available.
- There is no recycling chart available for natural tiles. The recycling chart of brick is used.
- There is no landfill chart available for natural tiles. It is assumed that it has no environmental impact. Transport to landfill is included.
- There is no recycling chart available for PU. It was based on the recycling chart of PE
- Passive frame PVC frame ecoinvent is used
- For the HR++ double glazing the double glazing of ecoivent is used
- There is no special PVC frame of triple glazing thus the same one as for double glazing is used.
- Based on the report building products from ecoinvent, the windows exist for 21% out of frame work and 79% out of glazing (Kellenberger, Althaus, Kunniger, Lehmann, & Jungbluth, 2007)
- An assumption is made for the enamelled glass panel that 21% is frame and 79% is glass like a normal window frame.
- The heat recovering balance ventilation unit is based on the Stork air WHR930 (J.E. StorkAir & Zehnder, 2011) as no corresponding balance ventilation box is adapted in ecoinvent. The weight of the heat recovering balance ventilation unit is 39 kg and the following amounts per material are assumed:
    - 15 kg Polystyrene, HIPS (heat exchanger)
    - 5 kg (expanded) Polypropylene (insulation and air tubes connections)
    - 3 kg Polyamide (ventilators)
    - 15 kg Polycarbonate (housing and frame)
    - 0.03 kg copper wiring
    - 0.35 kg electronics for control unit (in ecoinvent)

  The forming process used for the plastic is injection moulding
- Balance ventilation additional materials also includes:
    - 12 meter flex duct, aluminium (in ecoinvent)
    - 24 meter spiral seam duct, steel (in ecoinvent)
    - 3x in wall air valve for houses (in ecoinvent)
    - 2x silencer, steel, DN 125 (in ecoinvent)
    - 2x Exhaust air outlet 85*365 mm, also used for inlet (in ecoinvent)
- Electronics for control unit not accounted for in EOL because no chart is available
- 3x in wall air valve for houses (in ecoinvent)
- The mass radiator is on bases of (vringer&blok) assumed to be 40 kg steel and 3.8 kg steel for piping. The coated area is 4 m2.

- There is no chart for expanded Polystrene to landfill thus Polystrene, 0.2% water, to sanitary landfill chart is used

Renovation concept 3

The materials used for renovation concept 3 came from Mulder Obdam. The reports used are Mulder Obdam (2010), Mulder Obdam (2011) and Mulder Obdam (n.d.). The details of the wooden prefab elements came from SBR (n.d.).

Foundation
The inside floor area (5.25 x 7.75 meter) of building pit is filled with 10 cm sand. In the length of the dwelling a concrete foundation beam is poured to support the ground floor (8x0.35x0.5 meter). The footings are probably demolished for the concrete support beam, but the rest of the foundation stays intact.

table D19: Data of materials used for the foundation C3

Description	Material	Unit	Value
Ground work	Sand	m^3	4.1
Concrete beam	Concrete	m^3	1.4

Facade
The façade is made out prefab façade elements. If a cross section were taken the façade elements would consist of (SBR reference detail 201.4.2.01 and Mulder Obdam (2011)):

- 12 mm stone strip bricks (supplier: Wienerberger)
- 8 mm cement fibre facing (supplier: ETER-BACKER HD)
- 28 mm air cavity
- 12.5 mm water-resistant fibreboard
- 175 mm glass wool
- 1 mm PE-film
- 12,5 mm Oriented strand board

Between the stone strip bricks 10 mm of concrete mortar is used. The glue that is used to glue the stone strips to the cement fibre facing is not accounted for. To support the structure there are softwood beams (38 x 170 mm) placed every 50 cm. Battens to mount the cement fibre facing on is not accounted for. The windows are made out of HR++ double glazing with a PVC frame. The outside doors are insulated by PU foam and HR++ double glazing (Kergo). The door from the reference dwelling is used as basis on which 50 mm PU foam is added and the glazing type is changed to HR++ double.

table D20: Data of materials used for the facades C3

Description	Material	Unit	Value
Façade element	Bricks	kg/m^2 closed facade	12.4
	Mortar	kg/m^2 closed facade	2.85
	Cement fibre facing	kg/m^2 closed facade	15.4
	Fibreboard	m^3/m^2 closed facade	0.0125
	Glass wool	kg/m^2 closed facade	5.95
	PE film	kg/m^2 closed facade	0.92
	Oriented strand board	m^3/m^2 closed facade	0.0125
	Softwood	m^3/m^2 closed facade	0.0172
Window	PVC frame	m^2/m^2 window	0.79
	Triple glazing	m^2/m^2 window	0.21
Insulated door with glass	Hardwood (frame)	m^3/door	0.102
	Hardwood (door)	m^3/door	0.0373
	Double glazing	m^2/door	0.77
	PU rigid foam	kg/door	1.95

Floors

The floors are made from Kingspan floor-dek (see figure B2) (Mulder Obdam, 2010). The Kingspan floor-dek is a sandwich panel with a coated steel outer skin and PIR filling (Kinspan, 2010). The topside is fitted with softwood battens and a 20 mm thick OSB underlayment. The plasterboard finishing for the first and attic ceiling/floor is accounted to Facilities and decoration. The Kingspan floor-dek is mounted on every floor to the house separating walls by steel coated Z section of 2.7 mm. For the first and attic floor 2 m^2 per floor is subtracted for the stairs.

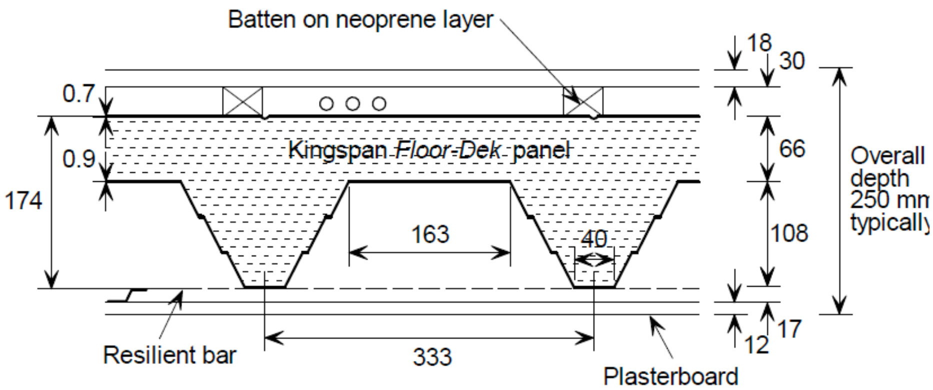

Figure B2: Cross section Kingspan floor-dek. Source: (Kinspan, 2010)

table D21: Data of materials used for the floors C3

Description	Material	Unit	Value
Kingspan floordek	Steel	kg/m^2	15.24
	PIR	kg/m^2	4
Battens	Softwood	m^3/m^2	0.0054
Underlayment	OSB	m^3/m^2	0.02
Z section	Steel	kg/Piece	74.4

Inside and dwelling separating walls

The inside walls are made from 12.5 mm gypsum plaster board and softwood support bars (38x89mm) placed every 50 cm and on the ends (SBR detail sketch 310.4.0.01). One of the stair walls is made from limestone bricks with a thickness of 120 mm. Its starts on the sand base of the foundation and is assumed to reach the attic floor with a surface area of 4.2 m^2. The total surface area of the inside walls is 57 m^2 (Vringer & Blok, 1993). The dwelling has a total of 8 inside doors (Sanjee, 2007). The doors are made from wood with a sheet steel frame (0.001x0.21x7.5 meter) (Vringer & Blok, 1993).

