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Flat roofs renovation: a life cycle approach for environmental impact assessment and economic effectiveness

Ristrutturazione di tetti piani: un approccio basato sull'intero ciclo di vita per la valutazione dell'impatto ambientale e della convenienza economica

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ABSTRACT

The high energy consumption caused by the building sector and the continuous growth and ageing of the existing housing stock show the importance of housing renovation to improve the quality of the environment. This research compares the environmental performance of flat roof systems (insulation, roofing membrane and covering layer) using Life Cycle Assessment (LCA). The aim is to give indications on how to improve the environmental performance of housing. This research uses a reference building located in the Netherlands and considers environmental impacts related to materials, energy consumption for heating and maintenance activities. It indicates impact scores for each material taking into account interconnections between the layers and between the different parts of the life cycle. It compares the environmental and economic performances of PV panels and of different materials and thermal resistance values for the insulation. These comparisons show that PV panels are convenient from an environmental and economic point of view. The same is true for the insulation layer, especially for materials as PIR (polyisocyanurate) and EPS (expanded polystyrene). It shows that energy consumption for heating causes a larger share of impact scores than production of the materials and maintenance activities. The insulation also causes larger impact scores comparing to roofing membrane and covering layer. The results show which materials are preferable for flat roof renovation and what causes the largest shares of impact. This gives indication to the roofers and to other stakeholders about how to reduce the environmental impact of the existing housing stock.

Key words: Life Cycle Assessment, flat roof renovation, environmental impact, PV panels, economic performance

RIASSUNTO

A partire dalla crisi energetica degli anni ’70 si è affermata la consapevolezza della necessità di attuare politiche per il risparmio energetico e per lo sviluppo sostenibile. Nel 1987, nel rapporto “Our Common Future”, la Commissione mondiale sull’ambiente e lo sviluppo definisce lo sviluppo sostenibile come quello sviluppo che soddisfa i bisogni del presente senza compromettere la possibilità delle generazioni future di soddisfare i propri bisogni (World Commission on Environment and Developement 1987).

Secondo stime del Programma delle Nazioni Unite per l'Ambiente (UNEP), il settore dell’edilizia è responsabile di circa il 36% dei consumi energetici dell’Unione Europea ed il solo settore residenziale lo è del 27,5% (UNEP 2007). Nell’UE il 70% delle abitazioni risale a prima del 1980 e il 23% a prima del 1945 (Federcasa 2006). La minor efficienza energetica rispetto agli edifici che vengono costruiti attualmente rende indispensabili azioni di riqualificazione energetica, preferibili da un punto di vista ambientale alla costruzione di nuove abitazioni. Questa tesi si occupa in particolare della ristrutturazione di tetti piani, con riferimento alla situazione olandese. È parte del progetto Woningkwaliteit 2020 (WK2020), che significa “qualità delle abitazioni” e ha come obiettivo lo sviluppo di conoscenza scientifica applicabile su larga scala per ottenere miglioramenti della prestazione energetica delle abitazioni.

Questa tesi mira ad individuare quali siano i materiali più sostenibili da un punto di vista ambientale, tenendo conto di tutto il loro ciclo di vita, con la metodologia del Life Cycle Assessment (LCA). Si vuole anche trovare in quale misura ogni fase del ciclo di vita (produzione e fine vita, manutenzione, consumo energetico) ed ogni strato costitutivo (isolante, membrana impermeabile, copertura) siano responsabili del totale danno ambientale. Inoltre viene eseguita una comparazione fra la prestazione ambientale e quella economica per l’isolante e per i pannelli fotovoltaici. I materiali presi in considerazione sono:

- Isolante: polistirene espanso (EPS), polistirene estruso (XPS), poliuretano (PUR), poli-isocianurato (PIR) e lana minerale; per ognuno si considerano tre valori di resistenza termica (R): 2,5 – 3 – 5 m^2K/W
- Membrana impermeabile: PVC, gomma EPDM, bitume modificato APP, bitume modificato SBS e bitume bianco
- Copertura: piastrelle in cemento, ghiaia e rivestimento riflettente

- Tetto verde (estensivo) e pannelli fotovoltaici (silicio multicristallino)

Le prestazioni ambientali dei materiali sono valutate secondo punteggi ottenuti con l'utilizzo del software per LCA SimaPro. Per prima cosa vengono analizzati i singoli materiali, tenendo conto delle diverse opzioni di installazione, ma escludendo le fasi di manutenzione e consumo energetico. Successivamente anche queste fasi sono prese in considerazione. Infine si scelgono i materiali più sostenibili dal punto di vista ambientale e si costituiscono possibili scenari completi, per quantificarne l'impatto totale e per analizzare in che misura ogni fase ed ogni strato ne siano responsabili.

Per quanto riguarda l'isolante, la scelta più conveniente sia dal punto di vista ambientale che da quello economico risulta essere l'opzione con R=5 m^2K/W, mentre come materiale il PIR ha la miglior prestazione ambientale e l'EPS la miglior prestazione economica. In generale gli indicatori ambientali hanno valori migliori di quelli economici, ma le indicazioni su quali materiali scegliere sono simili. Dal punto di vista ambientale vi è una convenienza in tutti i casi. Dal punto di vista economico, per i materiali più costosi, vi è una convenienza solo ipotizzando uno scenario in cui il prezzo del gas aumenterà molto rapidamente (+5,87% annuo) o utilizzando tassi di interesse inferiori al 4%.

Per la membrana impermeabile l'impatto ambientale minore è causato dall'utilizzo di un singolo strato in PVC, seguito dall'EPDM. Per la copertura la ghiaia causa i minori impatti. Considerando anche le diverse opzioni di installazione, si ha che le soluzioni preferibili sono quelle di un tetto con uno strato di isolante in PIR con un valore di R=5 m^2K/W, ed una membrana in PVC fissata meccanicamente o tenuta ferma dal peso della ghiaia.

La fase del ciclo di vita che causa il maggior impatto ambientale risulta essere il consumo energetico per il riscaldamento (60-80% del totale), pur considerando solo la quota relativa alle dispersioni attraverso il tetto ed un alto valore di resistenza termica. In un tetto costituito come appena descritto, l'isolante è responsabile per più del 50% degli impatti causati dalle fasi di produzione e manutenzione.

I pannelli fotovoltaici permettono di ottenere dal punto di vista ambientale un risparmio in 30 anni compreso fra il 16 e il 19% ed un payback time di 3 – 7 anni, e dal punto di vista economico un risparmio compreso fra l'8 e il 15% ed un payback time di 11-16 anni. L'installazione di pannelli fotovoltaici risulta quindi consigliabile, a prescindere dalle scelte effettuate per il resto del tetto.

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1 Introduction

Oil crisis in 1970's led to a need for energy saving. On 1987, the World Commission on Environment and Development published "Our common future". The report, also known as Brundtland-report, caused more attention to sustainable development. Sustainable development is development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs (World Commission on Environment and Developement 1987). To reach an environmentally sustainable development, the United Nations (UN) made strong efforts in the last two decades, leading to agreements as the Kyoto Protocol (to reduce greenhouse gas emissions) and the Montreal Protocol (banning the use of CFCs to protect the ozone layer).

One way to accomplish energy saving is insulation of the houses. To meet this goal, the European Parliament issued the Directive on the energy performance of buildings (EPBD, 2002), inspired by the Kyoto Protocol. The directive requires member states to comply with regulations on Energy Performance Certificates, inspection of boilers and inspection of air conditioning systems. Another factor increasing awareness for energy saving is increasing gas price, which has risen about 5% per year from 1994 to 2008 and 15% per year from 2006 to 2008 (Centre d'Etude de Recherche et d'Action en Architecture 2008).

The building sector consumes an estimated 30-40% of energy worldwide and around 36% in the European Union (EU): the non-residential sector accounts for 8.7% and the residential sector for 27.5% of the total (UNEP 2007). In the EU-25 countries, 70% of the existing housing stock was built before 1980 and 23% before 1945. In 2004, an average of approximately 1% of the existing housing stock was newly built, while up to 0.75% of the existing stock was demolished (Federcasa 2006). This means that the existing housing stock is both slowly growing and ageing. Moreover, the energy efficiency of the existing housing stock is, on average, lower than that of new housing (Itard, et al. 2008). Thus, in order to decrease the annual negative impact of housing on the environment, it would be more efficient to improve the environmental quality of the existing housing stock than to focus only on new houses. Despite that, little research has been conducted on existing buildings comparing to new ones. That is why this thesis focuses on existing residential buildings.

From an environmental point of view it appears that renovation-based interventions in the housing stock are better options than consolidation and new construction (Klunder 2005). Several components can be renovated to affect the environmental performance of a building, but research often regarded roof and façade, because (amongst other reasons) insulating these building parts leads to a lower energy consumption. The choice in this study is to analyse roofs in detail, while for research material on façades one can refer to a.o. the PhD thesis “Environmental impacts during the operational phase of residential buildings” (Blom 2010).

Since 1995, Dutch energy-efficiency regulations for dwellings have been based on the energy performance coefficient (EPC), a non-dimensional figure that expresses the energy efficiency of a building. EPC covers space heating, space cooling, hot tap water, humidification and the electricity needed for mechanical ventilation and lighting (Santín 2010). The required EPC that new houses must comply to has decreased in several steps. As an additional measure and in response to EPBD requirements, since January 2008 all transactions in the Dutch housing market need to be accompanied by an energy label (Brounen and Kok 2009).

In 2010, Dutch households were responsible for 24% of the total electricity consumption and 20% of the total gas consumption of the country. For their heating, 96% of the houses used direct connection to the natural gas network, while the remaining 4% were connected to heat supply networks. Over the last 30 years, average households gas consumption has decreased from 3,000 m^3 to 1,617 m^3 in 2010. About 80% of the gas consumption is caused by heating and the reduction is almost entirely the result of the introduction of high-efficiency boilers and the improvements in houses insulation. In 2010, 90% of Dutch houses had double glazed windows, 80% used high efficiency boilers, 60% had roof and wall insulation, and 40% had floor insulation (Energiezaak, Energie-Nederland and Netbeheer Nederland 2011).

In the effort to improve the environmental sustainability of buildings not only the energy consumption has to be considered. The impacts of materials are also of importance since they need to be produced and be disposed at the end of their life spans. Hence a trade-off can occur: the use of a certain building material can lead to higher energy efficiency but can at the same time have a higher environmental impact in its production and disposal phase than another which leads to lower energy efficiency but can e.g. be fully recycled. Therefore, to assess impacts in an appropriate way, every phase of the life cycle of a building component needs to be considered, so that all the environmental damages and benefits can be included. The Life Cycle Assessment (LCA) approach is a good methodology for this purpose since it evaluates a product system over its complete life cycle, i.e. resource extraction, raw materials processing, fabrication, transportation, use, maintenance, recycling and waste disposal. It is also called “cradle-to-grave analysis”. The European Commission concluded on Integrated Product Policy (IPP): LCAs provide the best framework for assessing the potential environmental impacts of products currently available (European Commission 2003).

In 2009 the research group of Housing Quality of the Delft University of Technology initiated the project Woningkwaliteit 2020 (WK2020), which means Housing Quality. The aim of this project is the development of scientifically based and practical useable knowledge for large-scale improvements of the energy performances of the housing stock. Thirteen Dutch housing associations and Aedes (the umbrella organisation of housing associations) are participating in the project (WK2020 2009).

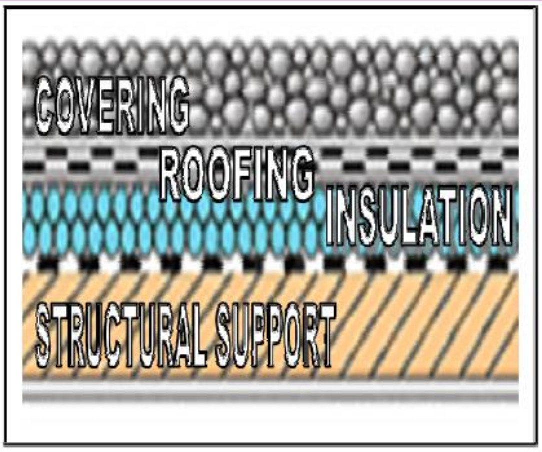
This thesis is part of one of the research projects within WK2020. The goal of this study is the environmental comparison of several technologies for housing renovation and maintenance to find out indications on the impact and sustainability of each solution, and its results can be used in the WK2020 project. Furthermore, the master thesis project can be used as input for the calculation tool GPR Maintenance (OTB and W/E consultants), which calculates the environmental performance of maintenance scenarios of several housing components on the basis of life cycle assessment.

A previous study was carried out by Daša Majcen for her master thesis in 2009. She compared four different scenarios formed by different combinations of roof components (covering layer, roofing and insulation), and assessed which solutions were more environmental friendly. A similar analysis will be carried out in this research, but the aimed result is a broader comparison which includes all the possible combinations of components alternatives and some considerations about the economic costs of the different solutions.

1.1 Previous study results

In her diploma thesis, Majcen made a first assessment of the environmental performance of four roof systems. First the composition of a roof was defined. Its main components are a covering layer, a roofing type and the insulation. For each component several options, as listed in Table 1, were investigated. The study considered flat roofs, but results can be extrapolated to any other roof type using the same materials.

Table 1: Roof components

Component	Alternatives for each component	Layers in a roof
Covering layer	Reflective coating Gravel Concrete Green roof PV cell	
Roofing type	Bitumen + Bitumen felt EPDM + Adhesive PVC + Adhesive	
Insulation	Polystyrene Polyurethane rigid foam Polyurethane flexible foam Glass wool Wool (sheep)	

Second, a partial LCA was done on each alternative considering only the impact due to the production phase, to be able to understand better the results and to help forming consistent scenarios, e.g. to prevent the use of an alternative with a high impact score in an environmentally friendly scenario.

Concerning the covering layer, the green roof was found to have the worst environmental performance in almost all the impact categories, due to its higher number of layers and weight. The quantity of material needed is also the reason for the better environmental performance of reflective coating compared to concrete and gravel. PV cells impact results were not reported here since they were discussed separately due to their characteristic of energy production.

Regarding roofing type, bitumen was found to have the highest environmental impact in every impact category. Fewer chemical processes requiring energy are involved in its production, but the six times higher weight of its roofing type negate this.

Concerning the insulation, the results obtained on each material impact didn't show an unambiguous outcome, as different materials had diverse scores in diverse categories.

After this first analysis, four scenarios were defined considering the results shown above and experiences of maintenance companies (Bouwteam P&O, The Netherlands). The scenarios are described in Table 2.

Table 2: Roof scenarios

		Insulation	Roofing type	Covering layer
Scenario	Traditional roof	Glass wool	Bituminous	Gravel
	EPDM roof	Polystyrene	EPDM[1]	Concrete
	Green roof[2]	Pumice, growing medium, waterproof membrane (EPDM), fleece		
	PV cell roof	Sheep wool	PVC	Reflective coating + PV cells

Then, the sustainability of each scenario was assessed considering material production, transport, maintenance activities and energy used for heating of the building. The final results showed the impacts after 50 years, including the energy benefits (due to insulation and PV electricity production) compared to the traditional roof scenario, chosen as reference. One can note that:

- The PV cell scenario had the lowest impact scores, due to electricity generation, although it had the highest impact scores for the production and maintenance parts
- EPDM roof had low impact scores as well, since it had the best insulation of all scenarios
- Green roof performed the worst, even worse than the traditional scenario. The problem is that the anticipated benefits are hardly quantifiable with current calculation methods and data. Little research has been conducted on it, elucidating beneficial impacts of green roof on storm water retention, biodiversity and air pollution (D. Majcen 2009).

Additional conclusions were found:

- All phases (production, maintenance and energy use) play a relevant role in the total environmental impact
- In almost every case, the environmental impact due to maintenance (calculated after 50 years) is larger than the environmental impact of production of the building materials
- More innovative solutions, not necessarily only material related, should be investigated. Maintenance burden could be decreased with better organization and cooperating parties (D. Majcen 2009).

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[1] Ethylene Propylene Diene Monomer, also known as rubber roofing.

[2] Green roof can also be installed on the top of an existing roof if this still performs satisfactory, but to make scenarios comparable this was not the case in Majcen's research. Furthermore, this scenario was not formed by three components as the other, but it had a more complex structure and no insulation since the resistance value was already sufficiently high.

There were some comments on the results of Majcen's thesis from people in the field:

- Thermal conductivity factor should be revised for bitumen, XPS (polystyrene) and green roof
- Life time of several materials should be revised; this can be done with the help of roofers
- Cleaning, inspecting and other maintenance activities should be revised, especially concerning frequency and travel distances.

These comments are taken into account in this study.

1.2 Goal and scope

The present study investigates additional roofing scenarios to get a broader vision of which sets of components are the most preferable and to get some more indications about the different materials and phases, considering the whole life cycle of the roof.

The goal of the study is the comparison of the environmental performance of roof systems using LCA, with the aim to improve the environmental performance of housing. Three roof layers are considered; the bearing structure is not taken into account. As in Majcen's diploma thesis, three main phases are assessed: material (including production, transport and waste treatment), maintenance and energy used for heating. The calculations are performed for a common apartment building in the Netherlands.

The research questions are:

- What is the environmental impact of each roofing scenario?
- Which phase is responsible for the most significant burden: material, maintenance or energy consumption?
- In what extent is each layer responsible for the environmental impact of the whole roof?
- Which measures can be suggested to improve the environmental performance of the traditional roofing scenario?
- Are environmentally friendly solutions convenient also from an economic point of view?

The thesis is structured as follows:

- Chapter 2 gives an overview on the materials assessed (section 2.1), a description of the Life Cycle Assessment approach (section 2.3) and explains how calculations were done and which data were used (sections 2.4 and 2.5).
- Chapter 3 presents and discusses the results found. First, the impact of the materials for each layer are determined (section 3.1). Then the scenarios and their environmental performances are described (section 3.2).
- In Chapter 4, the results are discussed.
- In Chapter 5, the conclusions are drawn.

2 Material and methods

In this section the building considered for the calculations, the materials for each roof layer, the software (SimaPro) and the impact methods are presented.

2.1 Building description

The building considered in these calculations is an apartment block in Leiden (The Netherlands), currently occupied by working youth. The building from the 60s is five floors high and has seven 45m^2 apartments per floor. The whole flat roof area is 300 m^2. Each apartment has the following characteristics:

- Two walls (east and west oriented), 8.5 x 2.6 m^2 each.
- Two façades (north and south oriented), each is 5.0 x 2.6 m^2, with a thermal resistance (R-value) of 4.40 m²K/W.
- Two windows, each is 7.0 m^2 with an R-value of 0.56 m²K/W.
- Two doors, one is 2.2 m^2 with an R-value of 0.33 m²K/W and one is 1.9 m^2 with an R-value of 0.12 m²K/W.

The current roofing is multi-layer bitumen with gravel ballast and no insulation. The building is constructed of brick, which is typical for The Netherlands. Although this building is not really similar to the official Dutch reference building as described by the Dutch agency SenterNovem, it is representative for the apartment buildings built in the Netherlands in that time period. The official Dutch reference buildings are a collection of typical Dutch dwellings of different construction types, sizes and building periods. They have been developed to assess measures to improve energy efficiency of existing dwellings, but are also frequently used for other environmental assessments (Novem 2001).

2.2 Characteristics of the materials assessed

A flat roof with a three layers structure is considered. Table 3 shows a list of those analysed in the present study together with their weight, density, thickness, thermal resistance (R) and thermal conductivity (λ).

Table 4 shows the percentages of the roof materials that are landfilled, incinerated and recycled at the end of the life cycle.

Table 3: List and characteristics of materials (weight, density, thickness, thermal resistance and thermal conductivity). Sources: Majcen, 2009; GPR Building, 2011; information from the roofers.