table D22: Data of materials used for the inside and dwelling separating walls C3

Description	Material	Unit	Value
Prefab inside wall	Softwood	m^3/m^2 wall	0.009578
	Gypsum	kg/m^2 wall	23.9
Limestone wall	Limestone	kg/m^2 wall	216
Inside door	Plywood	m^3/door	0.0137
	Softwood	m^3/door	0.015
Inside door frame	Steel	kg/door	12.4

Roof

The roof is made out of prefab elements. If a cross section were taken the façade elements would consist of (SBR reference detail 403.4.0.04 and Mulder Obdam (2010)):

- 2 mm Tyvek HDPE
- 10 mm Oriented strand board
- 195 mm glass wool
- 10mm Oriented strand board

The softwood roof battens take 0.0012 dm^3/m^2 roof (Vringer & Blok, 1993). To support the structure there is a beam placed every 50 cm (36x195 mm). The roof is supported by softwood beams that are attached to the house-separating wall (0.075x0.175x9.7 meter) (Mulder Obdam, 2010). The roof windows are excluded and the concrete roof tiles are reused. The drain and gutter are the same as that of the reference dwelling and have a total length of 8.8 meters (Vringer & Blok, 1993).

table D23: Data of materials used for the roof C3

Description	Material	Unit	Value
Façade element	PVC roofing	kg/m^2 closed facade	5.8
	Oriented strand board	m^3/m^2 closed facade	0.0304
	Cellulose fibre	kg/m^2 closed facade	16.5
	PE film	kg/m^2 closed facade	0.92
	Softwood	m^3/m^2 closed facade	0.00756
Ridge piece	Softwood	m^3/roof	0.0565
Purlins	Softwood	m^3/roof	0.113
Drain	Aluminium	kg/meter	3.49

Building services installations

The current HR100 condensing boiler is replaced by one HR107 condensing boiler. The data from the report Vringer & Blok (1993) is used for the boiler. During the lifetime extension it is assumed that the condensing boiler + chimney is replaced twice. The renovated dwelling is fitted with heat recovering balance ventilation system. The heat recovering balance ventilation unit is replaced twice during its lifetime extension. The sewage, gas piping etcetera needs to be installed again and is based on Vringer & Blok (1993). The radiators are also replaced. Because the dwelling is better insulated it can be fitted with smaller radiators. It is assumed that 25% less steel is needed for the radiators than was used for the reference dwelling. The radiator piping is assumed to stay the same.

table D24: Data of materials used for the building services installations C3

Description	Material	Unit	Value
Boiler	Steel	kg	20.1
	Aluminium	kg	14
	Copper	kg	0.25
	Polystyrene	kg	0.44
Chimney	HDPE	kg	0.7
	Aluminium	kg	1
Balance ventilation	Polystyrene, HIPS	kg	15
	Polyamide	kg	5
	(Expended) Polypropylene	kg	9
	Polycarbonate	kg	9
	Electronics for control unit	Piece	0.35
	Copper wiring	kg	0.3
Flexible duct	Aluminium	Meter	12
Spiral seam duct	Steel	Meter	24
Wall air valve	PVC	Piece	6
Silencer DN 125	Steel	Piece	2
Exhaust air outlet	Steel/ Aluminium	Piece	2
Piping central heating	Steel	kg	31
	Copper	kg	5
Radiators	Steel	kg	104
Natural gas piping	Copper	kg	8
Tap water piping	Copper	kg	21.6
Sewage	PVC	kg	20
Elektra	Copper wire	kg	1.86
	PVC	kg	2.6

Decoration and facilities

The same decoration and facilities are used as the reference dwelling, because it entirely needs to be replaced. Only the 12 mm plasterboard ceiling for two floors is added.

table D25: Data of materials used for decoration and facilities C3

Description	Material	Unit	Value
Plaster board ceiling	Plaster board	kg/ m^2	11.5
Kitchen	Particle board	m^3	0.129
	Steel sheet	kg	34
Closed stairs	Softwood	m^3	0.21
	Hardwood	m^3	0.00836
Open stairs	Softwood	m^3	0.19
	Hardwood	m^3	0.00836
Plaster	Stucco	kg	144
Plinths	Hardwood	kg	0.0272
Wallpaper	Paper	kg	29.75
Floor tiles	Ceramic tiles	kg	20
	Base plaster	kg	4.8
Wall tiles	Ceramic tiles	kg	10
	Base plaster	kg	2.4
Sanitary	Sanitary ceramics	kg	24

Assumptions

- There is no chart available for rigid Polyisocyanuraat (PIR). Its chemistry is similar to Ployurethane (PUR) except that the proportion of methylene diphenyl diisocyanate is higher and a polysester-derived polyol is used. The environmental impact of methylene diphenyl diisocyanate is almost the same as polyol (CML 2000 baseline impact assessment). There for the chart of PUR is used for PIR, also for EOL.
- Based on the report Inventories of building products (2007 data v2.0) from Ecoinvent, the windows exist for 21% out of framework and 79% out of glazing. The same assumption is made for the glass sandwich panels in the façade.
- For the façade a ratio for the bricks and mortar per m2 is assumed. Bricks occupy 85% per m^2 and mortar 15% per m^2.
- The radiators are also replaced. Because the dwelling is better insulated it can be fitted with smaller radiators. It is assumed that the 25% less steel is needed than that of the reference dwelling. The radiator piping is assumed to stay the same.
- Based on the report building products from ecoinvent, the windows exist for 21% out of frame work and 79% out of glazing (Kellenberger, Althaus, Kunniger, Lehmann, & Jungbluth, 2007)
- That the steel can be separated from the PIR of the floor-dek to be recycled

Energy calculations

The energy calculations are based on the results of the Vabi EPA-W program (see appendix E). The building services installations used are stated per renovation concept in this appendix (see previous sections).

For heating only the annual amount of natural gas needed for central heating is used, thus hot water is not included. This is done because there is no solar water heater included in the renovation concepts and the energy use for hot water is thus in all concepts the same.

The boiler (pump, electronics and ventilation) and ventilation also use electric energy. This auxiliary electric energy use is also accounted for in the LCA.

table D26: Annual energy use data

Description	Heating energy [MJ per year]	Auxiliary electricity for the boiler and ventilation [kWh per year]
Reference dwelling	79,692	261
Renovation concept 1	24,906	470
Renovation concept 2	4,084	627
Renovation concept 3	10,225	627

Assumptions:

- The ecoinvent chart (heat,natural gas, at boiler condensing modulating <100kW/RER U) has been adapted that 1 MJ input is 1 MJ output instead of 0,98 MJ. The energy efficiency is included in the Vabi EPA-W calculation, thus 1 MJ should be equal to 1 MJ.
- The ecoinvent chart (natural gas, burned in boiler condensing modulating <100kW/RER U) has been adapted. The auxiliary electric energy of the boiler is set at 0 instead of 0.00278 kWh. The auxiliary electric energy of inter alia the boiler has been calculated with Vabi EPA-W.
- The ecoinvent chart (natural gas, burned in boiler condensing modulating <100kW/RER U) has been adapted. The chart gas boiler/RER/I U is set on 0 instead of 0.00000066 pieces. It is assumed that the boiler including the pump only needs to be replaced after 15 years and not before. The difference in weight, 120 kg ecoinvent boiler and 35 kg the used boiler from Vringer & Blok (1993), is also to far apart to be accurate.

Comparing improvement options

Sandwich floor elements replaced by prefab wood elements renovation concept 3
In renovation concept 3 sandwich floor-dek panels are used. The sandwich panels have a high shadow cost and are therefore compared to prefab timber floors. It is assumed that for the ground floor sandwich panels are used, as for the first and attic floor prefab timber floors are used. These data come from and SBR reference detail 301.4.2.01 and Sanjee (2007).

The inside measurements of the dwelling are 5.25 x 7.75 meter (Hoogers, et al., 2004). The total inside floor area is thus 41 m^2 – 2 m^2 for the staircases. The floor finishing is made from 18 mm OSB. Under the floorboards 65x220mm softwood joints are placed for support. Between the softwood joints 80 mm of glass wool is placed. The floor is finished with 15 mm gypsum plasterboard table D27: Data of materials used for the prefab timber floor used for comparison

Description	Material	Unit	Value
Prefab timber floor	Softwood	m^3/ m^2 floor	0.0438
	OSB	m^3/ m^2 floor	0.018
	Gypsum plaster board	kg/ m^2 floor	14.4
	Glass wool	kg/ m^2 floor	2.47

Enamelled glazing replaced by hardwood parapet renovation concept 2

In renovation concept 2 enamelled glazing prefab elements are used as parapet between the floor and window frame. For the comparison the glazing is replaced by 1 cm thick hardwood with a varnish finish. The rest is based on the façade from renovation concept 2 to reach the same insulation requirements. The thickness of the parapet is now the same as the rest of the façade, which is not desired. Using glass wool could reduce the thickness but this is not accounted for.

table D28: Data of materials used for hardwood parapet used for comparison

Description	Material	Unit	Value
Prefab timber floor	Softwood	m^3/ m^2 closed facade	0.0159
	OSB	m^3/ m^2 closed facade	0.0125
	Hardwood	kg/ m^2 closed facade	0.01
	Acrylic varnish	kg/ m^2 closed facade	0.085
	Cellulose fibre	kg/ m^2 closed facade	16.5
	Fibreboard	m^3/m^2 closed facade	0.02
	PE film	kg/m^2 closed facade	0.92

E Energy performance calculations

To calculate the energy performance of the reference dwelling and renovation concept the software program Vabi EPA-W is used.

Name software: Vabi EPA-W
Designer: Vabi Software
Version: Standalone 3.02

Vabi EPA-W software is used for the energy label certification of dwellings and energy performance advice. The program is built in accordance with the BRL9501 standards.

General data input

table E1: Usable floor area

Usable floor area		
Ground floor	40	m^2
1st floor	40	m^2
Attic floor	7	m^2
Total	87	m^2

table E2: Inhabitants behaviour

Inhabitants behaviour		
Number of inhabitants	2.8	-
Average inside temperature	18[56]	°C
Heat production (lighting and electronic equipment)	6	W/m^2
Ventilation correction factor	1	-
Electric cooking	No	-

table E3: Climate data

Climate data	
Location	De Bilt
Number of days	365
Degree days	2,903[57]

[56] The set point differs from the set point used in “bestaande voorbeeld woningen 2011”, where it was 16,5 °C. For the label certificate calculation 18 °C is always used (Vabi EPA-W).
[57] The amount of degree-days is based on the average amount of degree-days between 1984 until 2006 in de Bilt (Senter Novem, 2007).

Reference dwelling

<u>Construction</u>

table E4: Air proofing RD

Air proofing	
Moving parts	Not present
Window frames	Not present
Utility feed connections	Not present
Crawl space hatch	Not present
Ridge of the roof	Not present
Roof and façade penetrations	Not present
Roof and façade connections	Not present
Seams in roofing	Not present

table E5: reference dwelling construction properties

Construction			
Type	Rc m^2.K/W	U [W/m^2.K]	ZTA [%]
Facade	0.35	-	-
Sloping roof	0.4	-	-
Floor	0.32	-	-
Door	-	3.5	-
Window 2	-	2.9	70
Window 1	-	5.1	80
Door	-	3.5	-

table E6: reference dwelling surface area input

Construction part	Area m^2	Adjacent to	Orientation
Floor	39.4	Ground or crawl space	-
Sloping roof	56.5	Outside air	-
Window 1 (front)	3.25	Outside air	South
Window 2 (front)	7.5	Outside air	South
Façade (front)	21.15	Outside air	-
Door 1 (front)	1.9	Outside air	-
Window 2 (back)	3.25	Outside air	North
Window 2 (back)	7.5	Outside air	North
Façade (back)	21.15	Outside air	-
Door 1 (back)	1.9	Outside air	-

<u>Building services installations</u>

table E7: ventilation RD

Ventilation	
System	Natural
Ventilators	No
Heat recovery	No

table E8: Heating RD

Heating	
System	Individual
Boiler type	HR100 boiler
Flow temperature	High (above 55°C)

table E9: Hot water RD

Hot water	
System	Individual
Boiler type	Combi HR
Kitchen boiler	No
Shower	Yes
Water saving showerhead	No
Dishwasher	No
Bath	No

Energy use current situation

Energy performance certificate

table E10: Energy label certificate RD

Energy label certificate	
Energy label	F
Energy Index	2.57
Total energy use	99,319 MJ
Energy use central heating	79,672 MJ

Calculated energy use

table E11: Energy data results RD

Description	Natural gas [m^3]	Electric [kWh]	Heat [GJ]	Primary energy [MJ_{prim}]	CO2 [kg]
Heating	2,260	0	0	79,487	
Hot water	352	0	0	12,397	
Auxiliary energy	0	261	0	2,410	
Lighting	0	522	0	4,818	
PV	0	0	0	0	
Micro CHP	0	0	0	0	
Total	2,613	783	0	99,112	5,094
Used in Simapro REF	**2,260**[58]	**261**[59]	**0**	**0**	0

[58] The annual natural gas use minus the hot water use
[59] Auxiliary energy for the boiler (pomp, electronics and ventilator). Electric energy use minus lighting (522 kWh)

Heat flows

table E11: Heat flow results RD

Heat flow	Heat loss [MJ]	Heat gain [MJ]
Transmission	65,268	0
Ventilation	18,067	0
Internal heat production	0	9,561
Solar heat through window	0	8,255
Total heat demand	65,523	MJ

Renovation concept 1

ISSO declarations used

table E12: ISSO declarations used C1

ISSO declarations used			
Coding	**Supplier**	**Type**	**Construction**
20110170GKBKUW	Knauf	Supafill	Facade
20120344GKBKUW	ISOVER	Comfortpanel	Floor
20120348GKBKUW	ISOVER	Sonestrong Pro	Roof and floor

Construction

table E13: Air proofing C1

Air proofing	
Moving parts	Present
Window frames	Present
Utility feed connections	Present
Crawl space hatch	Present
Ridge of the roof	Present
Roof and façade penetrations	Present
Roof and façade connections	Present
Seams in roofing	Present

table E14: constructional properties C1

	Construction			
Type	**Measure**	**Rc m^2.K/W**	**U [W/m^2.K]**	**ZTA [%]**
Facade	Glass wool flocks	1.61		
Sloping roof	Glass wool 100 mm	2.54		
Floor	Glass wool 120 mm	2.5		
Window 1	HR++ double glazing + frame		1.8	60
Window 2	HR++ double glazing + frame		1.8	60

Building services installations

table E15: Ventilation C1

Ventilation	
System	Mechanical
Ventilators	DC
Heat recovery	No

table E16: Heating C1

Heating	
System	Individual
Boiler type	HR107 boiler
Flow temperature	High (above 55°C)

table E17: Hot water C1

Hot water	
System	Individual
Boiler type	Combi HR

Energy performance certificate

table E18: Energy label certificate result C1

Energy label certificate	
Energy label	B
Energy Index	1.20
Total energy use	46,011 MJ_{prim}
Energy use central heating	24,906 MJ_{prim}

Calculated energy use

table E19: Annual energy use result C1

Description	Natural gas [m^2]	Electric [kWh]	Heat [GJ]	CO_2 [kg]
Current situation	2,613	783	0	5,094
Renovation concept 1	1,061	992	0	2,427
Used in Simapro C1	**708**[60]	**470**[61]	**0**	**0**

[60] Vabi EPA-W uses HHV of 35.17 MJ/m3 natural gas (GasTerra, n.d.). The annual natural gas use minus the hot water use.
[61] Auxiliary energy for the boiler (pomp, electronics and ventilator) and ventilation. Electric energy use minus lighting (522 kWh).