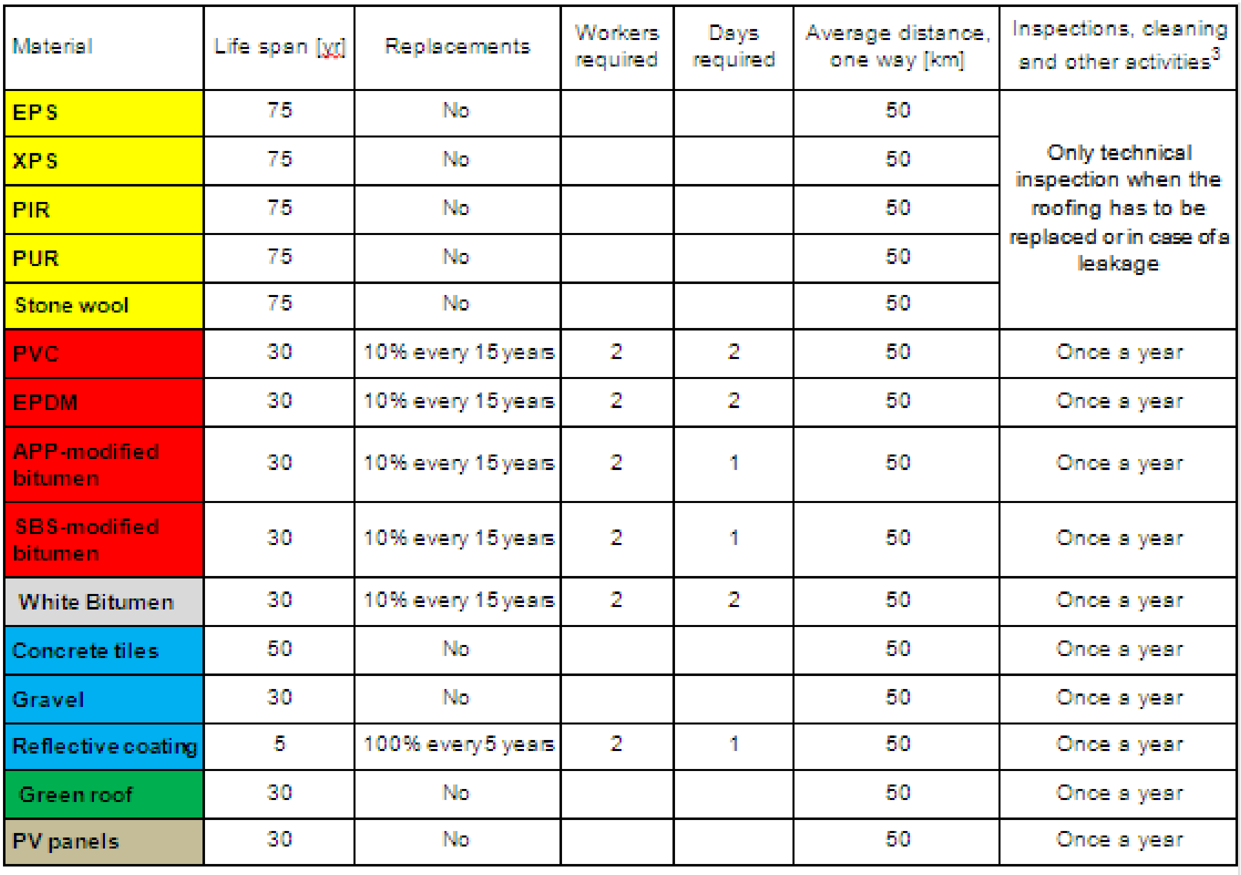
Layer	Material	Weight [kg/m²]	Density [kg/m³]	Thickness [mm]	R [m²K/W]	λ [W/mK]	Service life [years]
Insulation layer	**EPS (Expanded Polystyrene)**	1.8	20	90.0	2.5	0.036	75
		2.2	20	110.0	3	0.036	
		3.6	20	180.0	5	0.036	
	XPS (Extruded Polystyrene)	2.25	30	75	2.5	0.029	75
		2.7	30	90	3	0.029	
		4.5	30	150	5	0.031	
	PIR (Polyisocyanurate)	1.8	30	60.0	2.5	0.024	75
		2.2	30	70.0	3	0.024	
		3.6	30	120.0	5	0.024	
	PUR (Polyurethane, rigid foam)	2.3	38	60.0	2.5	0.025	75
		2.9	38	75.0	3	0.025	
		4.8	38	125.0	5	0.025	
	Stone wool	17.6	160	110.0	2.5	0.042	75
		20.8	160	130.0	3	0.042	
		33.6	160	210.0	5	0.042	
Roofing layer	**PVC**	1.6	1300	1.2			30
	EPDM	1.4	1180	1.2			30
	APP-modified bitumen	6.3	1050	6.0			30
	SBS-modified bitumen	6.3	1050	6.0			30
White bitumen	**White bitumen + APP**	7.6		7			30
Covering layer	**Concrete tiles**	113	2511	45			50
	Gravel	44.8					30
	Reflective coating	1.3					5
Green roof	**Substrate**	25.6					30
	Fleece	7.4					
	Pumice	6.5					
	Waterproof membrane (EPDM)	1.8	1180	1.5			
	Green roof (TOTAL)	41.3		100			
PV panels	**PV panels**						30

Table 4: Waste scenario per each material (Harmonized National Database)

Layer	Material	Landfill	Incineration	Recycling
Insulation layer	**EPS**	5%	90%	5%
	XPS	5%	90%	5%
	PIR	10%	85%	5%
	PUR	10%	85%	5%
	Stone wool	85%	5%	10%
Roofing layer	**PVC**	10%	20%	70%
	EPDM	10%	85%	5%
	APP-modified bitumen	5%	90%	5%
	SBS-modified bitumen	5%	90%	5%
Covering layer	**Concrete tiles**	1%	0%	99%
	Gravel	10%	0%	90%
	Reflective coating	Depending on roofing layer below		
White bitumen	**White bitumen + APP**	5%	90%	5%
Green roof	**Substrate**	1%	0%	99%
	Fleece	10%	85%	5%
	Pumice	1%	0%	99%
	Waterproof membrane (EPDM)	10%	85%	5%
PV panels	**PV panels**	0%	10%	90%
Fixing	**Steel (screws and rings)**	5%	0%	95%

In section 3.2, all results include all phases of the life cycle of the materials, using 30 years as a cut-off point for the cumulative impacts of maintenance activities and energy consumption. The choice is made according to the life span of most of the materials assessed. Transport of materials to the building location is also included. A return trip is considered to be 100 km long. Table 5 shows the activities required for maintenance. For the initial replacement, 10 days and 2 workers are required for the whole roof. No data were available for the initial replacement of the different layers separately, and different layers are often replaced simultaneously. Therefore, the impact caused by the transport of the maintenance workers is only included when considering complete scenarios (section 3.2.4). All inspections, cleaning and other activities require one day or less. Data are provided by the roofers.

Table 5: Replacement and maintenance activities in 30 years



Material	Life span [yr]	Replacements	Workers required	Days required	Average distance, one way [km]	Inspections, cleaning and other activities[3]
EPS	75	No			50	Only technical inspection when the roofing has to be replaced or in case of a leakage
XPS	75	No			50	
PIR	75	No			50	
PUR	75	No			50	
Stone wool	75	No			50	
PVC	30	10% every 15 years	2	2	50	Once a year
EPDM	30	10% every 15 years	2	2	50	Once a year
APP-modified bitumen	30	10% every 15 years	2	1	50	Once a year
SBS-modified bitumen	30	10% every 15 years	2	1	50	Once a year
White Bitumen	30	10% every 15 years	2	2	50	Once a year
Concrete tiles	50	No			50	Once a year
Gravel	30	No			50	Once a year
Reflective coating	5	100% every 5 years	2	1	50	Once a year
Green roof	30	No			50	Once a year
PV panels	30	No			50	Once a year

2.2.1 Insulation layer

In general, insulation (in roof, walls, floor and windows) is applied for preventing heat loss in winter and reducing the heat transfer into the house during summer. The former is more important in countries with a cold climate like the Netherlands. Insulated buildings consume 20% to 40% less energy than non-insulated buildings (Dzioubinski and Chipman 1999).

Three R value (2.5, 3 and 5) are analysed for each insulation material, to get a broader set of alternatives.

EPS and XPS

Polystyrene is an aromatic polymer made from the monomer styrene, a liquid hydrocarbon that is manufactured from petroleum by the chemical industry. Expanded polystyrene (EPS) foam is a closed-cell insulation that is manufactured by “expanding” a polystyrene polymer. Extruded polystyrene (XPS) foam is a rigid insulation that is also formed with polystyrene polymer, but manufactured using an extrusion process (McBride 2009). Pentane is used as blowing agent for EPS, while HFC-134a, HFC-152a or CO2 can be used for XPS; the calculation considered for XPS a production mix, taking into account these three options. XPS has higher water resistance and thermal resistance than EPS, due to the presence of voids in EPS structure (ASTM C578 standard).

PIR and PUR

Polyurethane (PUR) and Polyisocyanurate (PIR) rigid foams are polymers formed by reacting a monomer with isocyanate groups with a monomer with polyol groups. PUR has the same amount (in term of chemical groups) of isocyanate groups and polyol-groups, while PIR has 4 to 5 times more isocyanate groups than polyol-groups. They are often flammable and produce toxic fumes when they burn. They are available both in slabs and directly applied in work as foam. In this study, only slabs are taken into account.

Stone wool

Stone wool, also known as mineral wool or rock wool, is a furnace product of molten rock at a temperature of about 1600 °C. It is completely recyclable and non-combustible. Comparing to the other insulation materials assessed, it has a weight per m^2 about ten times higher (see Table 3).

2.2.2 Roofing layers

In the last years of the twentieth century a revolution in the choice of roof systems happened. The dominance of the previous 140 years of built-up bituminous roofing (BUR) system ended. In 2005 its world market share was 15%, while single-ply elastomeric and thermoplastic sheets had about half of the market. Modified bitumen accounted for 20% and metal roofing for 10% (Griffin and Fricklas 2006). The roofing membrane is the part that prevents water from leaking into the roof.

PVC

Polyvinyl chloride (PVC) is produced by polymerization of the monomer vinyl chloride. The roofing membrane owes its flexibility to a plasticizer, which soften the otherwise rigid PVC (Griffin and Fricklas 2006). It is inherently fire-resistant and to a large extent is recyclable (Fricklas 2011).

EPDM

EPDM compounds are made up of EPDM (Ethylene Propylene Diene Monomer), carbon black and other substances (softeners, plasticizers and fillers). The producers claim that EPDM is able to resist the mechanical and thermal forces of exposure on flat roofs very well. EPDM rubber roofing repels moisture and does not suffer with age from cracking or crazing, and it allows vapours to escape, thus preventing blisters. Another benefit is that it pollutes the runoff water less than bitumen (Clark, et al. 2008), which is crucial if the house owner wishes to use this water for personal sanitation or hygiene. EPDM has an excellent weather resistance, but it is vulnerable to chemical attack from oils and fats which weaken and swell the membrane. It is also a bad fire retardant (Griffin and Fricklas 2006).

APP and SBS-modified bitumen

APP-modified bitumen is a mixture of bitumen (65%), polypropylene (20%) and unknown material (15%). SBS (styrene-butadiene-styrene) modified bitumen is a mixture of bitumen (65%), EPDM (15%) and unknown material (20%). Due to lack of data for the two unknown materials, the data are obtained considering only the known components. On recommendation of roofers and from literature (Griffin and Fricklas 2006), for both APP and SBS-modified bitumen, two layers are considered.

White bitumen

White bitumen, as considered here, is made of APP modified bitumen (85%), a fiberglass reinforcement (5%, based on polyester) and a white acrylic reflective coating (10%). Roofers claim in warm periods it can lower the roof surface of about 40 ºC and the inside temperature of 4 or 5 ºC compared to traditional roofs, due to its solar reflectance of 0,81 and solar emittance of 0,94 (Nederlandse Bouw Documentatie). Thus it can be considered as a roof whit a reflective coating, whose benefits will be described in the next section. The white bitumen layer, 3 mm thick, is considered to be applied on the top of one APP-modified bitumen layer, 4 mm thick.

2.2.3 Covering layer

The main goal of this layer is to prevent damage to the roofing surface from ultraviolet radiation. Gravel and concrete are the most common solutions.

Concrete Tiles

The cement industry is the second largest CO_2 emitting industry behind power generation, creating up to 5% of worldwide man-made emissions of this gas, of which 50% is from the chemical process and 40% from burning fuel. Non-walkable tiles are considered in the study. Concrete tiles are easy to apply.

Gravel

Gravel can be used to protect against radiation from the sun to prolong the life of the roof. Consequently, energy saving is not calculated for gravel ballast, but it would most likely be negligible. Round gravel is used instead of crushed gravel.

Reflective coating

Alternatively, a reflective coating can be applied to the roofing membrane to decrease the roof temperature. A cool roof has a high solar reflectance and high thermal emittance (Figure 1); thus it can reduce the building cooling loads, mitigate the Urban Heat Island Effect[3] and prevent sun radiation to damage the roofing surface which decreases the roof life span. Achieving high solar reflectance in roofs can also help tackle global warming based on the principle of solar radiation management, provided that the materials used reflect more solar energy instead of absorbing it and causing the temperature of the body to rise. The reflectivity of roofs depends on the surfacing material and colour and it can be increased by using reflective coating. Reflecting sun radiation can lead to higher heating demand during winter, but this amount is usually insignificant compared to the cooling energy savings during the summer (Cool Roof Rating Council).

Only recently, life cycle analysis of green roofs has shown that these roofs also decrease environmental damage due to lower absorption of solar radiation and lower thermal conductance (Kosareo and Ries 2007). A more detailed description of green roofs will be given in the next section. Besides green roofs also ballasted roofs (gravel) were also recently proven to decrease the cooling demand (Desjarlais, Petrie and Atchley 2007).

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[3] Urban heat-island (UHI) is a common phenomenon where urban temperatures are significantly higher than those of its surrounding suburban and rural areas in summertime. Urban heat-islands can affect communities by increasing summertime surface temperature of building envelopes and infrastructures, intensifying thermal discomfort, elevating cooling energy use and peak energy demand, adding air pollution and raising risks in heat-related illness or mortality. A higher air temperature tends to increase cooling needs and reduce working efficiency of cooling systems for built environments, resulting in higher power demand and energy use. For example, a study estimated that an increase of 1ºC in air temperature would require the addition of about 500 megawatts (MW) for air-conditioning for buildings in the Los Angeles Basin (Akbari, Pomerantz and Taha 2001).

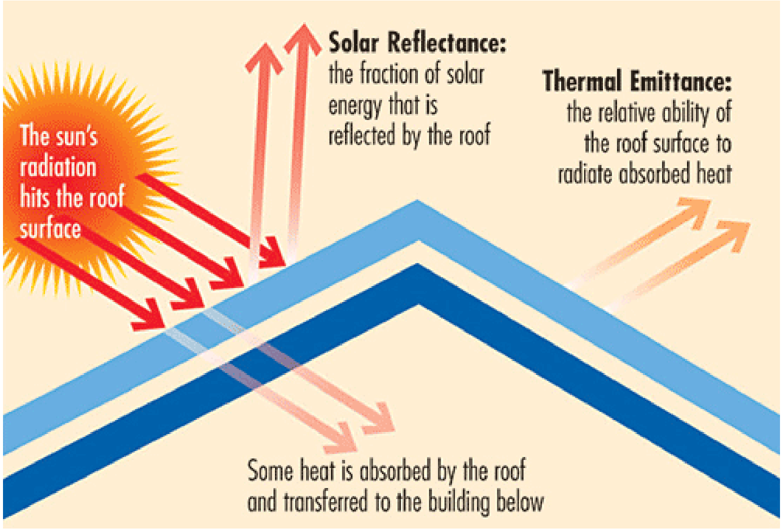

Figure 1: Roof solar reflectance and thermal emittance

The coating is based on polyurethane, it is bright white, it has a solar reflectance between 0,7 and 0,85 and a solar emittance between 0,8 and 0,95 (Griffin and Fricklas 2006). Roofers claim its benefits occur especially during summer, when it can lower roof temperature by 20ºC to 60ºC and indoor temperature by 7ºC to 10ºC, mostly depending on climate conditions (Rodriguez 2011). Thus electricity consumption for air conditioning can be reduced. Roofers also claim reflective coatings can extend roof life. Due to lack of data none of these two benefits are considered in this study, so the calculated total impact score of a scenario including reflective coating can be overestimated.

2.2.4 PV panels

Photovoltaic panels can be installed on the top of a roof to generate electricity converting solar radiation into electricity.

In the beginning of solar cell technology, crystalline silicon solar cells were made exclusively from mono-crystalline silicon material. In later years, multi-crystalline silicon cells were developed by several companies, due to their lower price which better met the market demand. Multi-crystalline silicon efficiency is lower because it contains more impurities (Phylipsen and Alsema 1995). Multi-crystalline silicon panels are considered in this study.

PV panels can be installed on all types of roofs considered here. Magallanes reported that some companies had an increased energy production up to 20% by installing PV panels on a cool roof. This was ascribed to the collection of reflected and diffused light by the PV panels or to the decreased surrounding temperature caused by the reflection of solar radiation due to the covering layer reflectivity (Magallanes 2011), raising the efficiency of the PV panels (Luque and Hegedus 2003). In general, the maximum power provided by a cell decreases of about 0,4% for each 1° C increase in temperature (Wenham, et al. 2007).

The shadow provided by PV panels on the roof was proven to decrease the temperature of interior ceiling surface of a building by 2,5 °C, but this data refers to San Diego, CA, which has a lower latitude than the Netherlands, (Dominguez, et al. 2010).

Due to the fast growth in the amount of PV panels installed happened in the last decade and to their life span, the estimated quantity of waste will have a first peak in 2020 and a higher one in 2030, as shown in Figure 2 (PV Cycle 2007). PV modules contain substances such as glass, aluminium and semiconductor materials that can be successfully recovered and reused, either in new photovoltaic (PV) modules or other products. The European Commission is likely to make the Waste Electrical and Electronic Equipment Directive (WEEE) applicable also for PV modules (Breyer 2011). Currently, economic incentives may be inadequate to move the PV industry into voluntary recycling. However, this may change in the future, as more economic incentives may be given to developing clean technologies, preventing pollution and reducing CO2 emissions. Moreover, companies may start recycling to emphasize their green brands (Larsen 2009). Few associations or companies has started developing processes to reuse or recycle materials from PV waste in the last 10 years.

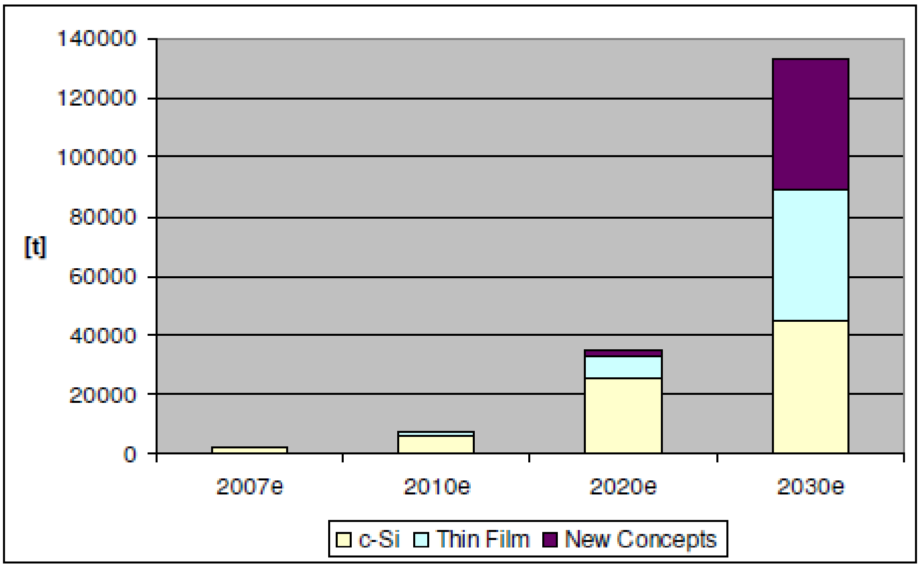

Figure 2: PV panels waste forecast per type, in tons

2.2.5 Green roof

Green roofs are vegetated layers on top of the conventional roof surfaces of a building. They can be classified by their purpose and characteristics in to two major types: intensive roofs and extensive roofs (Figure 3, on the left). Intensive roofs can support a wide range of plant types (trees, shrubs, perennials, grasses and annuals) but need a higher depth of soil and require skilled labour, irrigation, and constant maintenance. Extensive roofs have a relatively thin layer of soil (not more than 10 cm), grow sedums and moss and are designed to require minimum maintenance (Molineux, Fentiman and Gange 2009).

The environmental and operational benefits of green roofs are: reduction of energy demand for heating and cooling, mitigation of urban heat island effect, reduction and delay of storm water runoff, improvement of air quality, replacement of displaced landscape, enhancement of biodiversity, provision of recreational and agricultural spaces, and sound insulation of a building (Bianchini and Hewage 2011).

Green roofs are popular due to their environmental benefits, but they are relatively expensive and heavy (Nelms, Russell and Lence 2007). Green roof's experts stress the need to introduce materials like plastics into the market because it can reduce the overall weight and improve the performance of waterproofing layers without compromising the benefits of green roofs.