Renovation concept 2

ISSO declarations used

table E20: ISSO declarations used C2

ISSO declarations used			
Coding	**Supplier**	**Type**	**Construction**
2008-APD-KWI/00008	J.E. StorkAir	WHR 930	Ventilation
20130505GKBKUW	Verweij Houttechniek B.V.	Lamikon passiefkozijn met 3-voudig HR-glas	Glazing
20100004GKBKUW	Different	PUR	Floor

Construction

table E21: ISSO declarations used C2

Air proofing	
Moving parts	Present
Window frames	Present
Utility feed connections	Present
Crawl space hatch	Present
Ridge of the roof	Present
Roof and façade penetrations	Present
Roof and façade connections	Present
Seams in roofing	Present

table E22: Construction input C2

	Construction			
Type	**Measure**	**Rc $m^2.K/W$**	**U [$W/m^2.K$]**	**ZTA [%]**
Facade	Cellulose fibre	9.1	0.11	
Sloping roof	Cellulose fibre	10	0.1	
Floor	EPS and PUR	8		
Window 1[62]	Triple glazing + frame		0.87	47
Window 2[63]	Triple glazing + frame		0.87	47
Door	Insulated door	0.333		

Building services installations

table E23: Ventilation C2

Ventilation	
System	Balance ventilation
Ventilators	DC
Heat recovery	95%

[62] Based on the U-factor value of the window frame from Boonstra (2011)
[63] Based on the U-factor value of the window frame from Boonstra (2011)

table E24: Heating C2

Heating	
System	Individual
Boiler type	HR107 boiler
Flow temperature	High (above 55°C)

table E25: Hot water C2

Hot water	
System	Individual
Boiler type	Combi HR

Energy performance certificate

table E26: Energy label certificate result C2

Energy label certificate	
Energy label	A+
Energy Index	0.70
Total energy use	27,083 MJ_{prim}
Energy use central heating	4083 MJ_{prim}

Calculated energy use

table E27: Annual energy use result C2

Description	Natural gas [m^2]	Electric [kWh]	Heat [GJ]	CO_2 [kg]
Current situation	2,613	783	0	5,094
Renovation concept 2	469	1,149	0	1,432
Used in Simapro C2	**116**[64]	**627**[65]	**0**	**0**

Renovation concept 3

ISSO declarations used

table E28: Annual energy use result C3

ISSO declarations used			
Coding	Supplier	Type	Construction
2008-APD-KWI/00008	J.E. StorkAir	WHR 930	Ventilation

[64] Vabi EPA-W uses HHV of 35.17 MJ/m3 natural gas. The annual natural gas use minus the hot water use
[65] Auxiliary energy for the boiler (pomp, electronics and ventilator) and ventilation. Electric energy use minus lighting (522 kWh)

Construction

table E29: Air proofing C3

Air proofing	
Moving parts	Present
Window frames	Present
Utility feed connections	Present
Crawl space hatch	Present
Ridge of the roof	Present
Roof and façade penetrations	Present
Roof and façade connections	Present
Seams in roofing	Present

table E30: Construction input data C3

	Construction			
Type	Measure	Rc m^2.K/W	U [W/m^2.K]	ZTA [%]
Facade	Glass wool	3.5		
Sloping roof	Glass wool	4.5		
Floor	PIR insulation	4		
Window 1	HR++ double glazing + frame		1.8	60
Window 2	HR++ double glazing + frame		1.8	60
Door	Insulated door	0.33		

Building services installations

table E31: Ventilation C3

Ventilation	
System	Balance ventilation
Ventilators	DC
Heat recovery	95%

table E32: Heating C3

Heating	
System	Individual
Boiler type	HR107 boiler
Flow temperature	High (above 55°C)

table E33: Hot water C3

Hot water	
System	Individual
Boiler type	Combi HR

Energy performance certificate

table E34: Energy label certificate result C3

Energy label certificate	
Energy label	A
Energy Index	0.86
Total energy use	33,225 MJ_{prim}
Energy use central heating	10,225 MJ_{prim}

Calculated energy use

table E35: Annual energy use result C3

Description	Natural gas [m^2]	Electric [kWh]	Heat [GJ]	CO_2 [kg]
Current situation	2,613	783	0	5,094
Renovation concept 1	650	1,149	0	1,807
Used in Simapro C3	**290**[66]	**627**[67]	**0**	**0**

[66] Vabi EPA-W uses HHV of 35.17 MJ/m3 natural gas. The annual natural gas use minus the hot water use

[67] Auxiliary energy for the boiler (pomp, electronics and ventilator) and ventilation. Electric energy use minus lighting (522 kWh)

F Life Cycle Costing

In this appendix the data used during the LCC is shown. The VAT and labour are included in the cost.

General data used

table F1: General gas and electricity data used during the LCC

Description	Unit	Value	Source
Natural gas price	[EUR/m^3]	0.697	(CBS, 2013)
Electricity price	[EUR/kWh]	0.188	(CBS, 2013)
Yearly price increase of natural gas	[%/year]	6.3	(van Cann, 2011)
Yearly price increase of electricity	[%/year]	3.9	(van Cann, 2011)

Investment costs

Renovation concept 1

Renovation concept 1 is based on the combination of different renovation measures. In this study multiple investment costs per measures were used to define an average investment cost per measure. The different investment costs per measure can be found in table F2. The total average investment cost for renovation concept 1 is 14,670 EUR.

table F2: General gas and electricity data used during the LCC

Description	Unit	Value	Source
Cavity wall insulation	[EUR]	1,102	Vabi EPA-W
	[EUR]	1,083	(SenterNovem, 2009)
	[EUR]	550	(Milieu Centraal, n.d.)
	[EUR]	559	Offer from “van de bunt isolatie techniek”
Roof insulation	[EUR]	3,447	Vabi EPA-W
	[EUR]	3,135	(SenterNovem, 2009)
	[EUR]	850	(Milieu Centraal, n.d.)
	[EUR]	2,850	(Houhetwarm.nl, 2012)
Floor insulation	[EUR]	1,590	Vabi EPA-W
	[EUR]	1,034	(SenterNovem, 2009)
	[EUR]	2,000	(Milieu Centraal, n.d.)
	[EUR]	1,650	(Isoleren vloer, n.d.)
	[EUR]	1,500	Offer from “Maatwerk isolatie”
	[EUR]	1,775	Offer from “de kruipruimte isolatie specialist”
HR++ glazing with PVC frame	[EUR]	3,548	Vabi EPA-W
	[EUR]	3,469	(SenterNovem, 2009)
	[EUR]	4,988	(Vonk, de Wilde, & de Groot, 2012)
Air proofing	[EUR]	1,427	Vabi EPA-W
HR107 Condensing boiler	[EUR]	2,657	Vabi EPA-W
	[EUR]	2,770	(Archidat Bouwinformatie, 2013)
	[EUR]	1,690	Offer from “Tempres systems”

	[EUR]	2,832	(SenterNovem, 2009)
Mechanical ventilation	[EUR]	2,144	(SenterNovem, 2009)
	[EUR]	1,438	(Archidat Bouwinformatie, 2013)

The average investment cost (based on table F2) is shown in figure F1. The maximum and minimum investment costs are shown with the error bars. The total average investment cost for renovation concept 1 is 14,670 EUR (incl. VAT and Labour).

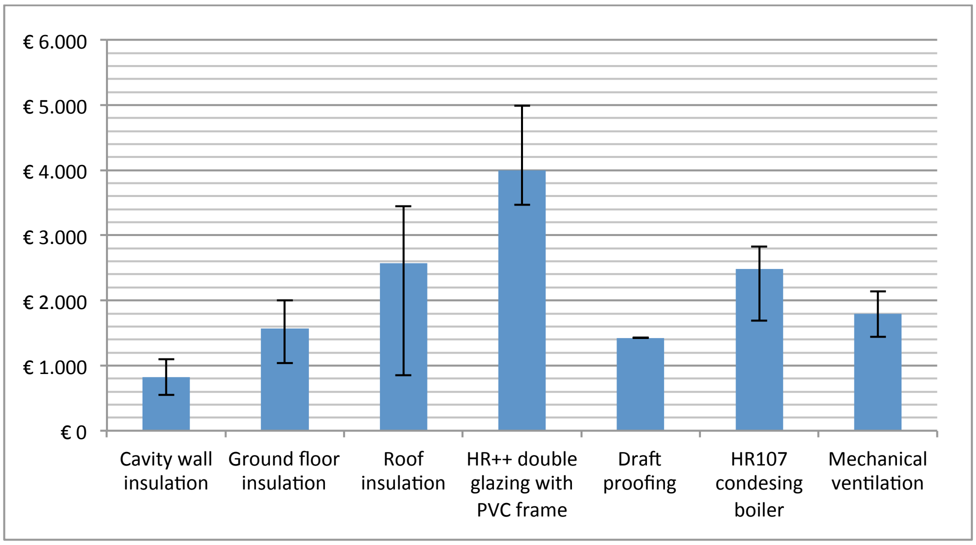

Figure F1: The average investment cost per renovation measure. The uncertainty bars show the highest and lowest investment cost found.

Renovation concept 2

In the document of Hoogevorst (2011) it's stated that the construction costs for "De Kroeven" is +/- 70,000 EUR (incl. VAT and Labour) per dwelling and the total building cost is more than 100,000 EUR (incl. VAT and Labour) per dwelling.

In the document Winket (n.d.) the total investment cost for "De Kroeven" is estimated at 116,640 EUR (incl. VAT and Labour) per dwelling. These calculations were done before the dwellings were realised.

In the project "de bestaande wijk van morgen", a similar project as "de Kroeven", the investment cost was around 100,000 EUR (incl. VAT and Labour) per dwelling (Rovers, 2012).

The investment cost lies properly somewhere between 70,000 EUR (incl. VAT and Labour) and 116,640 EUR (incl. VAT and Labour). In this study the investment cost is assumed to be 100,000 EUR (incl. VAT and Labour) per dwelling. Based on the previous discussed reports. This investment cost does have a big uncertainty as shown.

Renovation concept 3

For the investment cost of renovation concept 3 the budget estimate from Mulder Obdam (2010) is used. The total investment cost for the “inschuifwoning” is 95,290 EUR (incl. VAT and Labour). Aldo the budget estimate is used there is still a uncertainty. The first “inschuifwoning” investment cost was 79,000 (incl. VAT and Labour) (Mulder Obdam, n.d.) and a other budget estimate showed an investment cost of 99,303 EUR (incl. VAT and Labour).

In this study renovation concept 3 is also fitted with balance ventilation. In table F3 is shown that the additional cost for balance ventilation is 1,955 EUR (incl. VAT and Labour).

table F3: Additional investment cost balance ventilation

Description	Unit	Value	Source
Mechanical ventilation	[EUR]	1,438	(Archidat Bouwinformatie, 2013)
Balance ventilation	[EUR]	3.393	(Archidat Bouwinformatie, 2013)
Extra investment	[EUR]	1,955	

Replacement costs

The boiler and heat recovery ventilation unit need to be replaced around every 15 years (Nunen & van Bergen, 2011). The average investment cost per 15 years is 4,137 EUR (incl. VAT and Labour) (see table F4).

table F4: replacement cost boiler and ventilation

Description	Unit	Value	Source
HR107 Condensing boiler	[EUR]	2,657	Vabi EPA-W
	[EUR]	2,770	(Archidat Bouwinformatie, 2013)
	[EUR]	1,690	Offer from “Tempres systems”
	[EUR]	2,832	(SenterNovem, 2009)
Heat recovery ventilation unit (StorkAir WHR930)	[EUR]	1,854	Haarmanverwarming.nl
	[EUR]	1,525	Airshopping.eu
	[EUR]	1,570	Easyventstore.nl

Demolishing dwelling

The dwelling will be demolished at the end of its lifetime. The total cost (including material separation and transport) is 2,310 EUR (incl. VAT and Labour) per dwelling.

table F5: Demolition cost

Description	Unit	Value	Source
Complete demolition terrace house	[EUR]	2,310	(Vonk, de Wilde, & de Groot, 2012)

Results excel model

To calculate the NPC for the LCC a excel model was built of the different renovation concepts. In the next sections the outputs from the excel model of the baseline, renovation concept 1, renovation concept 2 and renovation concept 3 are shown.

Reference dwelling: Baseline + 5 years

Baseline (Reference dwelling)						
Year	*[year]*	2013	2014	2015	2016	2017
Counter	*[n]*	0	1	2	3	4
Investment and maintenance (real value)						
Total initial investement	*[EUR]*	0				
Replacement investment	*[EUR]*					
Annual maintenance costs	*[EUR/year]*	0	0	0	0	0
EOL (demolshing cost)	*[EUR]*					2310
Energy costs (real value)						
Natural gas use	*[EUR/year]*	1.575	1.674	1.780	1.892	2.011
Electricty use	*[EUR/year]*	49	51	53	55	57
Economical analysis (discounted)						
Total investment	*[EUR]*	0	0	0	0	2.052
Energy costs	*[EUR]*	1.624	1.675	1.728	1.782	1.838
Costs (Maintanance)	*[EUR]*	0	0	0	0	0
Cumalative cash flow	*[EUR]*	1.624	3.299	5.027	6.809	10.699
Net Cumalative cash flow	*[EUR]*	1.624	1.675	1.728	1.782	3.890
Net Present Cost (NPC)	*[EUR]*	10.699				
NPC investments	*[EUR]*	2.052				
NPC energy use	*[EUR]*	8.647				
Functional unit						
Total NPC baseline	*[EUR per year per m2]*	25				
Investment costs	*[EUR per year per m2]*	5				
Energy costs	*[EUR per year per m2]*	20				