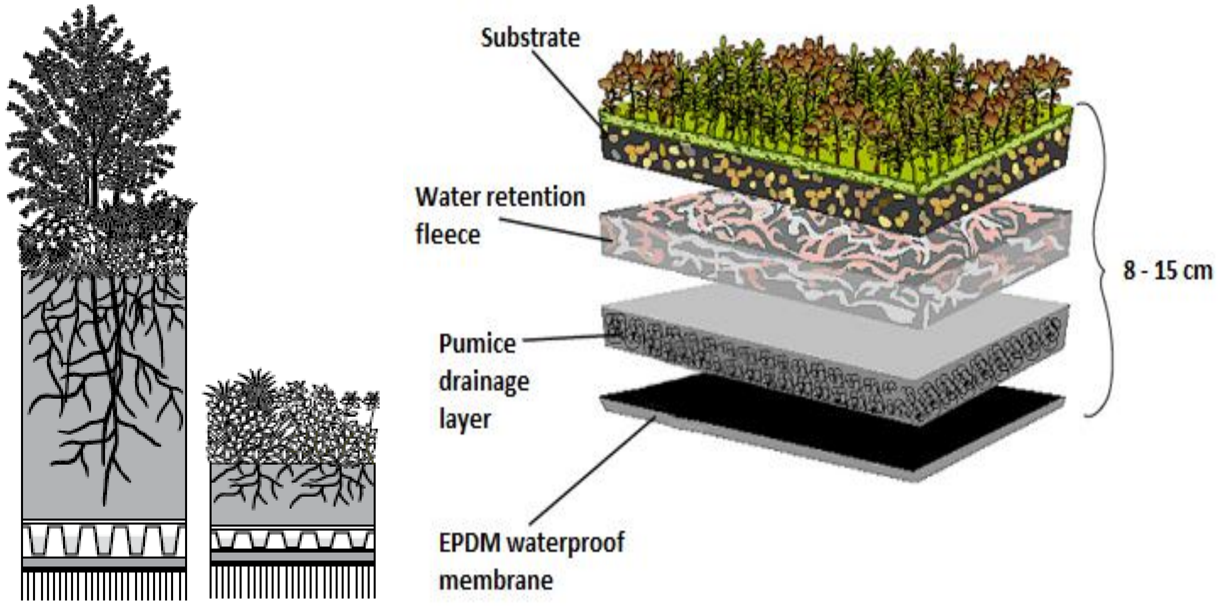

Figure 3: Intensive and extensive green roofs (left); Green roof layers (right)

The right part of Figure 3 shows the layers considered in this study for a green roof:

- The substrate is a mix of expanded clay and compost and serves as growing medium.
- The polyethylene water retention fleece layer prevents the particles of the upper layer from draining with water runoff, blocks the drainage layer retain water for runoff control and keeps the growing medium layer moist (Bianchini and Hewage 2011).
- The pumice drainage layer carries water away from the plant zone.
- The EPDM waterproof membrane avoid water to reach the roof and serves as a protection from roots and drainage layer for it.

If the existing roof of the building still performs satisfactory, green roof could in theory also be installed directly on top of it, according to manufacturers. In this study, only the new green roofs are considered.

2.2.6 Fixing material

The following fixing options are considered in this research. Data are gathered from roofers and from GPR Maintenance.

- Insulation: Table 6 gives the material and energy consumption for the fixing of the insulation layer. The length of the screws depends on the thickness of the insulation layer, which is proportional to the thermal resistance. No difference is considered between different insulating materials.

Table 6: Insulation layer fixing materials depending on its thermal resistance

Thermal resistance of the insulation layer	Fixing material and energy per m^2 of roof	Amount per m^2 of roof
2.5 and 3 m^2K/W	2 screws and 2 rings, made of steel and coated with zinc	0.022 kg
	Electricity for the screwdriver	2 KJ
5 m^2K/W	2 screws and 2 rings, made of steel and coated with zinc	0.036 kg
	Electricity for the screwdriver	2 KJ

- Roofing: for all materials fixing of the edges is the most critical part. It requires extra material and activities. PVC, EPDM, APP and SBS-modified bitumen can be left loose if a roofing ballast is applied above. Other fixing options are:

- PVC mechanically fixed (heated and fixed mechanically to the edges). Table 7 gives the material and energy consumption for the fixing of the PVC roof.

Table 7: PVC mechanically fixed: fixing materials

Fixing element	Material	Amount	Unit
Follower plate, square ring, 4x	Steel	0,1	kg/m^2
RVS screws, 4x	Steel, RVS	0,04	kg/m^2
Foil steel board trim	steel, coated, galvanized	0,49	kg/m^2
RVS screws	Steel, RVS	0,04	kg/m^2
PVC strip, 200 mm	PVC	0,31	kg/m^2
Drier, 2000 watt, 6 min.	Electricity	0,72	MJ/m^2
Screwdriver 800 watt, 4 min.	Electricity	0,2	MJ/m^2
Screwdriver, 5 min.	Electricity	0,013	MJ/m^2
Drier, 2000 watt, 10 min.	Electricity	1,2	MJ/m^2

- EPDM glued. No data is available at the roofers or in GPR Maintenance about the adhesive. Martineau (2011) used latex as approximation for the adhesive in his comparison of different mitigation measures of urban heat island effects. It was applied on two layers for a total weight of 0.68 kg/m^2. The same is done here.
- EPDM mechanically fixed. Table 8 gives the material and energy consumption of the fixing of EPDM roofs.

Table 8: EPDM mechanically fixed: fixing materials

Fixing element	Material	Amount	Unit
Follower plate', square ring, 1x	Steel	0,025	kg/m^2
RVS Screws 2x	Steel, RVS	0,02	kg/m^2
RVS Screws 3x	Steel, RVS	0,03	kg/m^2
Aluminum roof trim, coated	Aluminum, coated	0,3	kg/m^2
Tape	PVC, 70% recycled	0,012	kg/m^2
Bituminous kit	Sealant, polysulfide	0,015	kg/m^2
Screwdriver 800 watt, 4 min.	Electricity	0,2	MJ/m^2
Screwdriver 800 watt, 4 min.	Electricity	0,2	MJ/m^2

- APP-modified, white and SBS-modified bitumen heated. Table 9 gives the material and energy consumption of their fixing.

Table 9: APP-modified, white and SBS-modified bitumen heated: fixing materials

Material	Fixing material	Amount	Unit
APP-modified bitumen	Gas for heating	1	MJ/m^2
	APP-modified bitumen	2.1	kg/m^2
White bitumen	Gas for heating	1	MJ/m^2
	APP-modified bitumen	2.1	kg/m^2
SBS-modified bitumen	Gas for heating	1	MJ/m^2
	SBS-modified bitumen	2.3	kg/m^2

- Covering layer: reflective coating is applied as a paint, while gravel and concrete tiles act as ballast to fix the roofing membrane below.
- Green roof: its weight enables to apply it loose, directly on the insulation layer.
- PV panels can be fixed in many different ways. In this study they are assumed to be mounted on frames with concrete tiles (30 kg/m^2) as ballast.

XPS is only considered when the roofing membrane is left loose, i.e. when gravel, concrete tiles or green roof are applied. In section 3.2, all possible scenarios are shown considering all the relations and constrains caused by properties of materials and fixing options.

2.3 Life cycle assessment

2.3.1 General description

Life cycle assessment (LCA) is a methodology for assessing the environmental aspects associated with a product or service over its life cycle. The most important applications are:

- Analysis of the contribution of the life cycle stages to the overall environmental load, usually with the aim of prioritising improvements on products or processes.
- Comparison between products for internal or external communications.

LCA became popular in the early nineties. Initially many people thought that LCA would be a good tool to support environmental claims that could directly be used in marketing. Over the years, it has become clear that this is not the best application for LCA, but it is clearly important to communicate LCA results in a careful and well-balanced way (ISO 2006). LCA methodology is widely accepted and applied in scientific research to assess the environmental impact of products and services.

The standard for LCA has been defined by the International Organization for Standardization (ISO) with the goal of enhancing environmental protection awareness (ISO 14040). According with the standard, LCA studies environmental impacts throughout the life of a product from raw material acquisition through production, use and disposal. It is an environmental analysis of a product that includes the following four steps.

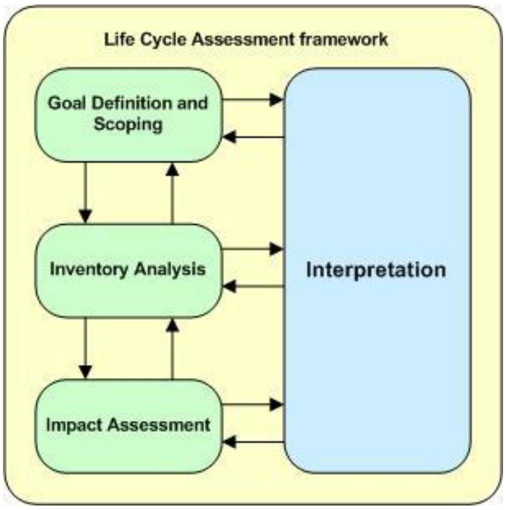

Figure 4: The four steps of LCA

The first step is to define the goal and scope of the assessment. These serve as a description of the type of study, e.g. a comparative analysis of products or a study to improve a production process. According with ISO, the definition of the goal must describe unambiguously the application, the intended audiences and the reasons for carrying out the study. The scope of the study describes the most important methodological choices, assumptions and limitations such as:

- Functional unit, i.e. the product quantity used as a reference for calculations of material and energy flows (e.g. a kg of product or a kWh of provided energy)
- System boundaries
- Criteria and threshold for inclusion of inputs and outputs (ISO recommendations exist)
- Allocation of the process environmental load to its different functions or outputs
- Data quality requirements: precision, consistency, sources, geographical and time coverage

The scope determines the processes to be included in the next step, the inventory analysis, which involves the compilation of an inventory of the flow of all substances to and from the environment (elementary flows) during the period of interest (H. Udo de Haes 1996). For this purpose, several databases are available, such as Ecoinvent (Ecoinvent Centre 2011), that contains data about inputs and outputs of materials, energy, transport and waste treatments for many products and processes.

In the third step, impact assessment, the potential contribution made by each substance to predefined environmental impact categories is calculated. Life cycle impact assessment (LCIA) is defined as the phase in the LCA aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system. In this section different methods can be used, each with its own calculation methods and characterisation factors to quantify environmental performance. After the method (and thus the impact categories) is chosen, the impact assessment, according with ISO 14042 (ISO 2006), defines a distinction between obligatory and optional elements:

- Obligatory elements:
    - *Classification*, assigning each elementary flow from or to the environment to one or more impact categories
    - *Characterisation*, characterisation factors reflecting the relative contribution of an LCIA result to the impact category were defined and calculated in the impact method. For example, on a time scale of 100 years the contribution of 1 kg CH_4 to global warming is 25 times as high as the emission of 1 kg CO_2. This means that if the characterisation factor of CO_2 is 1, the characterisation factor of CH_4 is 25. Thus, the impact score for global warming can be calculated by multiplying the LCI results with the characterisation factors (ISO 2006)
- Optional elements, used to make the interpretation of the results easier:
    - *Normalisation*, comparing the indicators values to a reference (e.g. average annual emission per inhabitant in Europe)
    - *Ranking*, sorting impact categories in descending order of significance
    - *Grouping*, presenting indicators with common features as a group
    - *Weighting*, comparing of different impact scores in function of the relative importance given to each impact category. According to ISO 14044, weighting is not allowed for public comparisons

between products (as in the present study), since it is a subjective issue and it increases the uncertainties of the results. The weighted scores of each category can be summed to obtain a *single score* value.

Once the environmental impacts have been determined, the last step in the assessment is to interpret the results of the calculations by, for example, comparing the calculated impacts with the results of similar research in the literature or with the overall environmental impacts in a region (normalisation), and by determining the sensitivity of the results to changes in the input variables. As shown in Figure 4, the process is iterative: the interpretation phase of the assessment may highlight unanswered questions or inconsistencies in the study which need to be addressed.

2.3.2 Life cycle assessment of buildings

The life cycle of a building consists of three main phases: construction, operation and deconstruction. The construction phase includes all processes from extraction of material resources to constructing the building on-site. The deconstruction phase includes all processes from deconstruction of building components to recycling and the final waste processing. The operational phase includes maintenance and operational energy consumption. In practice, a building might be refurbished or be given a new designation which adds phases to the life cycle and starts a new operational phase after the changes have been made (Blom 2010).

Application of LCA on whole buildings or element entities has some peculiarities that makes it more complex than LCA of more conventional products (a cup, a computer, …). This is due to several reasons:

- Presence of a larger number of unique components, unlike mass-produced products
- Long life span
- Difficulties in forecasting maintenance activities (frequency, entity, …) and end of life

An additional reason is that new technologies developed by other branches of industries during the building life span can affect the energy consumption and maintenance activities. This implies that there are many influences on the development of the building and construction industry, and it is difficult to predict what will be adopted and how they will be implemented (Klunder and Van Nunen 2002).

2.3.3 Life cycle assessment calculations

For LCA calculations, the SimaPro 7.3 software, developed by PRé Consultants was used (PRé Consultants 2008). It is one of the most widely utilized tools for LCA and it is designed according with the ISO 14040 series of standards (see section 2.3.1). It has four main sections, one for each LCA step (goal and scope, inventory, impact assessment and interpretation).

Data for many of the materials used come from the Ecoinvent 2.2 database, 2010 version (Ecoinvent Centre 2011). This database is developed by the Ecoinvent Centre which is a joint initiative of several Swiss research institutes (ETH Zurich, EPF Lausanne, PSI, Empa and ART). Ecoinvent 2.2 includes more than 4’000 LCI datasets based on industrial data, in the areas of agriculture, energy supply, transport, biofuels and biomaterials, chemicals, construction materials, packaging materials, basic and precious metals, metals processing, ICT and electronics and waste treatment (Ecoinvent Centre 2011).

For LCA calculations, following assumptions are made:

- Recycling is not taken into account, because in Ecoinvent, the environmental impacts of the recycling process are attributed to the production of the secondary materials instead of to the waste streams.
- Capital goods, such as factories and infrastructure, are included in the calculations

According to the first assumption, Figure 5 shows that recycling is outside from the system boundaries. The three phases considered in this study are also visible in Figure 5. Production, construction and waste treatment are part of the phase called “material”. Other two phases are “maintenance” and “energy consumption” for heating.

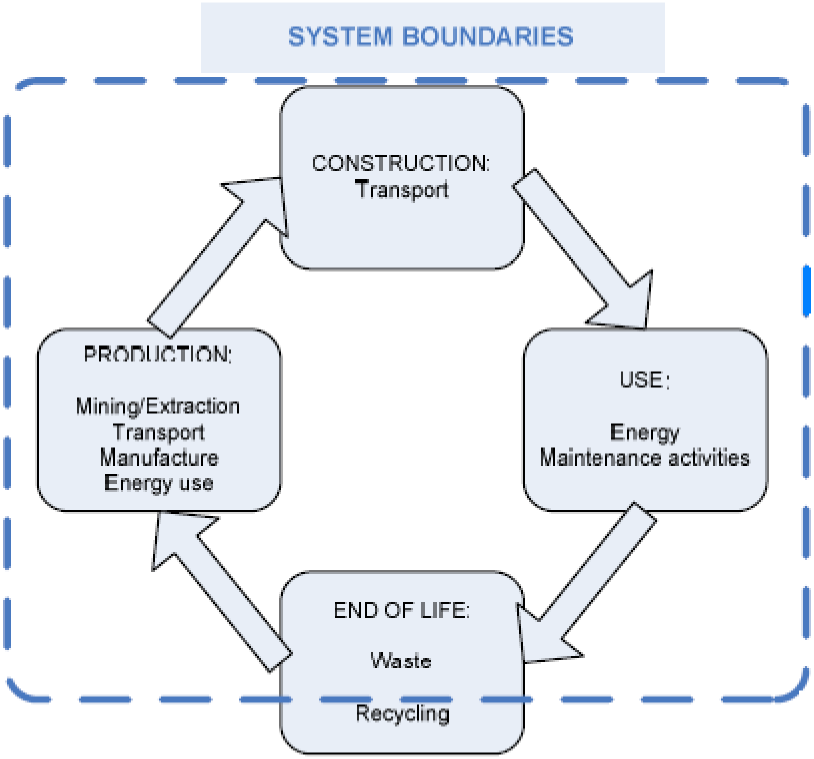

Figure 5: System boundaries for LCA calculations

Two frequently used methods in scientific LCA research are the CML 2001 baseline method and the Eco-indicator 99 method. The former uses multiple indicators at midpoint level (Guinée 2002), while the latter includes multiple endpoint indicators that can be combined in a single endpoint indicator (Goedkoop and Spriensma 2001). Endpoint indicators refer to the final damage and are easier to interpret, while midpoint indicators are halfway the route from emissions to damages, are more comprehensive and have a smaller level of uncertainty. At the beginning of the last decade, LCA experts agreed on the need of having a common framework in which both midpoint and endpoint indicators can be used. This consensus became the basis of the ReCiPe 2008 method, an impact assessment method which comprises harmonized category indicators at the midpoint and the endpoint level. The main contributors to this project are PRé Consultants, CML, RIVM and Radboud University.

The ReCiPe method is used in this study to have consistency between midpoint and endpoint indicators and to use the most recent and up-to-date method. In addition, CML 2001 method is used to facilitate comparison with Majcen's results, although a more recent and improved version is used here. Having results from two different methods also enables comparison between them, which is particularly interesting considering that ReCiPe is a relatively new method.

The next two sections contain some more information about CML 2001 and ReCiPe methods.

2.3.4 CML 2001

In 2001 a group of scientists under the lead of CML (Centre of Environmental Science of Leiden University) proposed a set of impact categories and characterisation methods for the impact assessment step. SimaPro 7.3 includes a “baseline” version and an extended version with “all impact categories” (SimaPro Database Manual 2008). The latter is recommended only in case of very detailed studies. In this thesis we use the CML 2001 baseline method, which will be further referred to as CML 2001 method.

The impact categories used in CML 2001 method are described below in Table 10.

Table 10: CML 2001 impact categories[4]

Impact categories	Characteristics	Unit
Depletion of abiotic resources	This impact category is concerned with protection of human welfare, human health and ecosystem health. This indicator is related to extraction of minerals and fossil fuels due to inputs in the system.	[kg Sb eq.]
Climate change	Climate change can result in adverse effects upon ecosystem health, human health and material welfare. Climate change is related to emissions of greenhouse gases to air.	[kg CO_2 eq.]
Stratospheric Ozone depletion	Because of stratospheric ozone depletion, a larger fraction of UV-B radiation reaches the earth surface. This can have harmful effects upon human health, animal health, terrestrial and aquatic ecosystems, biochemical cycles and on materials.	[kg CFC-11 eq.]
Human toxicity	This category concerns effects of toxic substances on the human environment. Health risks of exposure in the working environment are not included.	[kg 1,4-DB eq.]
Fresh-water aquatic eco-toxicity	This category indicator refers to the impact on fresh water ecosystems, as a result of emissions of toxic substances to air, water and soil.	[kg 1,4-DB eq.]
Marine eco-toxicity	Marine eco-toxicity refers to impacts of toxic substances on marine ecosystems, as a result of emissions of toxic substances to air, water and soil.	[kg 1,4-DB eq.]

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[4] (Guinée, 2002; Pre Consultants, 2008)

Terrestrial ecotoxicity	This category refers to impacts of toxic substances on terrestrial ecosystems, as a result of emissions of toxic substances to air, water and soil.	[kg 1,4-DB eq.]
Photo-oxidant formation	Photo-oxidant formation is the formation of reactive substances (mainly ozone) which are harmful to human health and ecosystems and which also may damage crops. This problem is also indicated with “summer smog”.	[kg C_2H_4 eq.]
Acidification	Acidifying substances cause a wide range of impacts on soil, groundwater, surface water, organisms, ecosystems and materials (buildings).	[kg SO_2 eq.]
Eutrophication	Eutrophication (also known as nutrification) includes all impacts due to excessive levels of macronutrients in the environment caused by emissions of nutrients to air, water and soil.	[kg PO_4^{3-} eq.]

The impact category marine aquatic toxicity is not taken into account because of significant problems associated with the calculation of the contribution to that category in the CML 2001 method (Doka, 2007; Sim et al, 2007) due to incoherent results. The normalization set used refers to the Netherlands in 1997.

2.3.5 ReCiPe 2008

The following two tables contain the lists of the midpoint (Table 11) and endpoint (

Table 12) impact categories considered in the ReCiPe method. It has been designed primarily as an attempt to align the CML 2002 midpoint and the Eco-indicator 99 methods. More information about all these categories can be found in ReCiPe 2008, Report 1: Characterisation (Goedkoop, et al. 2009). The normalization set used refers to Europe.

Table 11: ReCiPe midpoint categories (M. Goedkoop, R. Heijungs, et al. 2009)

Impact category name	Indicator name	Unit[5]
Climate change	Infra-red radiative forcing	W*yr/m^2
Ozone depletion	Stratospheric ozone concentration	ppt*yr □
Terrestrial acidification	Base saturation	yr*m^2
Freshwater eutrophication	Phosphorus concentration	yr*kg/m^3
Marine eutrophication	Nitrogen concentration	yr*kg/m^3

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5 The unit of the indicator here is the unit of the physical or chemical phenomenon modelled. In ReCiPe 2008, these results are expressed relative to a reference intervention in a concrete LCA study.