Renovation concept 1:low ambition renovation concept

Renovation concept 1: low ambition renovation																
Year	*[year]*	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027
Counter	*[n]*	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Investment and maintenance (real value)																
Total initial investement	*[EUR]*	14669														
Replacement investment	*[EUR]*															
Annual maintenance costs	*[EUR/year]*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EOL (demolshing cost)	*[EUR]*															2310
Energy costs (real value)																
Natural gas use	*[EUR/year]*	493	525	558	593	630	670	712	757	805	855	909	966	1.027	1.092	1.161
Electricty use	*[EUR/year]*	88	92	95	99	103	107	111	115	120	125	130	135	140	145	151
Economical analysis (discounted)																
Total investment	*[EUR]*	14.669	0	0	0	0	0	0	0	0	0	0	0	0	0	1.527
Energy costs	*[EUR]*	582	598	616	633	651	670	689	709	730	751	773	795	819	842	867
Costs (Maintanance)	*[EUR]*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cumalative cash flow	*[EUR]*	15.251	15.849	16.465	17.098	17.749	18.419	19.109	19.818	20.548	21.299	22.072	22.867	23.685	24.528	26.922
Net Cumalative cash flow	*[EUR]*	15.251	598	616	633	651	670	689	709	730	751	773	795	819	842	2.394
Net Present Cost (NPC)	*[EUR]*	26.922														
NPC investments	*[EUR]*	16.196														
NPC energy use	*[EUR]*	10.726														
Functional unit																
Total NPC C1	*[EUR per year per m2]*	21														
Investment costs	*[EUR per year per m2]*	12,41087														
Energy costs	*[EUR per year per m2]*	8,219258														
mitigation costs	*[EUR per year per m2]*															

Renovation concept 2: high ambition renovation concept

Concept 2 high ambition renovation																								
Year	[year]	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Counter	[n]	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Investment and maintenance (real value)																								
Total initial investement	[EUR]	100000																						
Replacement investment	[EUR]																4136,917							
Annual maintenance costs	[EUR/year]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EOL (demolshing cost)	[EUR]																							
Energy costs (real value)																								
Natural gas use	[EUR/year]	81	86	91	97	103	110	117	124	132	140	149	158	168	179	190	202	215	228	243	258	274	292	310
Electricty use	[EUR/year]	118	122	127	132	137	143	148	154	160	166	173	180	187	194	201	209	217	226	235	244	253	263	274
Economical analysis (discounted)																								
Total investment	[EUR]	100.000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.655	0	0	0	0	0	0	0
Energy costs	[EUR]	199	202	206	210	214	218	222	226	230	235	239	244	249	254	259	264	269	275	280	286	292	298	305
Costs (Maintanance)	[EUR]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cumalative cash flow	[EUR]	100.199	100.401	100.607	100.817	101.031	101.249	101.470	101.697	101.927	102.162	102.401	102.645	102.894	103.148	103.407	106.326	106.596	106.871	107.151	107.437	107.730	108.028	108.332
Net Cumalative cash flow	[EUR]	100.199	202	206	210	214	218	222	226	230	235	239	244	249	254	259	2.919	269	275	280	286	292	298	305
Net Present Cost (NPC)	[EUR]	121.943																						
NPC investments	[EUR]	104.902																						
NPC energy use	[EUR]	17.041																						
																								Functional unit
Total NPC concept 2	[EUR per year per m2]	28																						
Investment costs	[EUR per year per m2]	24,1155																						
Energy costs	[EUR per year per m2]	3,917438																						

2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049
23	24	25	26	27	28	29	30	31	32	33	34	35	36
							4136,917						
0	0	0	0	0	0	0	0	0	0	0	0	0	0
330	350	372	396	421	447	476	505	537	571	607	645	686	729
284	295	307	319	331	344	358	371	386	401	417	433	450	467
0	0	0	0	0	0	0	1.704	0	0	0	0	0	0
311	318	324	331	339	346	353	361	369	378	386	395	404	413
0	0	0	0	0	0	0	0	0	0	0	0	0	0
108.643	108.961	109.285	109.617	109.955	110.301	110.655	112.720	113.090	113.467	113.853	114.248	114.651	115.064
311	318	324	331	339	346	353	2.066	369	378	386	395	404	413

2050	2051	2052	2053	2054	2055	2056	2057	2058	2059	2060	2061	2062
37	38	39	40	41	42	43	44	45	46	47	48	49
0	0	0	0	0	0	0	0	0	0	0	0	0
												2310
775	824	876	931	990	1.052	1.118	1.189	1.264	1.343	1.428	1.518	1.614
486	504	524	545	566	588	611	635	659	685	712	740	768
0	0	0	0	0	0	0	0	0	0	0	0	543
422	432	442	452	463	474	485	497	509	521	533	546	560
0	0	0	0	0	0	0	0	0	0	0	0	0
115.487	115.919	116.361	116.813	117.276	117.750	118.235	118.732	119.240	119.761	120.295	120.841	121.943
422	432	442	452	463	474	485	497	509	521	533	546	1.102

Renovation concept 3: high ambition rebuilding concept

Concept 3 high ambition replacement																								
Year	[year]	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Counter	[n]	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Investment and maintenance (real value)																								
Total initial investement	[EUR]	96892																						
Replacement investment	[EUR]																4136,917							
Annual maintenance costs	[EUR/year]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EOL (demolshing cost)	[EUR]																							
Energy costs (real value)																								
Natural gas use	[EUR/year]	202	215	228	243	258	274	292	310	330	350	372	396	421	447	475	505	537	571	607	645	686	729	775
Electricty use	[EUR/year]	118	122	127	132	137	143	148	154	160	166	173	180	187	194	201	209	217	226	235	244	253	263	274
Economical analysis (discounted)																								
Total investment	[EUR]	96.892	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.655	0	0	0	0	0	0	0
Energy costs	[EUR]	320	328	335	343	351	360	368	377	387	396	406	416	426	437	447	459	470	482	494	507	520	533	547
Costs (Maintanance)	[EUR]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cumalative cash flow	[EUR]	97.212	97.540	97.875	98.218	98.570	98.929	99.298	99.675	100.062	100.458	100.863	101.279	101.705	102.141	102.589	105.703	106.173	106.655	107.150	107.657	108.177	108.710	109.258
Net Cumalative cash flow	[EUR]	97.212	328	335	343	351	360	368	377	387	396	406	416	426	437	447	3.114	470	482	494	507	520	533	547
Net Present Cost (NPC)	[EUR]	133.369																						
NPC investments	[EUR]	101.795																						
NPC energy use	[EUR]	31.575																						
																								Functional unit
Total NPC concept 3	[EUR per year per m2]	31																						
Investment costs	[EUR per year per m2]	23,40108																						
Energy costs	[EUR per year per m2]	7,258562																						

2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049
23	24	25	26	27	28	29	30	31	32	33	34	35	36
							4136,917						
0	0	0	0	0	0	0	0	0	0	0	0	0	0
824	876	931	990	1.052	1.118	1.189	1.264	1.343	1.428	1.518	1.613	1.715	1.823
284	295	307	319	331	344	358	371	386	401	417	433	450	467
0	0	0	0	0	0	0	1.704	0	0	0	0	0	0
561	576	591	607	623	639	656	674	692	710	729	749	769	790
0	0	0	0	0	0	0	0	0	0	0	0	0	0
109.819	110.395	110.986	111.593	112.216	112.855	113.511	115.889	116.581	117.291	118.020	118.769	119.539	120.329
561	576	591	607	623	639	656	2.378	692	710	729	749	769	790

2050	2051	2052	2053	2054	2055	2056	2057	2058	2059	2060	2061	2062
37	38	39	40	41	42	43	44	45	46	47	48	49
0	0	0	0	0	0	0	0	0	0	0	0	0
												2.310
1.938	2.060	2.190	2.328	2.475	2.630	2.796	2.972	3.160	3.359	3.570	3.795	4.034
486	504	524	545	566	588	611	635	659	685	712	740	768
0	0	0	0	0	0	0	0	0	0	0	0	543
812	834	857	881	905	930	956	982	1.010	1.038	1.067	1.097	1.128
0	0	0	0	0	0	0	0	0	0	0	0	0
121.141	121.975	122.832	123.713	124.617	125.547	126.503	127.486	128.495	129.534	130.601	131.698	133.369
812	834	857	881	905	930	956	982	1.010	1.038	1.067	1.097	1.671

Sensitivity analysis of the net present cost

To calculate the sensitivity of parameters used for the NPC a “what-if” analysis is implemented in the excel model. The “what-if” analysis shows the NPC result when the parameters (discount rate, annual increase natural gas price, annual increase electricity price and initial investment) would differ from the value that is used in the excel model to calculate the NPC. The high and low values that are used in the “what-if” analysis are shown in table F5.

table F5: input data used for the “What-if” analysis

Description	Used value	High value	High value per cent deviation of used value	Low value	Low value deviation of used value
Discount rate	3%	10%	233%	0%	-100%
Annual increase natural gas price	6.3%	10%	59%	-2%	-132%
Annual increase electricity price	3.9%	7%	79%	-2%	-151%
Initial investment C1	14,670 EUR	17,940 EUR	22%	10,460 EUR	-29%
Initial investment C2	100,000 EUR	116,640 EUR	17%	95,300 EUR	-30%
Initial investment C3	15,290 EUR	99,300 EUR	4%	79,000 EUR	-17%

The “what-if” analysis shows the effect that the parameters have on NPC by a per cent deviation of the used parameter value. If the NPC reaction is high to a small per cent deviation of the used parameter value, it NPC end results is sensitive to a change in that parameter. The results of the “what-if” analysis are shown for renovation concept 1 in figure F1, renovation concept 2 in figure F2 and renovation concept 3 in figure F3. In section 5.2 there is referred to these figures.

In figure F1 is shown that renovation concept 1 is very sensitive to a per cent deviation of the investment cost. After the investment cost it is most sensitive to the annual increase of natural gas use and discount rate. The low sensitivity to the electricity price increase is caused by the low amount used in comparison to natural gas.

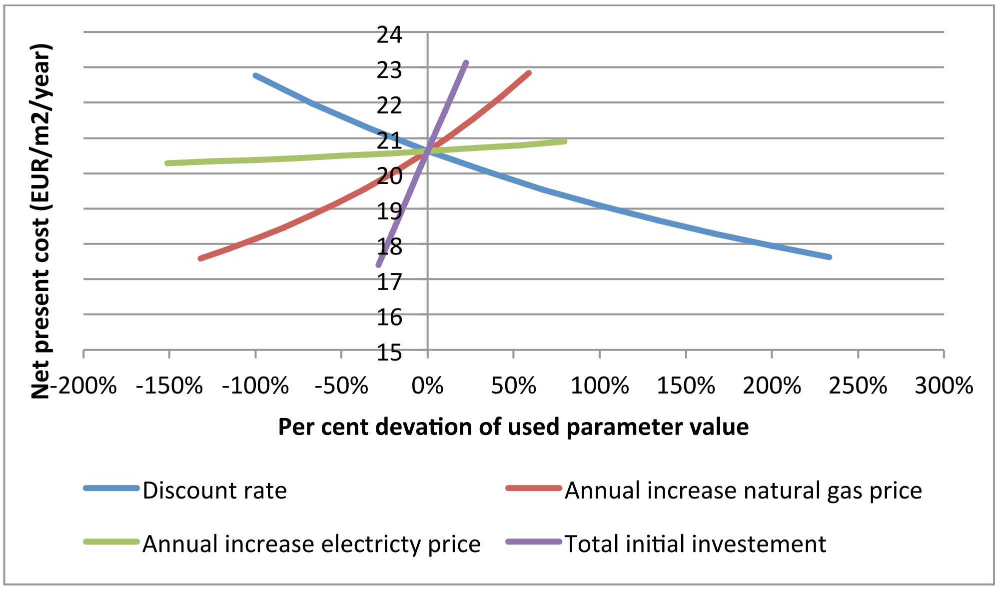

figure F1: Sensitivity analysis of the NPC renovation concept 1

In figure F2 is shown that renovation concept 2 is very sensitive to a per cent deviation of the investment cost. After the investment cost it is most sensitive to the annual increase of natural gas use and discount rate. In comparison to the other renovation concepts, renovation concept 2 is less sensitive to the per cent deviation of natural gas because it uses less natural gas. The sensitivity of the electricity price increase is getting near the sensitivity of the natural gas because the increase in electricity use compared to renovation concept 1.

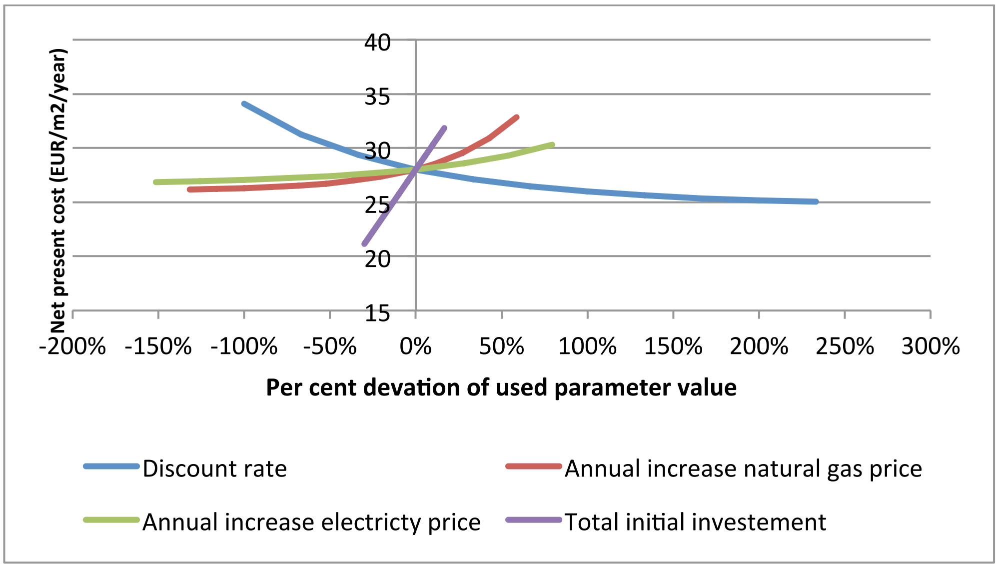

figure F2: Sensitivity analysis of the NPC renovation concept 2

In figure F3 is shown that renovation concept 3 is very sensitive to a per cent deviation of the investment cost. After the investment cost it is most sensitive to the annual increase of natural gas use and discount rate. The low sensitivity to the electricity price increase is caused by the low amount used in comparison to natural gas.