□ The unit ppt refers to units of equivalent chlorine.

Human toxicity	Hazard-weighted dose	-
Photochemical oxidant formation	Photochemical ozone concentration	kg
Particulate matter formation	PM10 intake	kg
Terrestrial ecotoxicity	Hazard-weighted concentration	m^2*yr
Freshwater ecotoxicity	Hazard-weighted concentration	m^2*yr
Marine ecotoxicity	Hazard-weighted concentration	m^2*yr
Ionising radiation	Ionising radiation	man×Sv
Agricultural land occupation	Occupation	m^2×yr
Urban land occupation	Occupation	m^2×yr
Natural land transformation	Transformation	m^2
Water depletion	Amount of water	m^3
Mineral resource depletion	Grade decrease	kg-1
Fossil resource depletion	Upper heating value	MJ

Table 12: ReCiPe endpoint categories (Goedkoop, et al. 2009)

Endpoint category	Indicator name	Unit of indicator
Damage to human health	DALY[6]	yr
Damage to ecosystem diversity	Loss of species during a year	yr
Damage to resource availability	Increased cost	$

Figure 6 shows the relations between the impact indicators at midpoint and endpoint levels. These relations are the results of choices made in the development of the method, based on assumptions. There are of course doubts on the correctness of assumptions and choices, which are called fundamental uncertainties. Different perspectives, inspired by Thompson’s concept of Cultural Theory (Thompson, et al. 1990; Hofstetter 1998), are included in the model: the hierarchic, individualist, and egalitarian perspectives. These refer to the principles guiding the choices in case of uncertainty (Table 13). In this study the hierarchic version is chosen since it’s the recommended one. It includes facts that are backed up by scientific and political bodies with sufficient recognition (Goedkoop, et al. 2009; Pré Consultants 2000).

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[6] Disability-adjusted loss of life years, i.e. the weighted sum of years of life lost and the years of life disabled

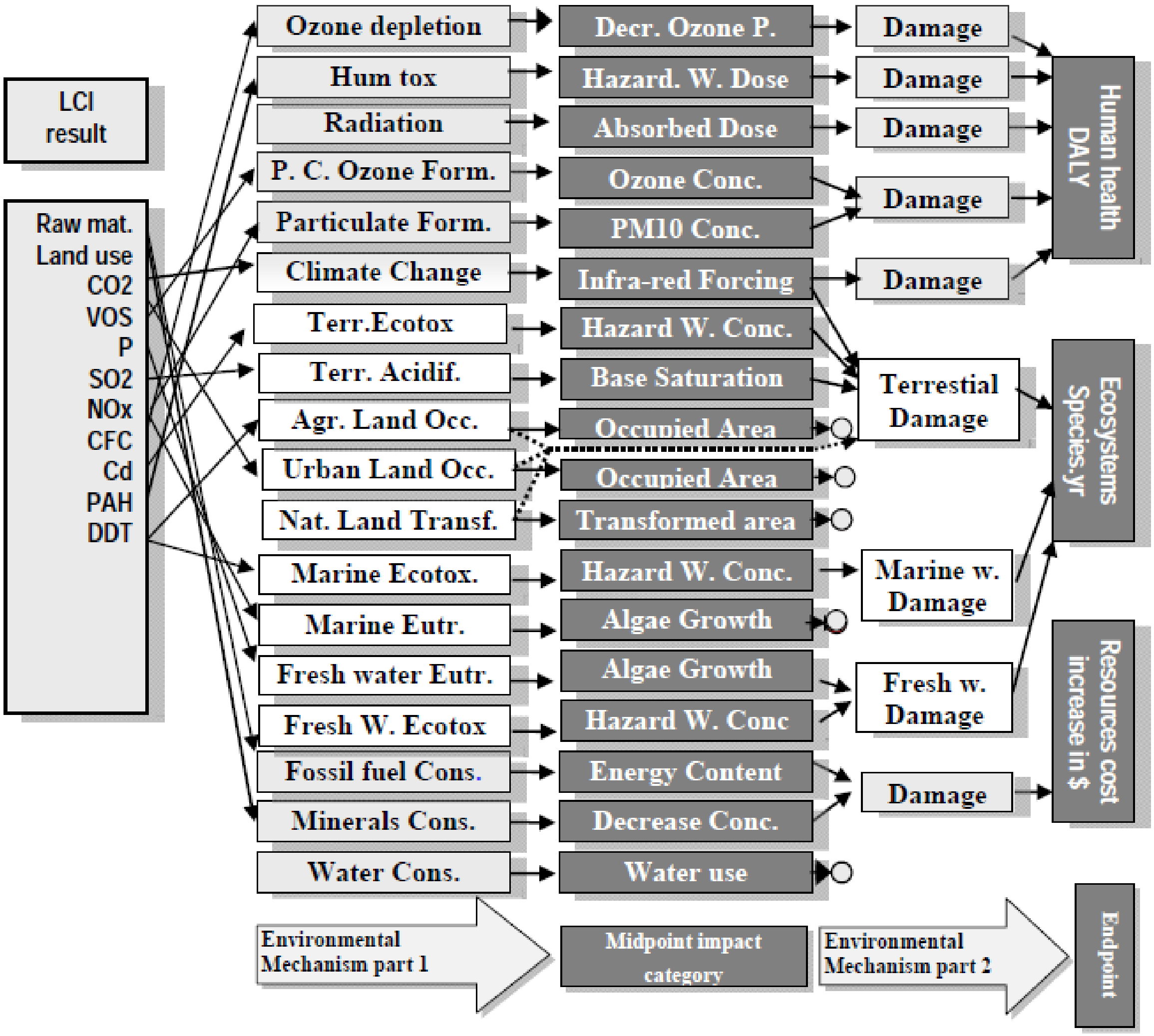

Figure 6: ReCiPe, relations between midpoint and endpoint indicators (Goedkoop, et al. 2009)

Table 13: Overview on hierarchic, individualist and egalitarian perspectives[7]

	Time perspective	**Manageability**	**Required level of evidence**
Hierarchic	Balance between short and long term	Proper policy can avoid many problems	Inclusion based on consensus
Individualist	Short time	Technology can avoid many problems	Only proven effects
Egalitarian	Very long term	Problems can lead to catastrophe	All possible effects

2.4 Energy calculations

For the energy performance, the energy saving for heating due to insulation is calculated, compared to a reference scenario with a thermal resistance value of

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[7] (M. Goedkoop 2011)

2.5 m²K/W. Roof insulation directly influences the energy consumption of the apartments below it. To obtain the energy saving enabled by improved insulation, first the energy consumption caused by heat losses through the roof is calculated per every top apartment. It is the difference in energy consumption for heating between an apartment on the top floor and an apartment below the top floor, as described in formula 1:

$$\mathrm{Energy}_{\mathrm{losses\ roof}} = \left(\mathrm{Energy}_{\mathrm{use\ top}} - \mathrm{Energy}_{\mathrm{use\ below}}\right) \tag{1}$$

Second, this is deducted from the same amount for the reference scenario, obtaining the energy saving per apartment, as described by formula 2:

$$\mathrm{Energy}_{\mathrm{saving}} = \mathrm{Energy}_{losses\ roof}^{Reference\ scenario} - \mathrm{Energy}_{losses\ roof}^{Assessed\ scenario} \tag{2}$$

Then, the total energy saving of the building is calculated as the sum on all the top apartments of the energy saving per apartment. The energy consumption of the apartments below the top ones is constant since it is assumed that they are not affected by the thermal insulation of the roof. Thus, the same results for energy saving would be obtained applying formula 2 to the total consumption for heating and formula 1 could be removed. Calculating the amount of energy losses through the roof is used to calculate the impact of the different phases (see section 3.2.4).

For the energy consumption calculations, the Dutch software Vabi EPA-W is used. It contains all the characteristic values for the Dutch climate, thus the energy use for the building is calculated under standard conditions. The actual climate and user behaviour are not considered in this study. The input data for the characteristics of the building are described in section 2.1

For the PV installation, it is assumed that 58 panels are installed on the roof. The number of panels to install takes into account the size of the panels, the distance between rows to avoid shading, and the geometry of the reference roof. The size of the panels is 1.64 by 0.994 meter, and the power is 215 Wp per panel. The total capacity is 12.47 KWp and a total surface of 95 m^2. The output of the PV panels, calculated with Vabi EPA-W, is an annual electricity production of 12,530 kWh. In the Netherlands, the average electricity demand per apartment was 3480 KWh in 2011 (Ministry of the Interior and Kingdom Relations 2012). The average size of a dwelling in the Netherlands is 103.9 m^2 (Itard and Meijer 2008). Majcen and Itard (2011) found that electricity consumption per m^2 is about constant per type of apartment. Therefore, with an average electricity consumption of 33.5 KWh per m^2 per year, the total electricity consumption of the building is assumed to be 52,753 KWh per year. An annual efficiency drop of 0.7% due to physical degradation of the modules is assumed. Different values are found in the literature and according to manufacturers, ranging from 0.3% to 1.1% (Chianese, et al. 2003; Verhelst, et al. 2010; Technology Centre for Alternative s.d.; Solar Panel Direct, 2011).

2.5 Environmental and financial performances

In order to find whether the most sustainable solutions are also economically convenient, environmental and economic payback times as well as savings in 30 years and net present value are calculated. In this part of the study a life cycle approach is used too. These calculations are done only for the insulation layer and for PV panels, since they are the only materials enabling quantifiable environmental and economic savings during their life span.

For the environmental comparison of the materials (section 3.1), 1 m^2 is used as functional unit, while for further sections the comparisons are made considering the whole roof surface, i.e. 300 m^2.

2.5.1 Environmental performance

To quantify environmental saving, energy saving are quantified as avoided energy consumption for heating for the insulation layer and as avoided electricity consumption for PV panels (see section 2.4). These amounts aere transformed in environmental impact scores using the ReCiPe endpoint method and in primary energy demand using the Cumulative Energy Demand (CED) method. Primary energy is the total internal energy or energy content needed to produce a final energy service (secondary energy), including all fuel inputs and losses along the energy chain (Gustavsson and Joelsson 2010).

CED method enables to calculate the total primary energy use throughout the whole life cycle. It is based on the method published by Ecoinvent and implemented by PRé Consultants.

Table 14 (Hischier, et al. 2010) shows the categories for the Ecoinvent database.

Table 14: Impact assessment method cumulative energy demand (CED) implemented in Ecoinvent (Hischier, et al. 2010)

Category	Subcategory	Includes
Non-renewable resources	Fossil	Hard coal, lignite, crude oil, natural gas, coal mining off-gas, peat
	Nuclear	Uranium
	Biomass	Wood and biomass
Renewable resources	Biomass	Wood, food products, biomass from agriculture, e.g. straw
	Wind	Wind energy
	Solar	Solar energy (used for heat and electricity)
	Geothermal	Geothermal energy
	Water	Run-of-river hydro power, reservoir hydro power

There is no normalisation in this method. To get the total energy demand, each impact category is given the weighting factor 1 (SimaPro Database Manual 2008).

In general, a payback time is defined as the period of time over which the savings of a project equal the amount expended since project inception. The environmental payback time (EPBT) of a material in one category can be calculated as its impact score in that category throughout its life cycle, divided by the annual environmental saving it enables, as shown in formula 3:

$$EPBT = \frac{Life\ cycle\ impact\ score}{Annual\ saving} \qquad (3)$$

Similarly, the energy payback time can be calculated as the total primary energy use related to that material life cycle, divided by the annual primary energy saving it enables.

For the insulation layer, the aim of this analysis is to compare the environmental and financial benefit of the different materials and thicknesses considered. Nowadays, when making a renovation, insulation of the roof has an R value of at least 2.5. Therefore, calculations for energy use and environmental impact scores are all related to a reference scenario with a thermal resistance of 2.5 m²K/W. This means that environmental impact scores for the materials are calculated as “extra material” impact scores, i.e. the difference between the impact score of the current scenario and the one of the reference scenario. The primary energy use related to the material is calculated similarly. Energy savings are calculated as described in section 2.4. The energy and environmental payback times are calculated by formula 4:

$$\mathrm{EPBT_i} = \frac{\mathrm{EIS\ current\ scenario_i} - \mathrm{EIS\ reference\ scenario_i}}{\mathrm{EIS\ heating\ reference\ scenario_i} - \mathrm{EIS\ heating\ current\ scenario_i}} \quad (4)$$

where the index *i* indicates the impact category and EIS stands for environmental impact score.

For PV panels, in the reference scenario all electricity demand is supplied by the grid, while in the current scenario it is assumed that all the electricity produced is consumed in the building, avoiding production and transport.

Savings in 30 years are calculated for each endpoint category of the ReCiPe endpoint method and for primary energy. This is done for every impact category *i* using the following formula 5.

$$\%\ \mathrm{saving_i} = \frac{\mathrm{cumulative\ impact\ reference\ scenario_i} - \mathrm{cumulative\ impact\ current\ scenario_i}}{\mathrm{cumulative\ impact\ reference\ scenario_i}} \times 100\% \quad (5)$$

The cumulative impact of a scenario includes:

- the impact score of the material throughout its life cycle
- the impact score caused by extra energy consumption for heating caused by losses through the roof, compared to the energy consumption for heating of the apartment below for the insulation. The impact score caused by production and transport of electricity supplied from the grid for the PV panels.
- the impact score caused by maintenance activities in 30 years, which for the insulation itself is null, since this layer doesn’t require any such activities, unless a problem (e.g. a leakage) occurs.

2.5.2 Financial performance

In finance, the principle of time value of money, that is “a euro today is worth more than a euro tomorrow”, is fundamental for investment analysis. This is because money can be invested and generates interest. To compare present and future cash flows, the latter must be discounted using the opportunity cost of capital, i.e. the interest rate of an alternative investment (Anthony, et al. 2005). In this study, a free risk alternative investment is considered, thus Dutch bonds interest rate is chosen. A more accurate analysis would consider the weighted average cost of capital (WACC) as rate to discount the future cash flows. WACC is the average of the costs of a company’s sources of financing, each weighted by its respective use in the given situation. By taking a weighted average, it shows how much interest the company has to pay for every euro it finances. This is not the case since this study is not firm-specific and it aims to compare environmental and financial performances of insulation and PV panels investments.

The discounted present value (*DPV*) of a future cash flow (*FV*) occurring after *n* years is:

$$DPV = \frac{FV}{(1+r)^n} \tag{6}$$

where *r* is the interest rate.

To evaluate or to compare one or more investments, the Net Present Value (NPV) is often used. NPV is the sum of all future cash flows, discounted to present value, as shown in formula 7:

$$NPV = \sum_{i=0}^{n} \frac{FV_i}{(1+r)^i} \tag{7}$$

Outgoing cash flows have a negative sign. If the NPV is greater than zero, the investment results in higher total net savings than the alternative investment.

Another method to support investment analysis is the payback time (or payback period), i.e. the length of time required to recover the cost of an investment. This method ignores the benefits occurring after the payback time, thus it might be used together with other methods, e.g. NPV. Payback times can be simple or dynamic. Simple payback times don't consider time value of money. It is calculated as the cost of the project divided by the annual cash inflows. Dynamic payback times use discounted cash flows, thus they are more accurate. Dynamic payback times are generally longer than simple payback times.

In this study, the NPV, dynamic payback time and saving in 30 years are considered to assess the economic performance of the investments and to compare it with the environmental performance.

The saving is calculated as:

$$Saving\ (\%)\ in\ 30\ years = \frac{\sum outgoing\ DCF_{reference} - \sum outgoing\ DCF_{current}}{\sum outgoing\ DCF_{reference}} \times 100\% \tag{8}$$

where DCF stands for discounted cash flows.

The assumptions for the economic calculations made in this study are now reported.

A period of analysis of 30 years is chosen, according with ISO 15686-5 (ISO, 2008), which states that the preferred period of life cycle costing (LCC) analysis is ‘the period of foreseeable need or occupation of the constructed asset’. In a literature review, Vrijders and Delem collected the most relevant existing sources and conclusions from existing research on costs and environmental aspects of energetic renovations. They also found that making reliable costs forecasts beyond 40 years is impossible because of high uncertainty and that the cash flows occurring in the latest years of analysis tend to be discounted to such a degree that they would become irrelevant (Vrijders e Delem 2009). Vrijders and Delem also give guidelines about making assumptions about many parameters.

For the interest rate to discount the cash flows, the 30 years Dutch government bonds rate is used, according with the length of the period of analysis. This rate fluctuated between annual 2.5% and 5% from 2008 (Bloomberg 2012). A value of 2.5% is chosen, which was approximately the value of the rate from December 2011 to February 2012. A sensitivity analysis is made to assess how the results change with higher interest rates.

Another important parameter that strongly influences the analysis is energy price (gas and electricity). The last current prices available in the Eurostat database (Eurostat 2011) are from the first semester of 2011. The prices, including taxes, were 0.0199 €/MJ for gas and 0.1743 €/KWh for electricity. Prices evolution is hard to predict, and in the last 5 years, a more rapid increase than in the previous decades has occurred. Devogelaer and Gusbin (2006) assessed two scenarios of development of gas and electricity prices: an average scenario with an annual increase of 3.47% and a high scenario with an annual increase of 5.87% (Devogelaer and Gusbin 2006). These two scenarios are considered in this study.

For the financial performance of the insulation layer, prices for EPS, PIR, PUR, and stone wool are taken from the Dutch magazine Bouwmarkt (2011), and prices for XPS are selected after an internet research (Isolparma s.d.). The prices used in this study, including VAT and installation cost, are given in Table 15. These refer to the whole roof surface (i.e. 300 m^2).

Table 15: Prices of insulation materials, including VAT and installation costs (Bouwmarkt 2011; Isolparma)

Material	R [m^2K/W]	Price per 300 m^2	Extra price comparing to R 2.5
EPS	2.5	€ 4,766	-
	3	€ 5,409	€ 643
	5	€ 7,676	€ 2,910
XPS	2.5	€ 5,869	-
	3	€ 7,545	€ 1,676
	5	€ 12,579	€ 6,709
PIR	2.5	€ 6,426	-
	3	€ 7,140	€ 714
	5	€ 10,942	€ 4,516
PUR	2.5	€ 6,230	-
	3	€ 7,051	€ 821
	5	€ 10,735	€ 4,506
Stone wool	2.5	€ 5,908	-
	3	€ 7,211	€ 1,303
	5	€ 11,817	€ 5,908

For the financial analysis of PV panels, commercial prices from one of the largest Dutch PV panels vendor are taken. The price of 58 PV panels is € 21,908 plus a mounting cost of € 3,500. The concrete tiles needed as ballast to fix the frames cost € 1,350. Total price is € 26,758. The prices are for PV panels with mechanical and electrical data similar to those used for the environmental impact assessment. Currently, PV panels prices are decreasing quickly, but this development is not taken into account in this study. In some European countries, e.g. Italy, there are subsidies to stimulate PV panels installation. This is not the case in the Netherlands, therefore subsidies are not taken into account. In the Netherlands, for feeding back electricity to the grid large commercial producers get only the actual electricity prices, excluding taxes. Private households are allowed to deduct the electricity fed back to the grid from the electricity that they get from the grid, avoiding to pay the price including taxes. The assumption made here is the latter.

Other assumptions needed in the calculations are made in analogy with those for the environmental performance assessment.

3 Results and discussion

First, a partial LCA is done considering only the impact of the materials, without energy consumption for heating and maintenance (section 3.1). Then, an assessment of all feasible scenarios is done including maintenance activities and energy consumption (section 3.2), to find which are the most sustainable ones.

3.1 Environmental comparison of the materials

The life cycles of the materials include the quantity (in kg per m²) of materials and all the activities related to it (from raw material extraction to waste treatment, including transport and fixing materials). Considering the weight per m² allows a comparison between materials requiring different thicknesses for the same performance or having different densities. In this section results are presented separately for insulation, roofing and covering layers. Results for green roof and white bitumen are presented in section 3.2.2. Results for reflective coating are not shown because the waste scenario depends on the roofing layer it is applied on. Results for PV panels are not reported in this section but are reported in section 3.2.3, where the reduction in energy consumption is included.

Normalized data are presented to know not only which material has the highest score in each category, but also to have an idea of the contribution to the total environmental burden in a certain environmental category in a year (Dutilh, et al. 2001). For the comparison with Majcen's results, non-normalized data are used. For the ReCiPe midpoint method, water depletion is not taken into account, since all material considered have no impact score in that category.

3.1.1 Insulation layer

Data for the insulation alternatives are shown only for the R = 2.5 m²K/W option, since for the other two options the results would have the same proportion. This is because for every material, the thickness of the insulation layer grows linearly with the R value and, with a fixed density, the weight per m² grows with the R value as well. The results also include the fixing materials for the insulation (see section 2.2.6).

Figures 7, 8 and 9 show the normalized impact scores of each insulation material calculated with the CML 2001, ReCiPe midpoint and ReCiPe endpoint methods, respectively.

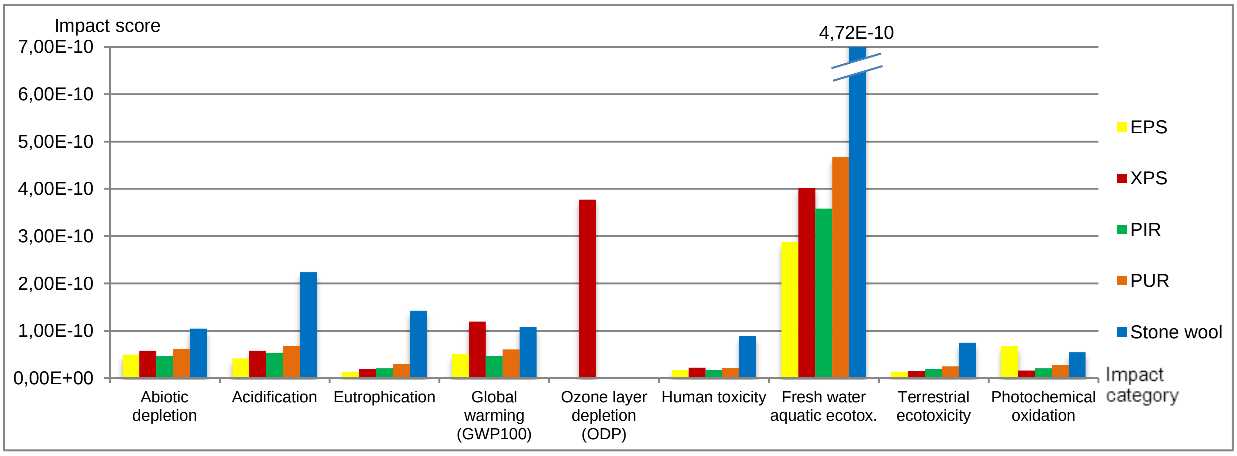

Figure 7: Normalized impact scores of insulation layer alternatives with R = 2.5, calculated with the CML 2001 method

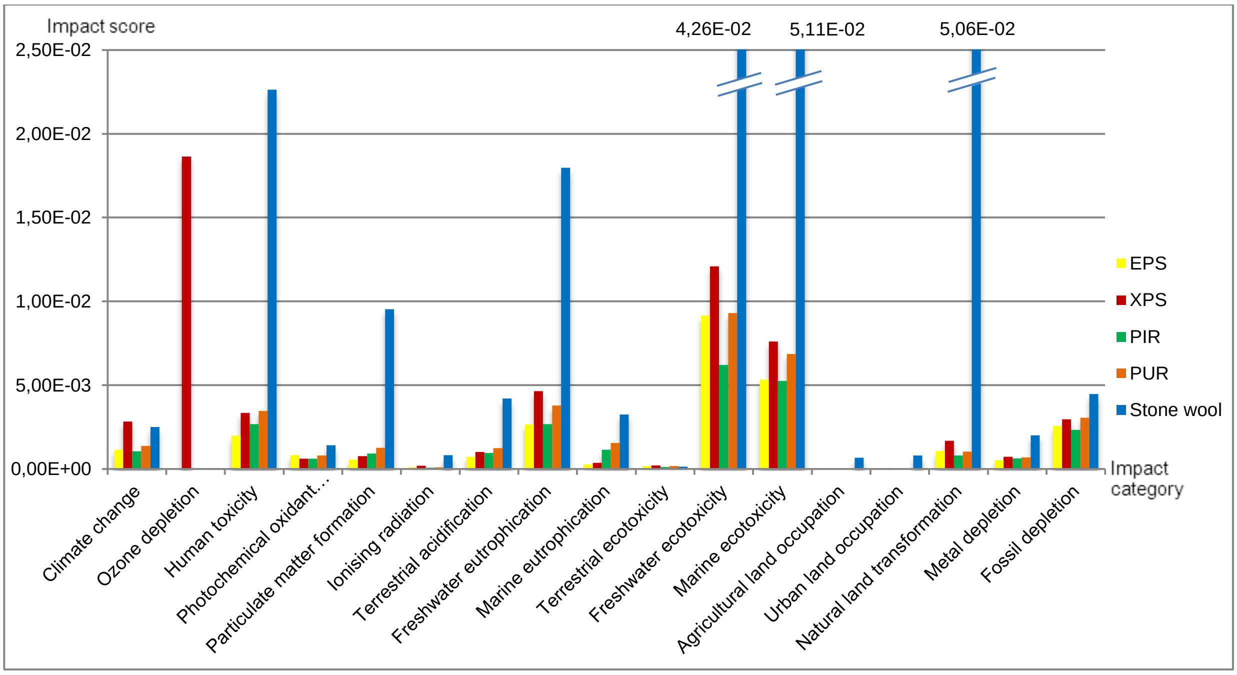

Figure 8: Normalized impact scores of insulation layer alternatives with R = 2.5, calculated with the ReCiPe midpoint method

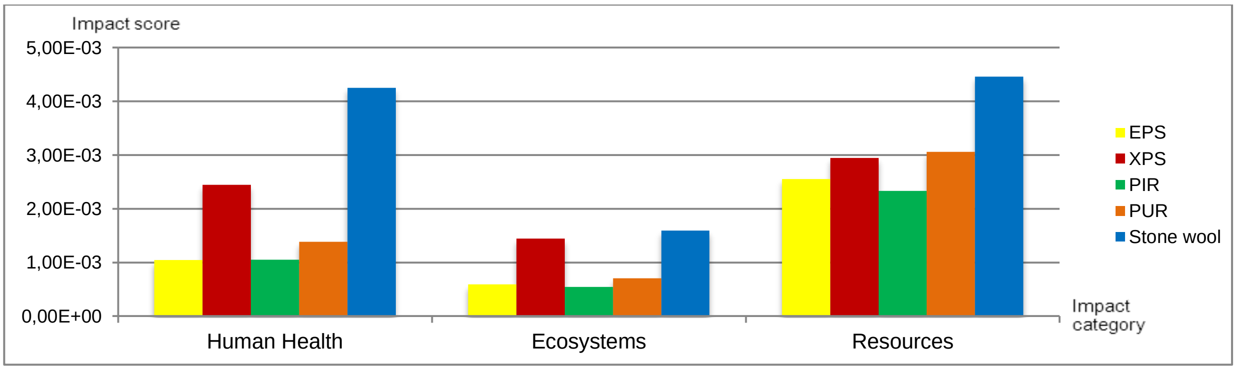

Figure 9: Normalized impact scores of insulation layer alternatives with R = 2.5, calculated with the ReCiPe endpoint method

Figure 7 shows that stone wool has the highest impact score in almost every impact category, due to its higher weight. Stone wool has a 4 to 8 times higher density and also requires a thicker layer to provide the desired R values, hence stone wool requires about ten times the weight of the other materials to provide the same thermal resistance (Table 3).

The other materials have similar impact scores in every impact category except for ozone layer depletion (ODP), where XPS has an impact score about one thousand times bigger, due to the emissions of HCFC-124 and CFC-113 during the production process of HFC-134a (Tetrafluoroethane), used as blowing agent. For fresh water aquatic ecotoxicity, the impact score related to waste treatment is higher than the impact score related to the production process of the materials. The waste treatment, both dominated by incineration (EPS, XPS, PIR and PUR) and by landfill (stone wool), causes about 75% of the impact score of all materials in this category.

The calculations with ReCiPe midpoint as presented in Figure 8 show similar results. The proportion between the material are about the same as those calculated with the CML 2001 method. For freshwater ecotoxicity and marine ecotoxicity waste treatment causes again about 75% of the impact score of all material.

The calculations with ReCiPe endpoint as presented in Figure 9 also show similar results, but the impact of waste treatments causes only 1 to 6% in the category resources and causes between 20 and 40% of the impact scores in categories human health and ecosystems.

Figures 8 - 10, show that the impact scores of PUR are about 20% higher than those of PIR. These differences are caused by the differences in weight per square meter, as the impact scores per kg of material are about the same.

The results for insulation in this study are not compared with Majcen’s results, since in her study, ten times smaller weights per square meter were used for the insulation layers, probably due to different assumptions.

3.1.2 Roofing layer

For APP- and SBS-modified bitumen, impact scores might be underestimated, since calculations are made considering only the known components. Also, both materials are commonly used with coatings to protect them from ultraviolet light (Merritt and Ricketts 1994), but these coatings are not taken into account here.

Figure 10 shows the normalized impact scores of the roofing materials calculated with the CML 2001 method.

APP- and SBS-modified bitumen (both heated or loose) have the highest impact scores for most impact categories. This can be explained by the higher weight per square meter they require and, to a lesser degree, by the bitumen production process. PVC mechanically fixed has the highest impact scores for terrestrial ecotoxicity due to the production process of steel, which is required about ten times more than for mechanical fixing of EPDM. The heating process used to fix APP- and SBS-modified bitumen has a negligible effect on their final impact score. For EPDM glued, the latex adhesive causes the highest impact scores for most categories. The differences in impact scores between the fixing options are the largest for PVC, mainly because of the large amount of steel required. All materials have their highest impact score in category fresh water aquatic ecotoxicity. This is mainly due to waste treatment, which causes more than 90% of the impact scores of APP- and SBS-modified bitumen and about 50% of the impact scores of EPDM and PVC.

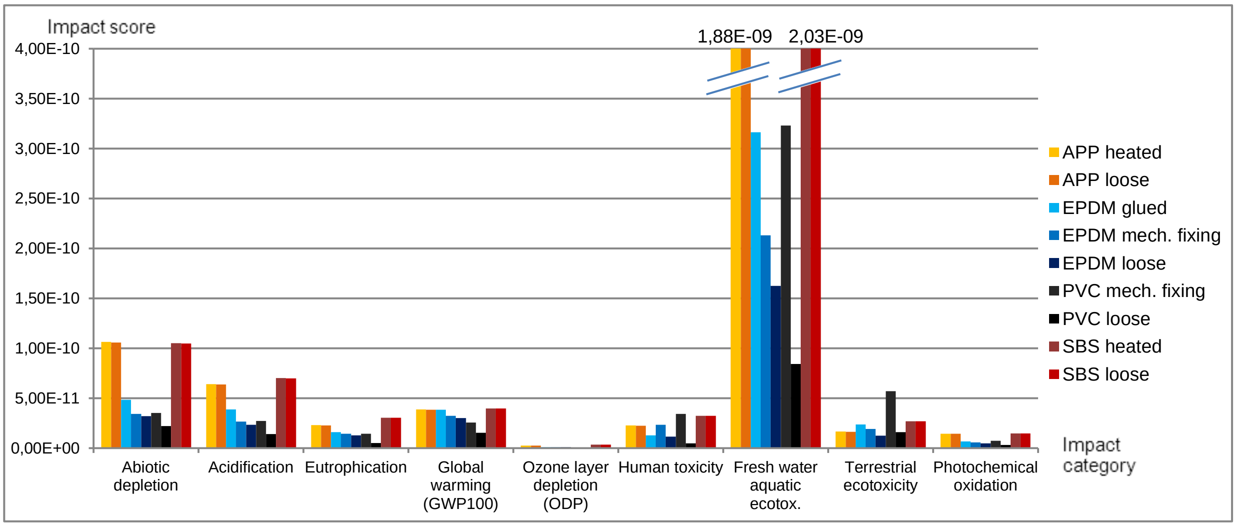

Figure 10: Normalized impact scores of roofing layer alternatives, calculated with the CML 2001 method

Figure 11 gives the normalized impact scores, calculated with the ReCiPe midpoint method. PVC loose has the lowest impact score for almost every category. The impact scores of EPDM are mainly caused by the electricity consumption and the production of crude oil. APP- and SBS-modified bitumen have the highest impact scores for most categories. For freshwater ecotoxicity and marine ecotoxicity, the waste treatment (90% incineration) causes 85% of the impact scores. 85% of EPDM is incinerated as well, but its lower weight causes a lower contribution to the total impact scores. For natural land transformation, the very high impact score is mainly caused by the use of wells for exploration and production of crude oil. About the different fixing options the same comments of previous paragraph can be made.

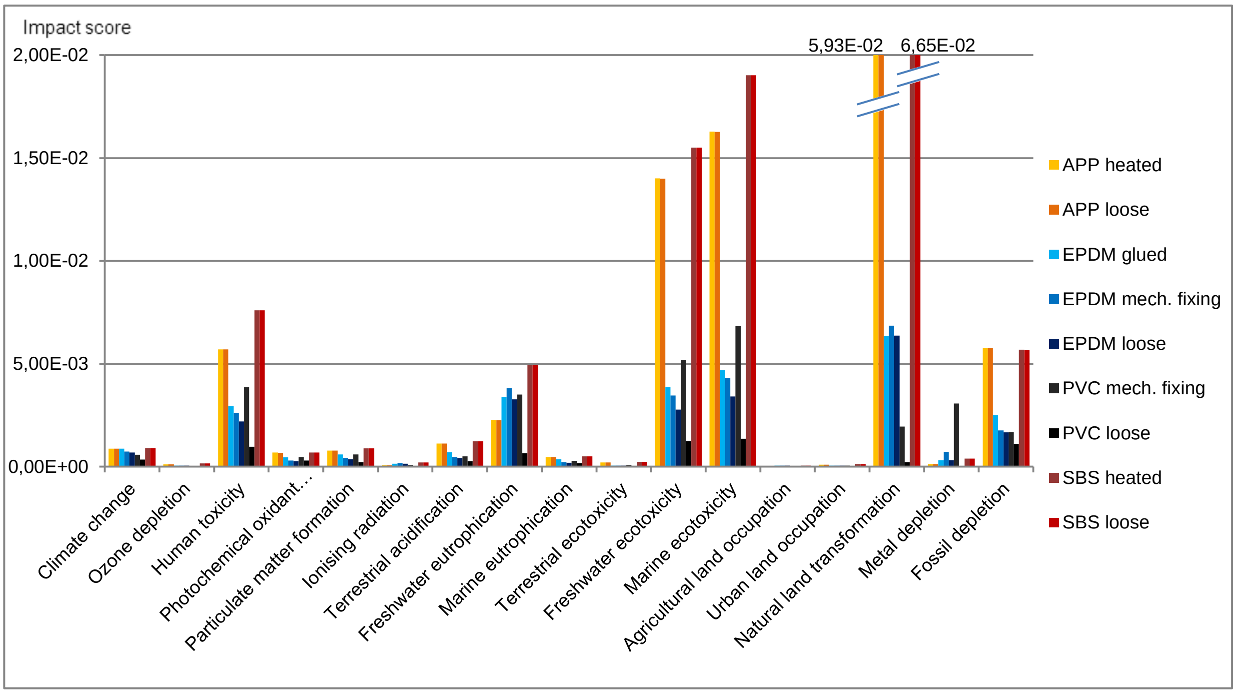

Figure 11: Normalized impact scores of roofing layer alternatives, calculated with the ReCiPe midpoint method

Figure 12 shows the normalized impact scores of the roofing layer alternatives at endpoint level calculated with ReCiPe. PVC loose has the lowest impact score in every impact category, while APP- and SBS-modified bitumen have the highest impact scores, especially for resource depletion. This is caused by the highest weight per m² of bitumen.

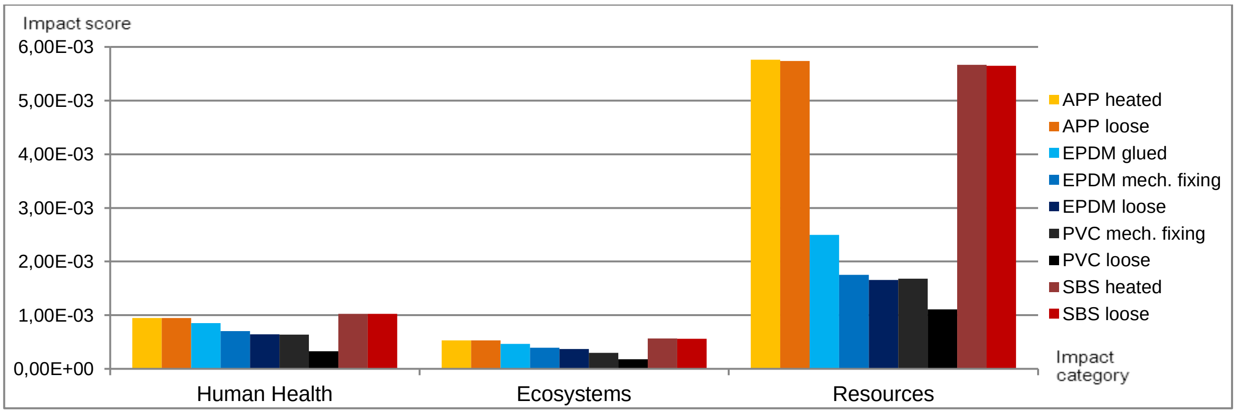

Figure 12: Normalized impact scores of roofing layer alternatives, calculated with the ReCiPe endpoint method

In figures 13 and 14, the normalized impact scores of PVC loose and EPDM loose respectively, calculated with the CML 2001 method, are given for this study and the study of Majcen (2009). The impact scores are only given for the roofing layers, The characteristics used here for APP, SBS and white bitumen are too different form the bitumen layer ones considered in her study to make a fair comparison. Results don’t include waste scenarios and transport because of different assumption made in the two studies. For PVC and EPDM, the materials considered are the same, but the weights are larger in Majcen’s study (1.8 vs. 1.5 kg per m² for EPDM loose and 1.84 vs. 1.7 kg per m² for PVC loose). Therefore, the impact scores calculated by Majcen are higher than the impact scores calculated in this study, except for eutrophication, human toxicity and fresh water aquatic ecotoxicity. These differences of impact score per kg are probably caused by the differences between the Ecoinvent 2.2 database and the 2.0 version that Majcen used.

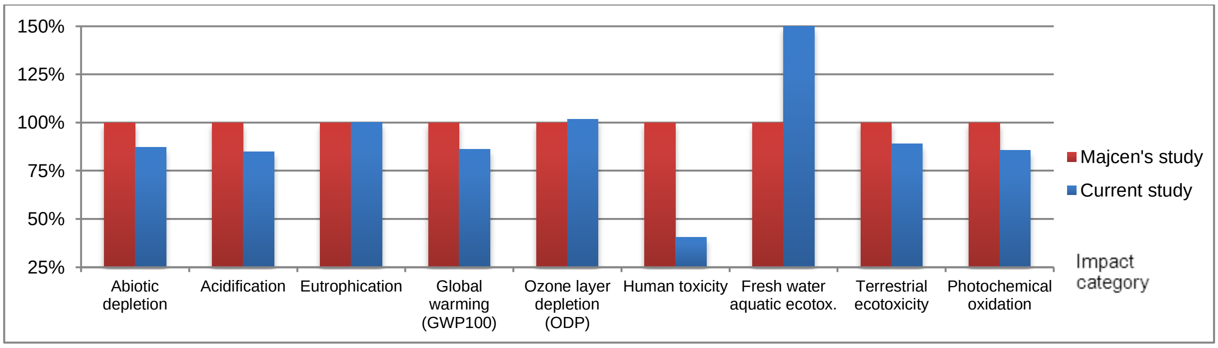

Figure 13: Impact scores of the PVC (loose) roofing layer, calculated by Majcen (2009) and in this study, both assessed with the CML 2001 method

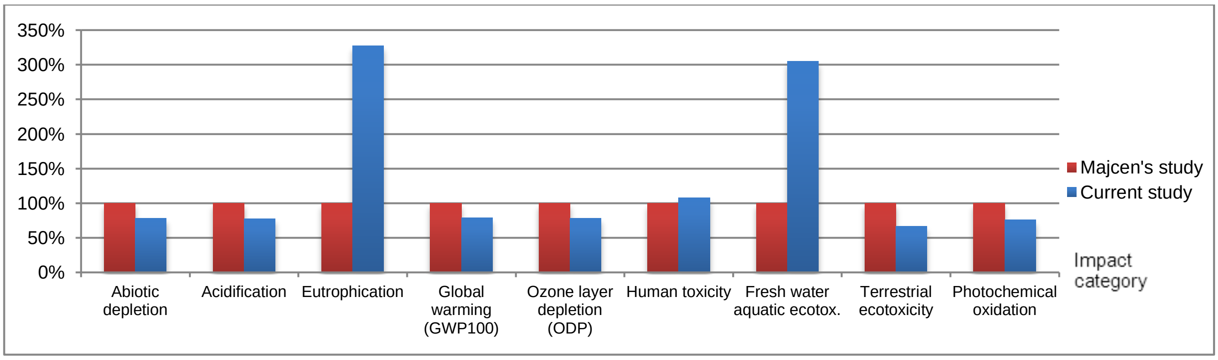

Figure 14: Impact scores of the EPDM (loose) roofing layer, calculated by Majcen (2009) and in this study, both assessed with the CML 2001 method

3.1.3 Covering layer

In figures 15, 16 and 17, the normalized impact scores for the covering layer materials are shown, using the CML 2001, the ReCiPe midpoint and the ReCiPe endpoint methods, respectively.