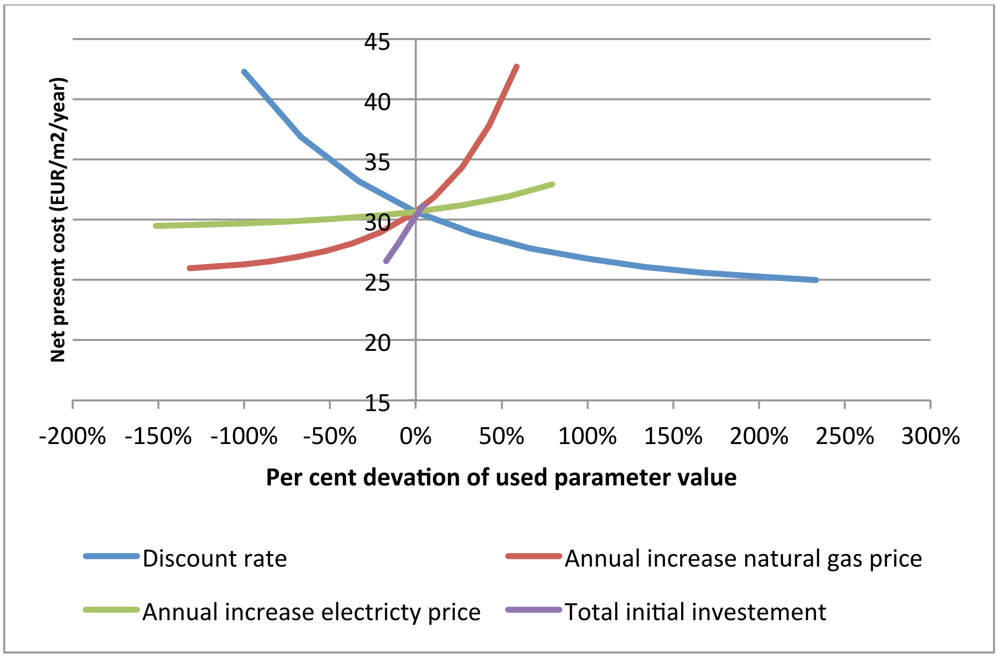

figure F3: Sensitivity analysis of the NPC renovation concept 3

G Sensitivity analysis GHG-emissions and mineral resource depletion

The results shown in this appendix are referred to in section 5.1. In this appendix the graphical results of the sensitivity analysis of the GHG-emissions and mineral depletion are shown.

In figure G1 is shown that for GHG-emissions mitigated renovation concept 2 is the best option and is not depended on the different lifetime extensions.

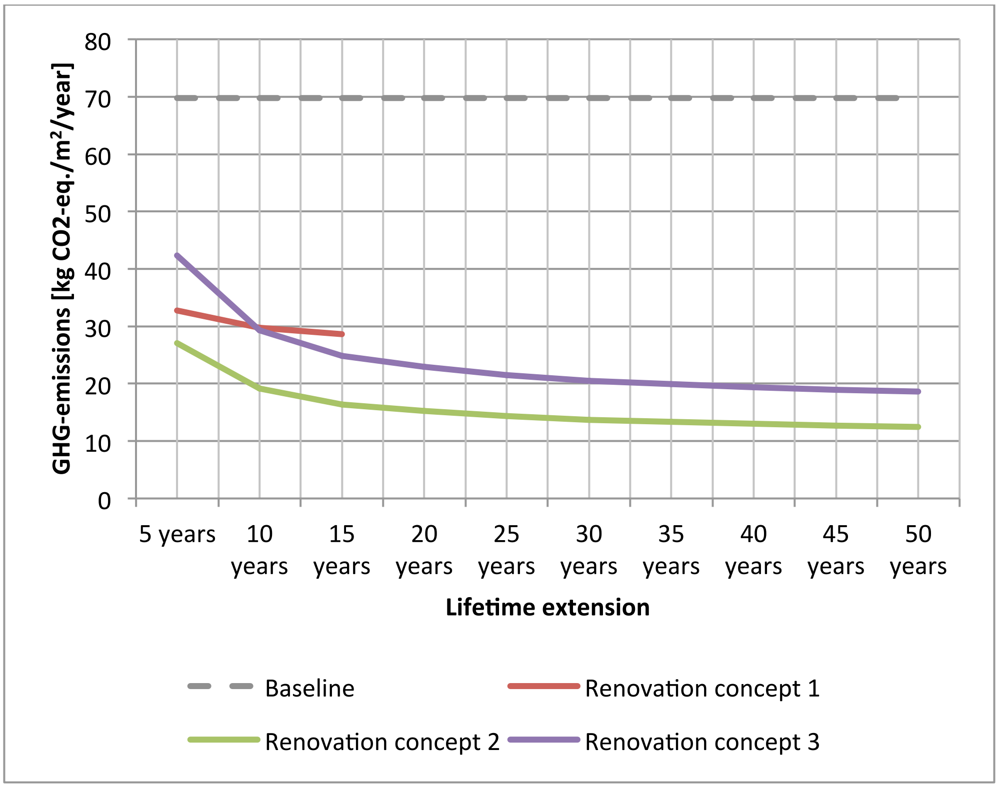

figure G1: Sensitivity analysis of the GHG-emissions (see section 5.1.4)

In figure G2 is shown that for mineral resource depletion both renovation concept 1 and renovation concept 2 are the best option out of the three renovation concepts. Renovation concept 2 surpasses the baseline after scenario after 40 years.

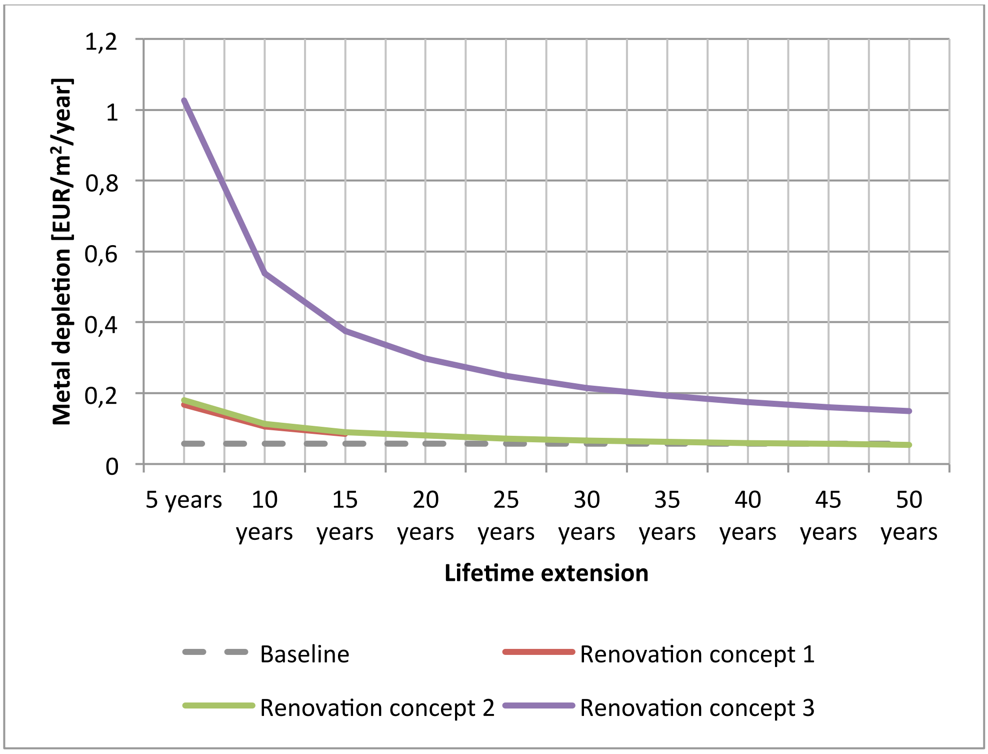

figure G2: Sensitivity analysis of the metal depletion (see section 5.1.4)