The impact scores of gravel are lower than those of concrete tiles in almost every category, with every method.

Figure 15 shows that both gravel and concrete tiles have the highest impact score in category fresh water aquatic ecotoxicity. Waste treatment causes more than 90% of gravel impact score in most categories, even though 90% of it is recycled and only 10% is buried in landfill. For concrete tiles, waste scenario has a relevant impact only in fresh water aquatic ecotoxicity (58%), eutrophication (24%) and marine aquatic ecotoxicity (21%) categories; most of concrete tiles impact scores are caused by the use of clinkers in concrete production process.

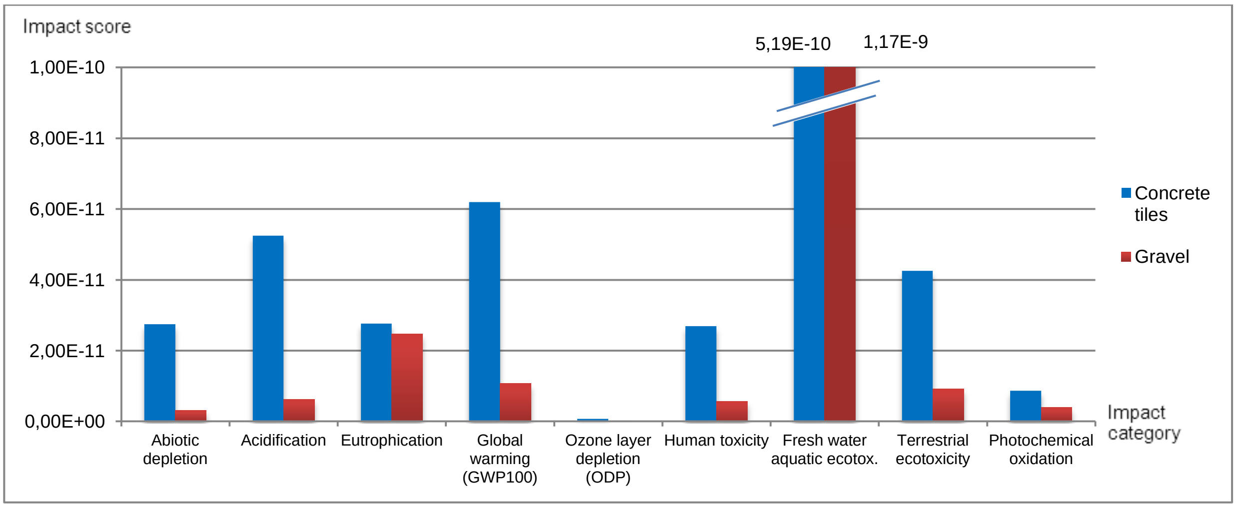

Figure 15: Normalized impact scores of covering layer alternatives, calculated with the CML 2001 method

Similar comments can be made for Figure 16. The higher impact scores of gravel in categories freshwater ecotoxicity, marine ecotoxicity and human toxicity are caused almost totally (about 99%) by its waste treatment. For concrete tiles, there are no single process or material explaining all the impact scores, but they were caused more or less equally by the processes along its life cycle.

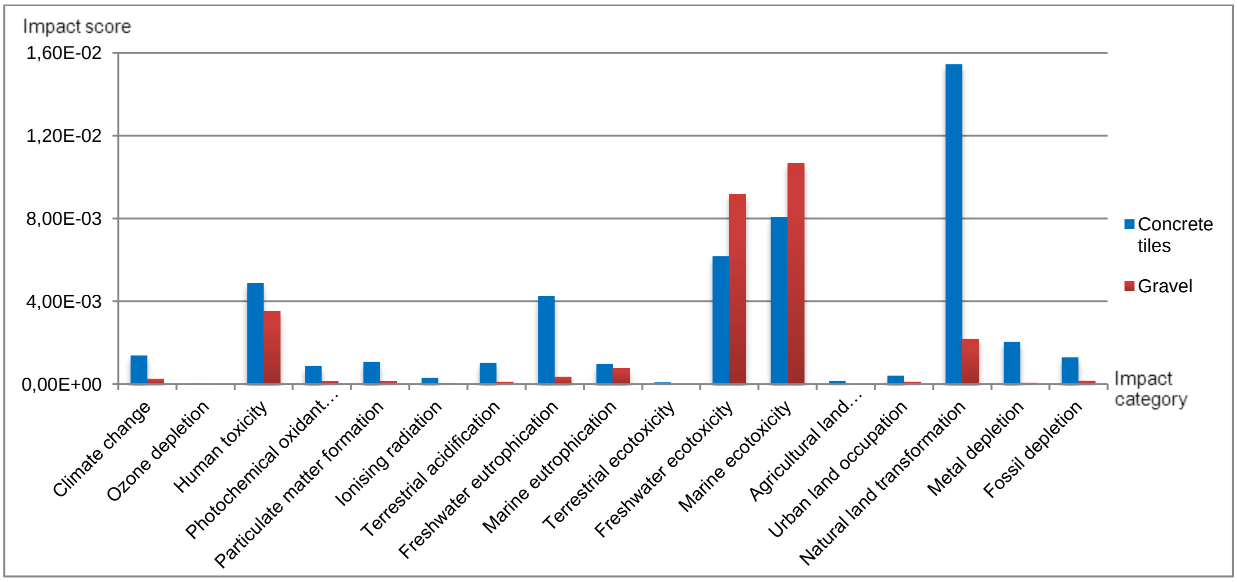

Figure 16: Normalized impact scores of covering layer alternatives , calculated with the ReCiPe midpoint method

For the results calculated with the ReCiPe endpoint method (Figure 17), the impact scores of concrete tiles are 5 to 8 times higher than the impact scores of gravel.

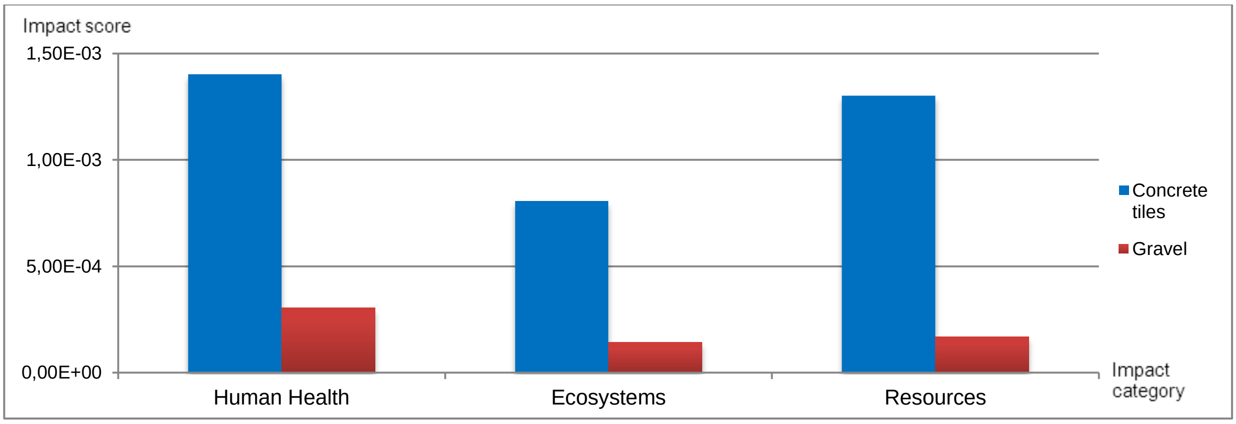

Figure 17: Normalized impact scores of covering layer alternatives, calculated with the ReCiPe endpoint method

The results for covering layer in this study are not compared with Majcen's results, due to the following inconsistencies in the input data:

- In Majcen's study, a different density and thickness were used for concrete tiles.
- In Majcen's study, crushed gravel was considered instead of round gravel (not crushed) used here, resulting in higher impact values because of the crushing process.

3.2 Scenarios

Considering all the feasible options resulting from the combination of different materials and thermal resistance values for each layer would result in more than five hundred different scenarios. An overview of these possibilities is given in Figure 18 (scenarios with XPS) and in Figure 19 (scenarios with EPS, PIR, PUR or stone wool). There are fewer feasible combinations with XPS than for the other insulation materials, because it is used only with a loose roofing membrane (see section 2.2.6). When the roofing membrane is fixed without ballast, reflective coating can be applied. It is not applied on white bitumen, which has a reflective surface itself. The base structure of the roof is assumed to be the same in every scenario. Its environmental impact is not taken into account. PV panels are considered to be an option for all scenarios.

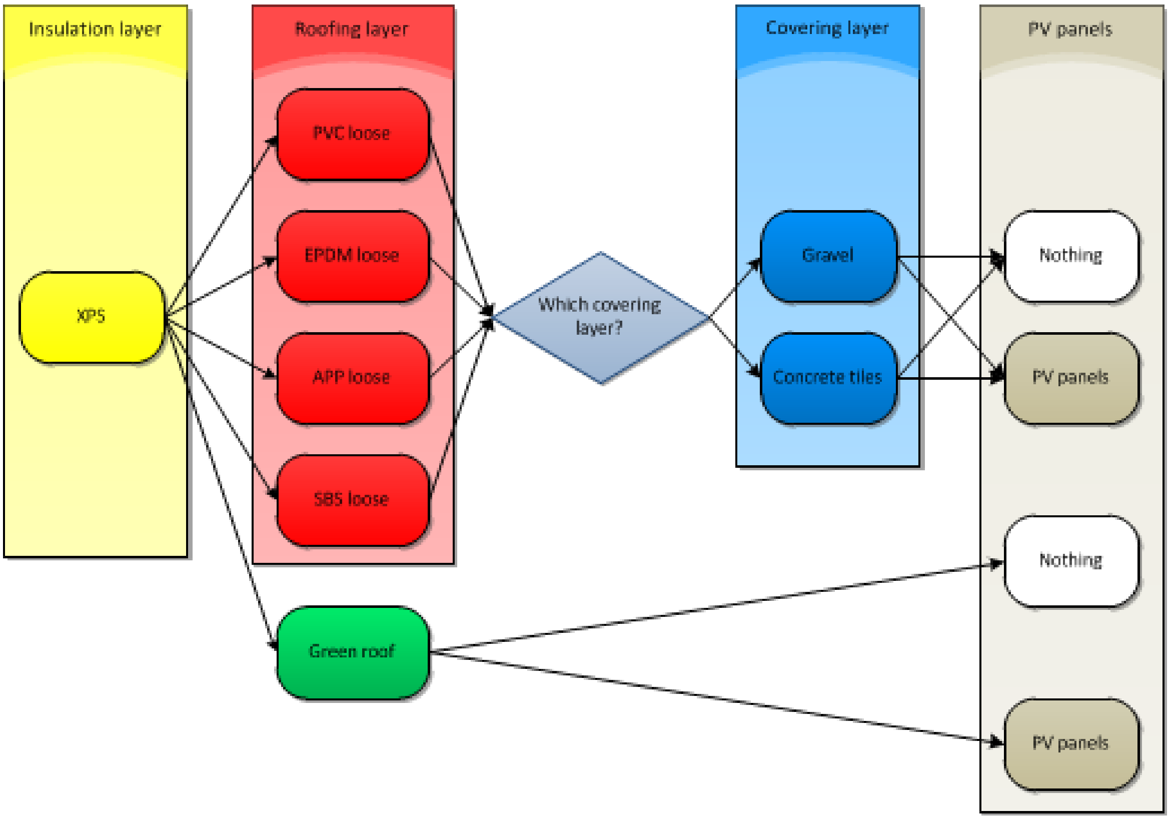

Figure 18: Scenarios with XPS

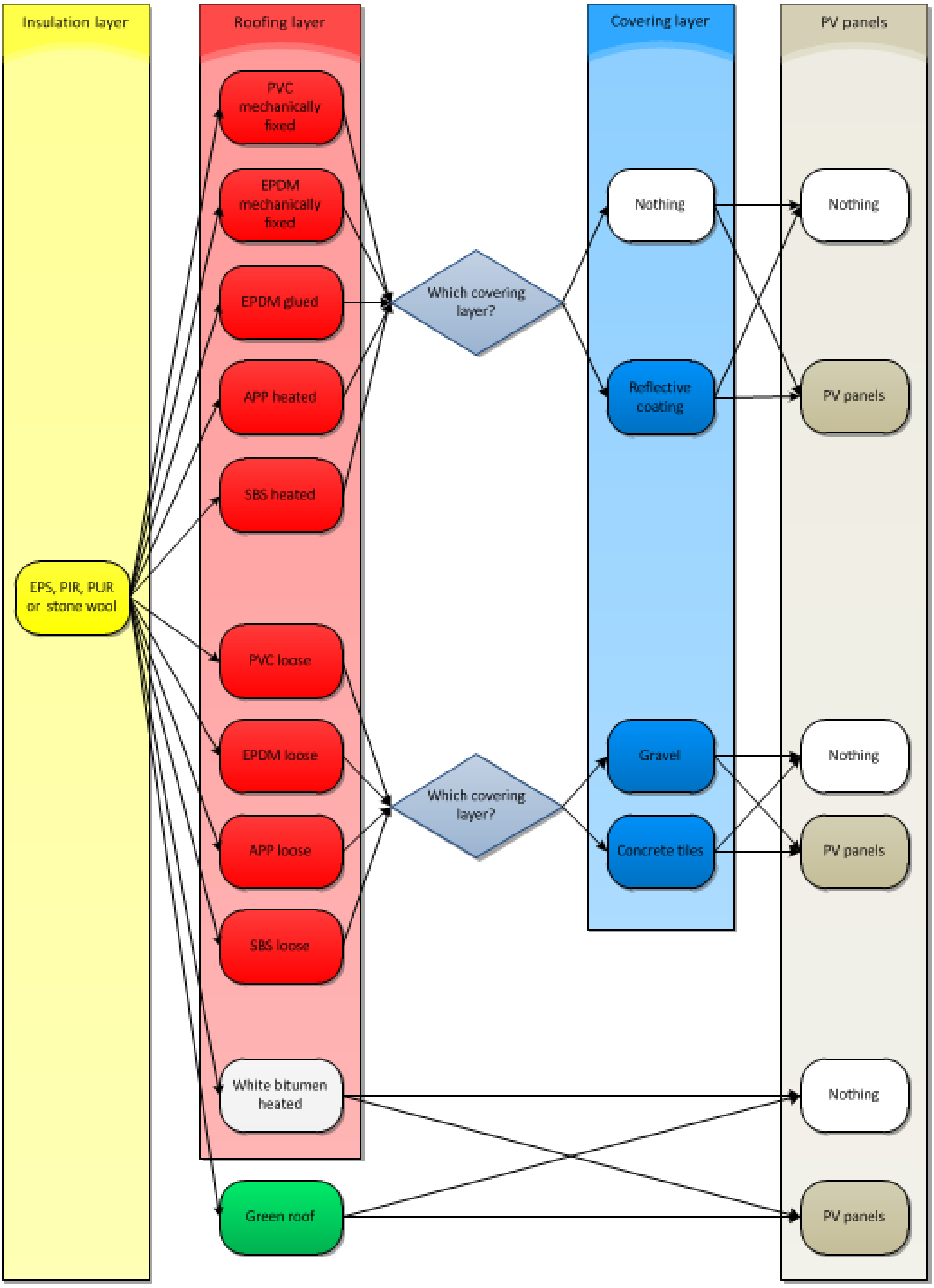

Figure 19: Scenarios with EPS, PIR, PUR or stone wool

Because of the high number of feasible scenarios, in this section results are presented separately for:

- The insulation layer: for each material and thermal resistance value, the environmental performance (EPBT and saving after 30 years) and the financial performance (economic payback time, NPV and saving after 30 years) are given (section 3.2.1).
- All the feasible combination of roofing membrane and covering layer materials (section 3.2.2)
- PV panels: the environmental performance (EPBT, saving after 30 years) and the financial performance (economic payback time, NPV and savings after 30 years) are given (section 3.2.3).

Then four complete scenarios including the insulation layer are analysed (section 3.2.4). These are formed using the materials with the lowest environmental impact scores.

For the environmental performances of insulation layer and PV panels, only the ReCiPe endpoint and Cumulative Energy Demand methods are used. For roofing and covering layer, only the ReCiPe endpoint method results are shown here. Results calculated with the CML 2001 and ReCiPe endpoint methods are shown in Appendix A.

3.2.1 Environmental and financial performance of the insulation materials

To assess the environmental and financial performances of the insulation layer, the energy consumption is calculated with the Vabi EPA-W software, using the data of the reference building. Calculations aim to find only the part of energy consumption caused by losses through the roof, as described in section 2.4. Table 16 shows the results obtained for all the apartments of the top floor and of the floor below it, losses through the roof and energy saving comparing to the reference scenario.

Table 16: Energy consumption for heating of the reference building

	R 2.5 m^2K/W	R 3 m^2K/W	R 5 m^2K/W	Unit
Total energy consumption of the top 7 apartments	176,534.0	173,350.7	165,798.0	[MJ/yr]
Total energy consumption of the 7 apartments below	154,125.7			[MJ/yr]
Losses through the roof	22,409.3	19,226.0	11,673.3	[MJ/yr]
Energy saving comparing to R 2.5 m^2K/W	-	3,183.3	10,736.0	[MJ/yr]

Figures 20 to 23 show the cumulative impact scores of the insulation layer with different materials and thermal resistance values. The methods used are ReCiPe endpoint (human health in Figure 20, ecosystems in Figure 21, resources in Figure 22) and Cumulative energy demand (Figure 23). The options with a thermal resistance of 2.5 m^2K/W have the highest impact score for all materials in every category, because of the significantly higher contributions of energy consumption for heating. XPS and stone wool have the highest impact scores for the categories human health and ecosystems. The impact scores for the categories resources and primary energy consumption are similar for all materials, with stone wool having the highest impact scores.

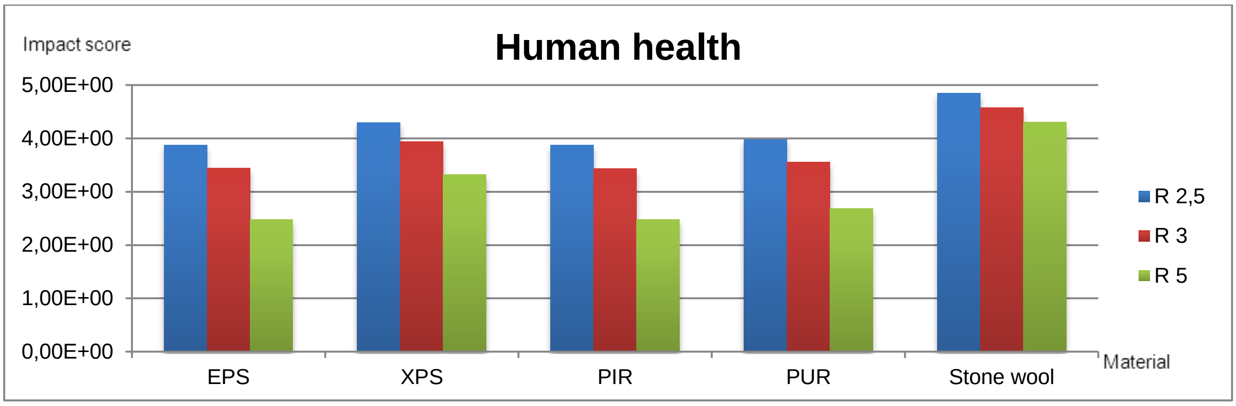

Figure 20: Normalized impact scores of the different insulation layer options after 30 years, calculated with the ReCiPe endpoint method, category human health

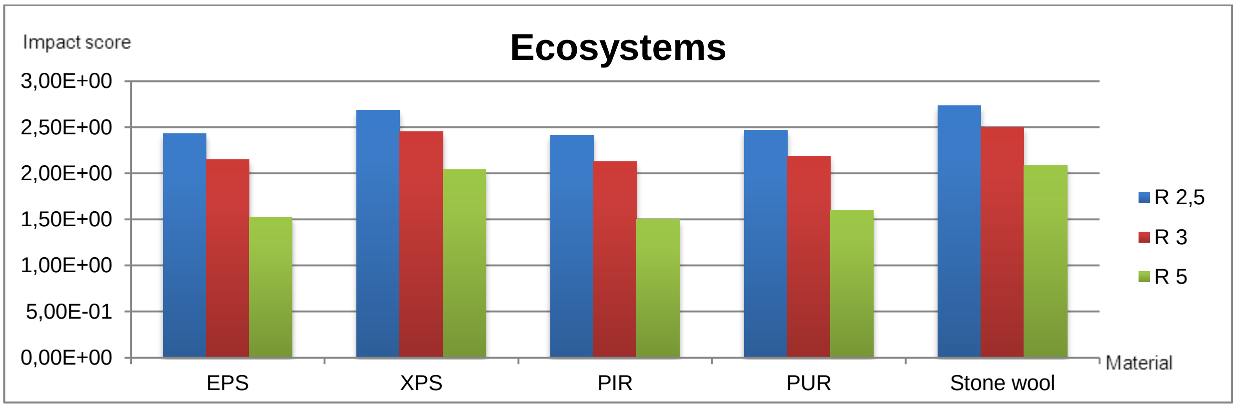

Figure 21: Normalized impact scores of the different insulation layer options after 30 years, calculated with the ReCiPe endpoint method, category ecosystems

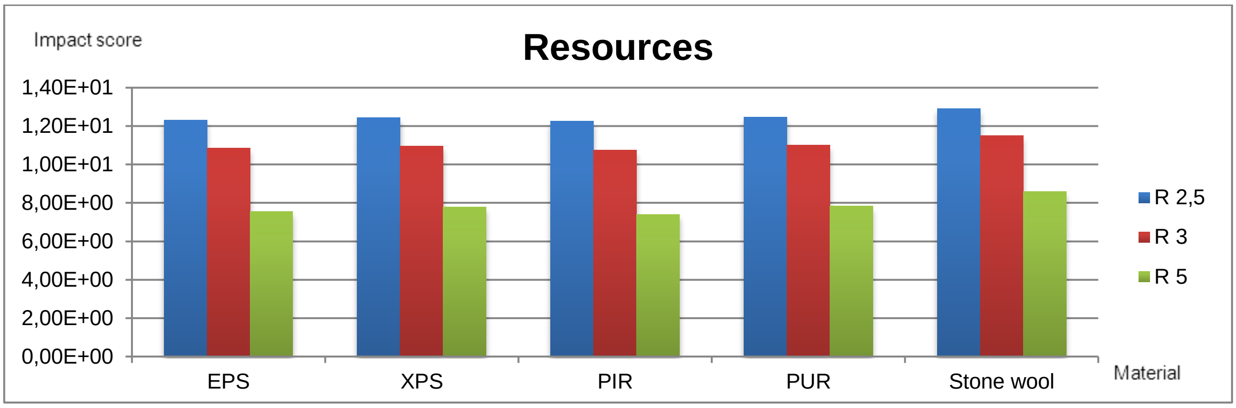

Figure 22: Normalized impact scores of the different insulation layer options after 30 years, calculated with the ReCiPe endpoint method, category resources

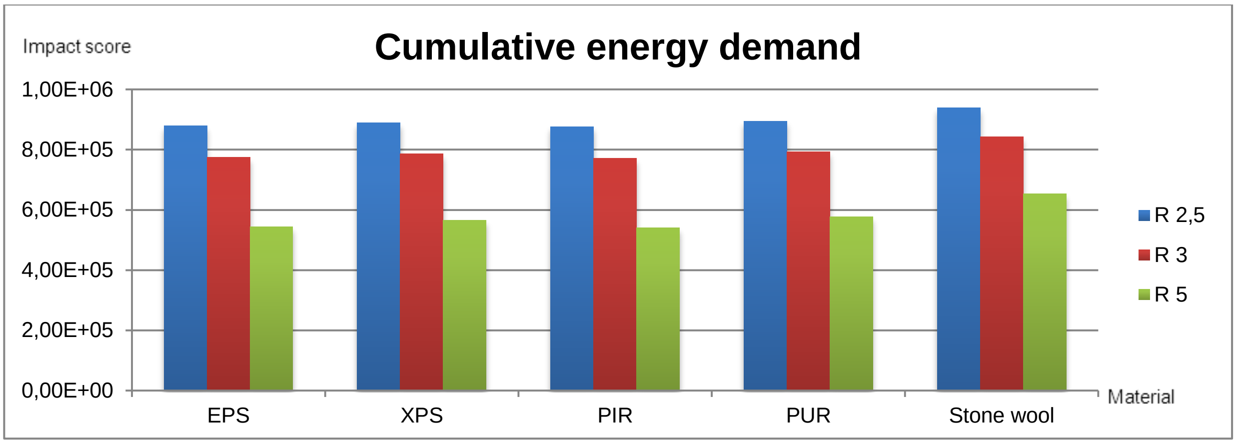

Figure 23: Cumulative energy demand of the different insulation layer options after 30 years, calculated with the Cumulative energy demand method

The environmental and energy payback times and savings after 30 year are shown in Table 17. They are calculated with the ReCiPe endpoint method and refer to a scenario with a thermal resistance of 2.5 m^2K/W. The table shows results similar to those presented in section 3.1.1. Stone wool has the highest EPBT and the lowest saving after 30 years, especially in the categories human health and ecosystems. The other materials have similar performances, except for XPS in the categories human health and ecosystems. PIR has the lowest payback times and the highest savings after 30 years. EPS has the second best results, but the differences with PIR are small. For all materials, the option with R=3 has shorter EPBTs because of the lowest impact scores caused by the "material" part, but the option with R=5 has a larger saving after 30 years because heat losses and therefore energy consumption are lower. Because the life span of the insulation layer is much longer than the considered period (75 vs. 30 years), all material have a positive effect from an environmental and energetic point of view. The EPBTs are much shorter than the life spans and applying a layer with a high thermal resistance value results in environmental savings up to 39.5%.

Table 17: Environmental and energy payback times and savings after 30 years of the different options for the insulation layer

		Human Health		**Ecosystems**		**Resources**		**Primary Energy [MJ]**	
Material	R-value [m^{2}K/W]	Payback time [yr]	Saving after 30 yr	Payback time [yr]	Saving after 30 yr	Payback time [yr]	Saving after 30 yr	Payback time [yr]	Saving after 30 yr
EPS	3	4.0	11.3%	3.6	11.6%	3.1	12.0%	3.3	11.8%
	5	5.4	36.1%	4.9	37.2%	4.1	38.8%	4.4	38.2%
XPS	3	8.6	8.4%	8.1	8.7%	3.2	11.8%	3.5	11.6%
	5	12.8	22.8%	12.0	24.1%	4.8	37.4%	5.2	36.5%
PIR	3	3.6	11.5%	3.0	11.9%	2.5	12.3%	2.9	12.0%
	5	5.4	36.1%	4.5	38.1%	3.7	39.5%	4.3	38.4%
PUR	3	4.8	10.7%	3.9	11.3%	3.3	11.7%	3.8	11.4%
	5	7.2	32.6%	5.9	35.2%	4.9	37.1%	5.7	35.6%
Stone wool	3	13.7	5.7%	8.2	8.5%	4.5	10.8%	5.5	10.1%
	5	20.4	11.3%	12.1	23.6%	6.6	33.4%	8.2	30.5%

Table 18 gives the economic payback time, the NPV and the saving in 30 years of an investment in extra insulation layer, using a thermal resistance of 2.5 m^{2}K/W as reference. The results are calculated with an interest rate of 2.5%. A material with thermal resistance of 5 m^{2}K/W costs more, so the investment takes longer to pay off, but this enables a higher saving and NPV. All payback times are higher than the environmental payback times; for XPS and stone wool, they are higher than 20 years. Economic savings are all lower than the savings on environmental impact by 3 to 6 percentage points for a thermal resistance of 3 m^{2}K/W and 10 to 20 percentage points for a thermal resistance of 5 m^{2}K/W.

From an environmental point of view, PIR and EPS with an R value of 5 m^{2}K/W are the best options. From an economic point of view EPS has the best values for all performance indicators, while PIR has results similar to PUR.

Table 18: Economic payback time, NPV and saving after 30 years of the insulation layer with an interest rate of 2.5%

Material	**Thermal resistance**	**Average scenario for gas price evolution**			**High scenario for gas price evolution**		
		Payback time	NPV after 30 years	Saving in 30 years	Payback time	NPV after 30 years	Saving in 30 years
EPS	R 3	10	€ 1,563.87	7.7%	9	€ 2,619.55	9.5%
	R 5	13	€ 4,532.00	22.3%	12	€ 8,092.39	29.2%
XPS	R 3	24	€ 530.71	2.5%	19	€ 1,586.39	5.5%
	R 5	28	€ 732.37	3.4%	28	€ 1,018.46	4.6%
PIR	R 3	11	€ 1,492.47	6.8%	10	€ 2,548.15	8.7%
	R 5	20	€ 2,925.50	13.3%	16	€ 6,485.89	22.1%
PUR	R 3	13	€ 1,385.37	6.4%	11	€ 2,441.05	8.4%
	R 5	20	€ 2,935.87	13.5%	16	€ 6,496.26	22.3%
Stone wool	R 3	19	€ 903.42	4.2%	16	€ 1,959.10	6.8%
	R 5	25	€ 1,533.20	7.2%	20	€ 5,093.59	17.6%

A sensitivity analysis is carried out to see how economic performance indicators would change with higher interest rates. The results are shown in figures 24 and 25 for EPS and XPS with a thermal resistance of 5 m^2K/W. For XPS, assuming the average scenario for gas price evolution, the NPV after 30 years is positive only with an interest rate of 3% or lower, while for the high scenario, the NPV after 30 years is negative only with an interest rate of 6%. Considering the whole life span of the XPS layer (i.e. 75 years), the investment in extra insulation would pay off in all scenarios; in the worst case it would pay off after 61 years. From an economic point of view, such an investment is not recommendable, also because of the high uncertainty for a period of analysis longer than 40 years (section 2.5.2).

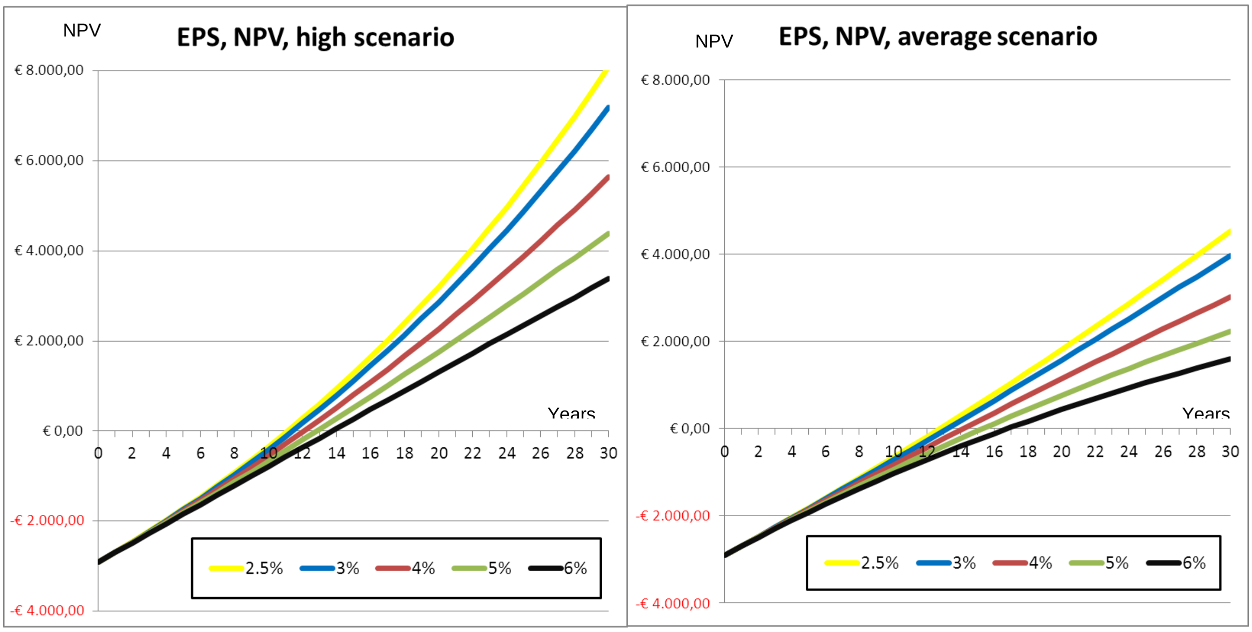

Figure 24: Sensitivity analysis of the NPV for EPS

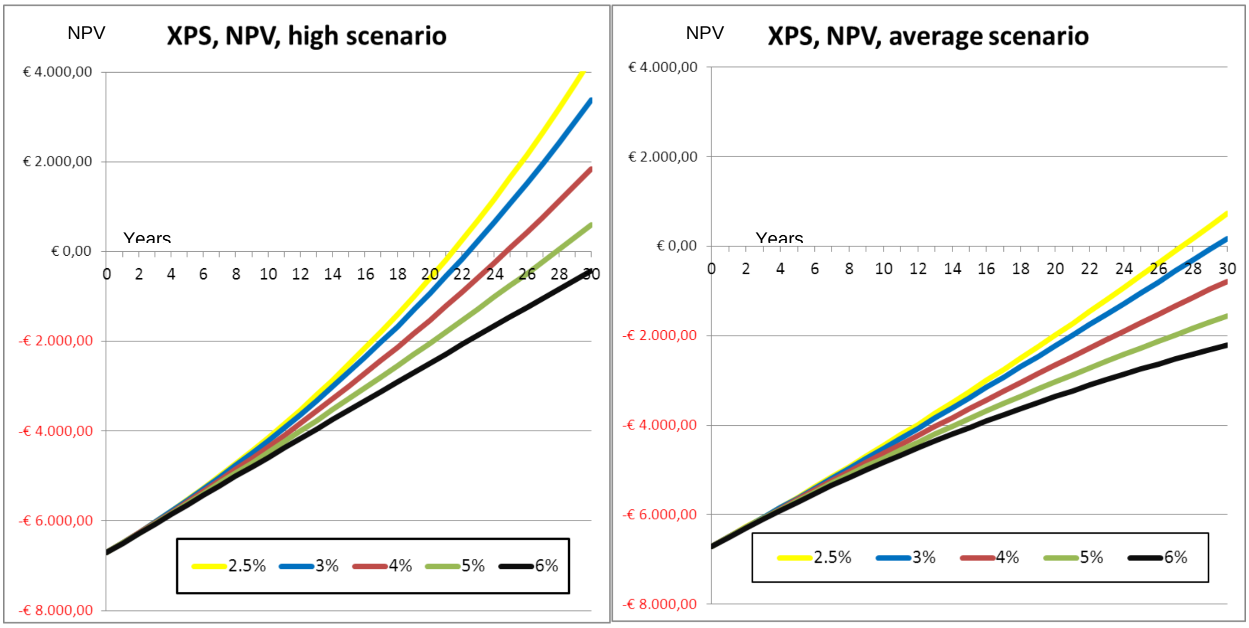

Figure 25: Sensitivity analysis of the NPV for XPS

3.2.2 Environmental comparison of roofing and covering layer

Figures 26 to 28 show the normalized impact scores, calculated with ReCiPe endpoint method (categories human health, ecosystems and resources, respectively), of the feasible combinations of roofing and covering layers. Impact scores calculated with the CML 2001 and ReCiPe midpoint methods are shown in Appendix A. For APP- and SBS-modified bitumen, the same assumption reported at the beginning of section 3.1.2 is valid, thus their impact scores might be underestimated. All three charts show similar results. Green roof has the highest impact score in categories human health and ecosystems, and one of the highest in category resources. All combinations with reflective coating have about 2 or 3 times higher impact scores than the same roofing layer with the other covering options, because of the frequent replacements of the reflective coating layer (every five years). The benefits of green roof and reflective coating in terms of e.g. cooling or air quality are not taken into account here. PVC mechanically fixed has the lowest impact scores in every category. EPDM mechanically fixed has lower impact scores than EPDM glued in every category. Gravel only causes a small increase of the total impact scores of the scenarios where it is used, especially in the category resources. All the scenarios with concrete tiles have higher impact scores than scenarios with gravel, except for the category resources, where the combinations of gravel with APP- and SBS-modified bitumen have higher impact scores than those of concrete tiles with PVC or EPDM. This is caused by the higher impact scores of the bituminous layers in category resources. White bitumen has impact scores between the ones of APP- and SBS-modified bitumen heated with no ballast and the ones of APP- and SBS-modified bitumen applied loose with gravel. The composition of white bitumen is similar to the one of APP-modified bitumen, but it has a higher thickness and thus a higher weight per m^2. Its fiberglass reinforcement and acrylic coating have a small contribution to the total impact scores at endpoint level. However, the benefits of the reflective coating in terms of cooling are not taken into account here.

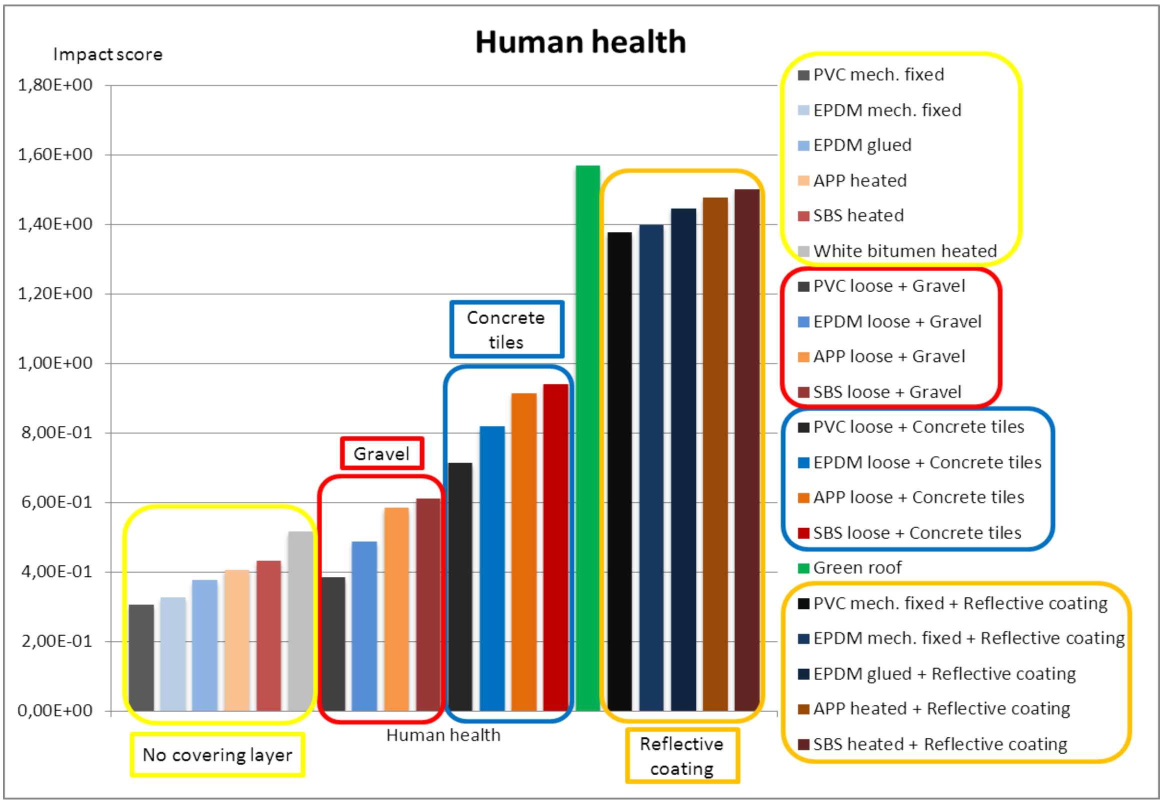

Figure 26: Normalized impact scores of feasible combinations of roofing and covering layer, calculated with the ReCiPe endpoint method, category human health

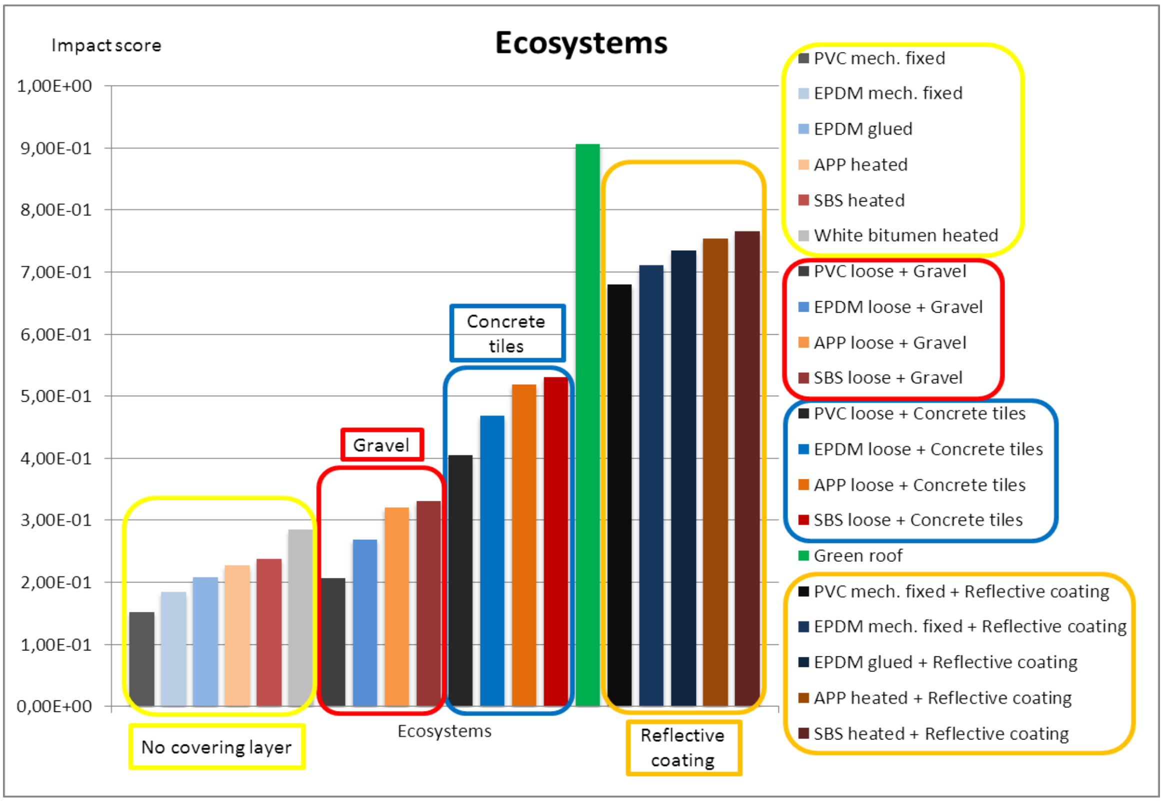

Figure 27: Normalized impact scores of feasible combinations of roofing and covering layer, calculated with the ReCiPe endpoint method, category ecosystems

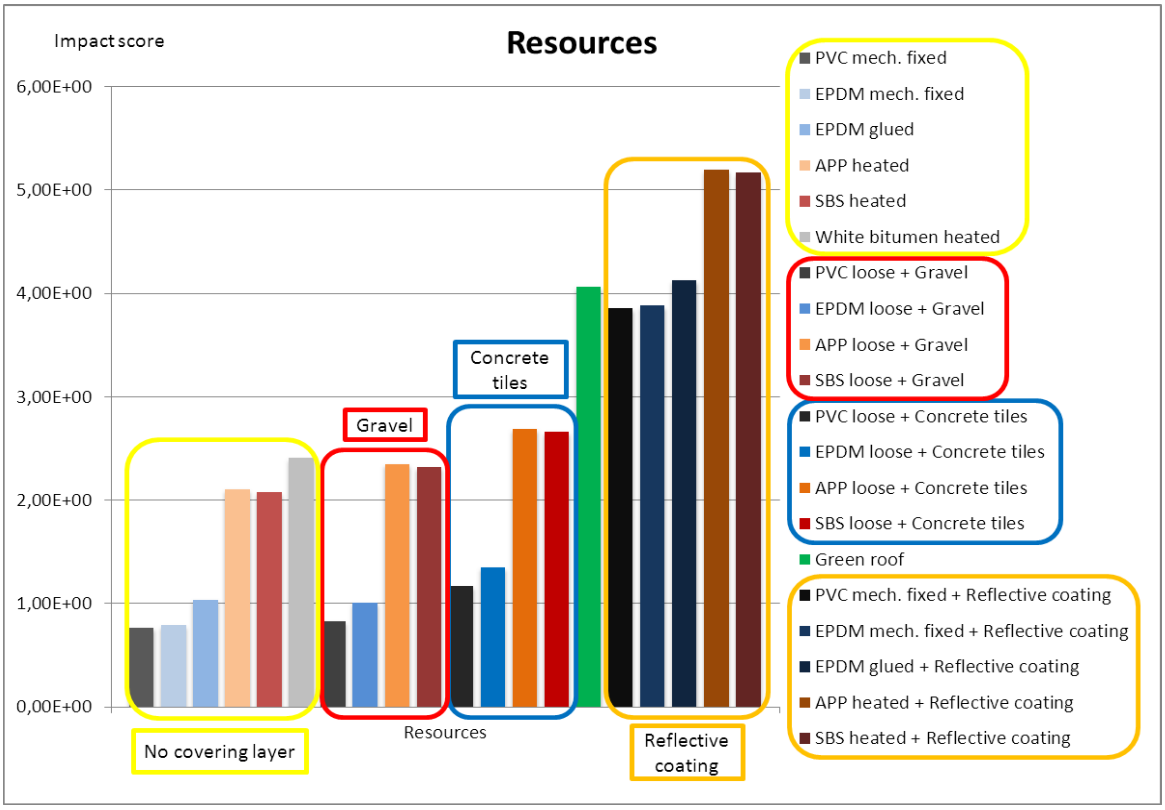

Figure 28: Normalized impact scores of feasible combinations of roofing and covering layer, calculated with the ReCiPe endpoint method, category resources

3.2.3 Environmental and financial performance of PV panels

The environmental and energy payback times and savings after 30 year of the PV panels are shown in in Table 19. They are calculated with the ReCiPe endpoint method and with the Cumulative energy demand method.

The payback times are 2.5 to 6.9 years, compared to a life span of 30 years. The environmental saving in 30 years is between 18.1% and 19.4%, and the primary energy saving is 15.9%. In the first year, considering no efficiency drop, the avoided electricity consumption is 23.8% of the demand.

Table 19: Environmental performance of PV panels with ReCiPe endpoint and Cumulative energy demand methods[8]

	Human health	Ecosystems	Resources	Cumulative energy demand
Environmental payback time [yr]	4.1	3.0	2.5	6.9
% Saving in 30 years	18.1%	19.0%	19.4%	15.9%

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[8] An annual drop of efficiency of 0.7% is considered.

Table 20 shows the economic payback time, NPV and saving after 30 years (i.e. the expected life span) of the PV panels, with different interest rates and price evolution scenarios. Costs for annual inspections are not included here. The economic payback times are 11 to 16 year; 2 to 4 times longer than the EPBTs. The economic savings in 30 years range from 7.8 to 15.3%; a few percentage points lower than the savings on environmental impacts. The NPV after 30 years is higher than the initial investment (i.e. € 26,758) for all interest rates assuming a high price increase and for interest rates up to 4% assuming an average price increase.

Table 20: Economic payback time, NPV and saving after 30 years of installation of PV panels

	Average price increase			**High price increase**		
Interest rate	Payback time [yr]	NPV after 30 years	Saving in 30 years	Payback time [yr]	NPV after 30 years	Saving in 30 years
2.5%	12	€ 41,215.78	12.9%	11	€ 72,414.00	15.3%
3%	13	€ 36,296.31	12.3%	11	€ 64,477.58	14.8%
4%	14	€ 27,844.18	10.9%	12	€ 50,953.37	13.8%
5%	15	€ 20,914.46	9.4%	13	€ 39,990.97	12.7%
6%	16	€ 15,193.62	7.8%	13	€ 31,046.33	11.5%

Compared with the results for EPS with an R value of 5 m^2K/W (section 3.2.1), payback times are similar, savings are higher for the insulation, and NPVs are higher for PV panels, but the initial investment is also higher for PV panels. For both PV panels and insulation, the period of analysis is 30 years, but this is equal to the actual life span for PV panels, while the insulation layer might last for 75 years. Furthermore, the economic performance of EPS is calculated as a difference with a reference scenario that has an R value of 2.5, thus the savings are smaller.

3.2.4 Selected scenarios

A selection of the materials with the lowest impact scores is made for each layer, according with the results shown in the previous sections.

For the insulation layer (section 3.2.1), PIR with a thermal resistance of 5 m^2K/W is the best options, with a reduction of impact scores of about 38% after 30 years in every category. EPS is the second best option and is cheaper than PIR, but with the latter, the same thermal performance can be achieved with a lower thickness: 12 cm instead of 18 cm. For the scenarios described below, PIR is chosen, but for EPS, the results are similar.

For the roofing and covering layers (section 3.2.2), the following options are considered:

- PVC mechanically fixed, with no covering layer. It is chosen because it has the lowest impact score in every category.
- EPDM glued, with no covering layer. It is one of the options with the lowest impact scores. It enables to consider an option with a roofing membrane without ballast or fixing with screws to the insulation layer.
- White bitumen. It has the highest impact scores of the options with no covering layer, but the scores are lower than most options with a ballast or a reflective coating. It is included to assess the environmental impact of a roof with benefits regarding cooling.
- PVC loose with gravel as ballast. This has the lowest impact score of the options with a covering layer in every category.

PV panels are not included in any scenario, since the impact scores of the production of the PV panels are much higher than those of the other materials, and the (negative) impact scores of the electricity production of the PV panels is much higher than the total impact scores of all scenarios.

Table 21 gives a summary of the four scenarios that are assessed in this study.

Table 21: List of assessed scenarios

	Insulation layer	**Roofing membrane**	**Covering layer**
Scenario 1 (S1)	PIR, 5 m^2K/W	PVC mechanically fixed	-
Scenario 2 (S2)	PIR, 5 m^2K/W	EPDM glued	-
Scenario 3 (S3)	PIR, 5 m^2K/W	White bitumen	-
Scenario 4 (S4)	PIR, 5 m^2K/W	PVC loose	Gravel

Figure 29 gives the normalized impact scores of the assessed scenario, split up per layer. The PIR insulation layer accounts for 55 to 70% of the total impact score of all scenarios, except for category resources in Scenario 3, where white bitumen accounts for 60% of the total impact score. The impact scores caused by the workers during the initial installation (i.e. 10 days travelling by car) is not ascribed to any layer. The results are in line with the findings in the previous sections. Scenario 1 has the lowest impact score in every category; Scenarios 2 and 4 have similar results, with a higher impact score of Scenario 2 in category resources; Scenario 3 has the highest impact score in all category, but the cooling benefits of white bitumen are not included.

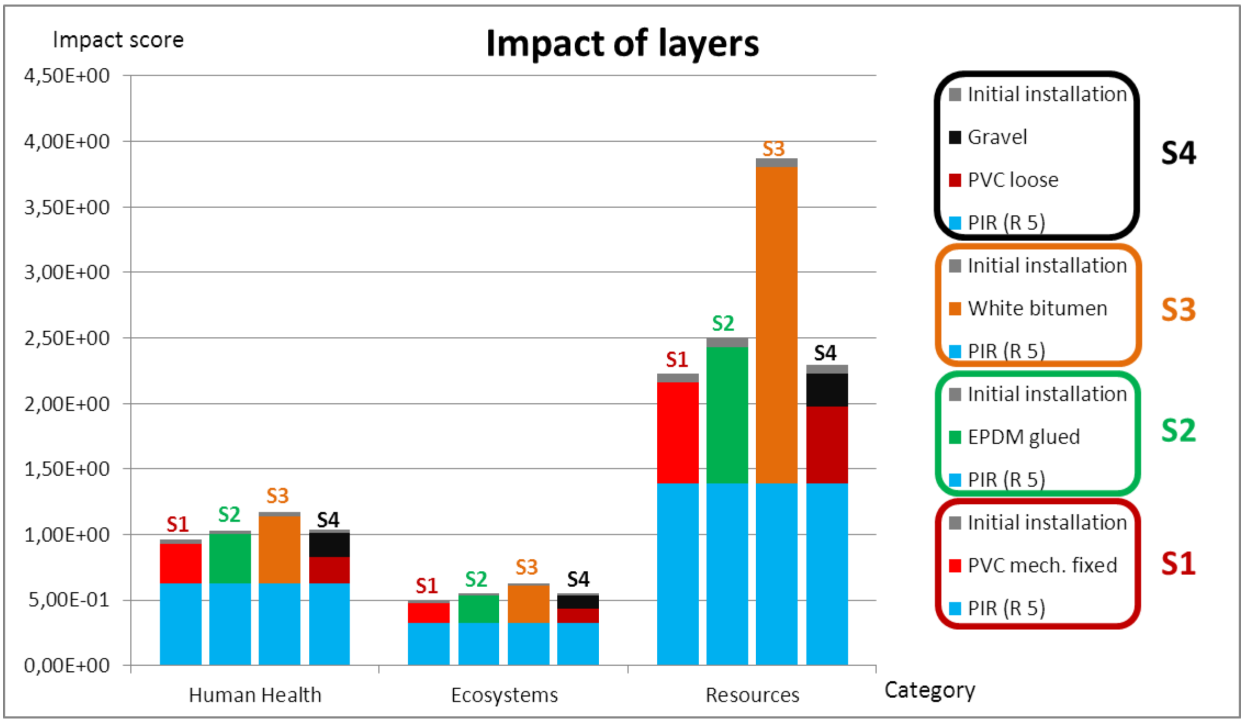

Figure 29: Normalized impact scores of the scenarios per layer, calculated with the ReCiPe endpoint method

Figure 30 shows the normalized impact scores of the scenarios, divided in material, maintenance and energy consumption caused by losses through the roof. The initial replacement (transport of materials and the workers travelling by car) is included in the material part. Only activities occurring during further replacements and annual inspections are included in the maintenance part.

Energy consumption due to losses through the roof causes 60% to 77% of total impact scores, depending on categories and scenarios. The material accounts for 20 to 35% of total impact scores and maintenance for 3-4%. The sum of the impact scores of the material and maintenance parts is equal to the sum of the impact scores of all the layers and of the initial installation in Figure 29. This is true for every category and scenario, except for Scenario 4, where the annual inspections required for PVC and gravel are counted only once. The assumption behind is that the roofers will always inspect the whole roof at the same time. With this assumption, Scenario 4 has the lowest impact scores in the categories Human health and Resources, while Scenario 1 has the lowest impact score in the category Ecosystems.

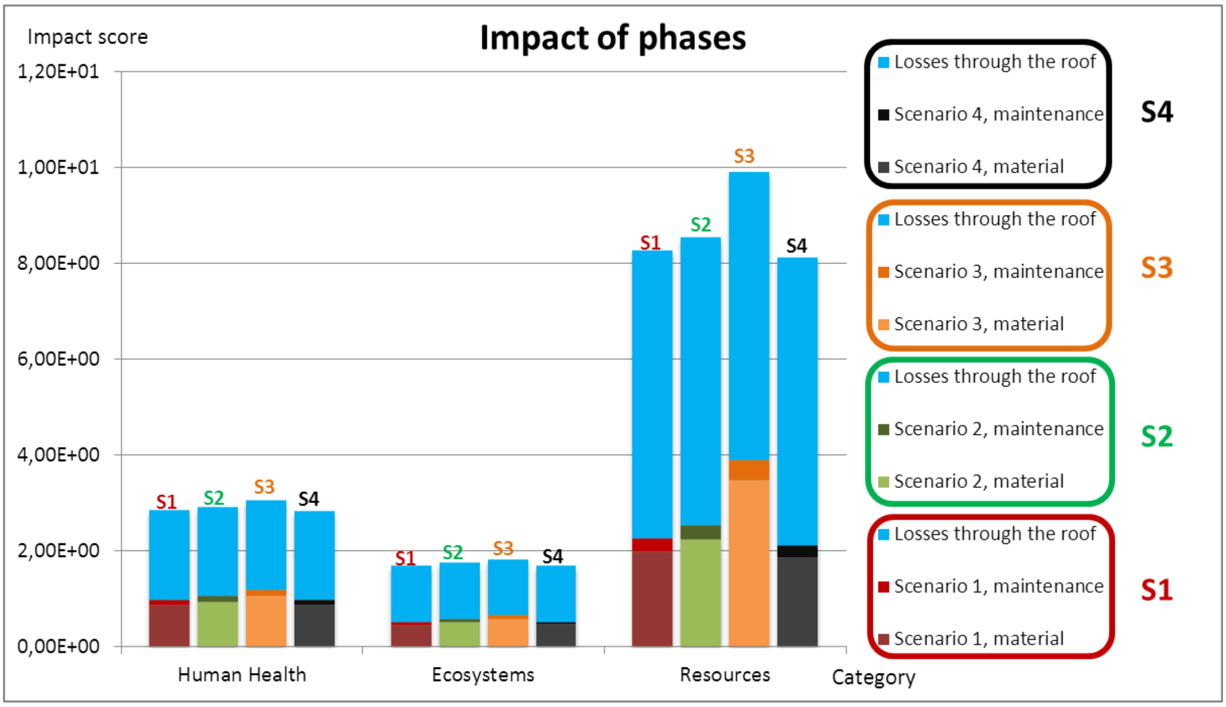

Figure 30: Normalized impact scores of the scenarios, divided in material, maintenance and energy consumption because of losses through the roof, calculated with the ReCiPe endpoint method

Table 22 shows the share of the installation of PV panels (i.e. material part) on the total impact scores of each scenario. The total scores include the material part of PV panels and of the layers, initial installation and maintenance activities in 30 years, assuming that the roofers will always inspect the whole roof at the same time. Energy benefits are not included. The impact scores associated with the PV panels are higher than those associated with the other layers.

Table 22: Share of the impact scores of the material part of PV panels on the total impact scores of material and maintenance of each scenario

	Human health	Ecosystems	Resources
Scenario 1	75.3%	71.6%	65.6%
Scenario 2	75.6%	69.4%	63.0%
Scenario 3	73.2%	66.5%	52.4%
Scenario 4	77.1%	71.5%	67.1%

4 Discussions

The holistic approach used in this research enables to deeply assess the environmental impact of few scenarios built with materials which have the lowest impact scores. Deeply means that not only the most sustainable scenario is sought, but also the materials that are responsible for the impact scores. This is done on two levels: the contribution of each layer, and the contribution of the materials, maintenance and energy consumption. To find out which materials would fit for the most sustainable scenarios, limited assessments are made of the different layers: insulation, roofing plus covering, and PV panels. This gives an idea of the impact scores of more than 500 feasible scenarios.

This study is affected by different forms of uncertainty. Some are caused by the assumptions made on the materials chosen and their physical characteristics. The data used refer to the typical behaviour of the materials, as indicated by the roofers where possible, or as found in the literature elsewhere. Most likely, these don’t reflect the actual behaviour of the building materials, but can be considered a good estimate. Other forms of uncertainty as limitations of data quality in the database, model uncertainty, choice of functional unit and system boundaries, choice of allocation and characterization methods, normalization, spatial and temporal variability affect the LCA methodology and occur during its different steps (Björklund 2002). The length of the life span of a roof increases uncertainty because of unpredictable technology development. It may be concluded that the complexity of a roof and these uncertainties make it impossible to obtain an accurate environmental assessment (Blom 2010). The goal of this study is not to obtain a complete environmental profile, but to compare alternative materials for roof renovation. Huijbregts and van Zelm (2012) underlined the relevance of investigating uncertainty. SimaPro enables to calculate importance of some types of uncertainty, using Monte Carlo simulation method. This is not done in this research due to lack of time, but should be calculated in further studies. The assumptions made are the same for all the materials considered and the effect of uncertainties probably do not change significantly the outcomes and the conclusions of this study. Furthermore, the methodology chosen to calculate energy consumption for heating and to assess the environmental impact of the materials and of maintenance makes the results representative also for other building types. Types of materials generally used and data as energy consumption, PV panels production and energy prices refer to the Netherlands. The results might change for countries with a different climate. A research on roof materials for warmer countries should also take into account energy consumption for cooling, which is more common and more significant, and benefits on it occurring when a reflective coating or green roof are applied.

The first assessments (section 3.1) shows the high relevance of the weight per m^2 of the material used. For the insulation layer, PIR and EPS are the two materials with the lowest impact scores in most categories, and are also the two materials with the lowest weight per m^2. Stone wool has the highest weight per m^2 and also the highest impact scores. The higher amount of materials required causes also higher impact scores for the bituminous roofing membranes. Exception are the EPDM roofing membrane, which has higher scores than PVC, though it has a lower weight per m^2, and gravel, which would have lower impact scores than concrete tiles even with the same amount of material per m^2. This can be explained by differences in the processes needed for the production of these materials.

Improving the insulation from 2.5 to 5 m^2K/W results in reductions of the impact scores from 11 to 40%, and in environmental payback times from 3.7 to 20.4 years. From an economic point of view, it is found to be a good investment as well, for most cases. For expensive materials such as XPS and stone wool, the results of the investment get worse significantly with the parameters. Considering a high interest rate and a low increase of the gas price, the investment have still a positive NPV after the whole life span, but the high uncertainty of a so long perspective would advise against such an investment. In general, PIR, EPS and PUR have both low environmental and economic payback times and high savings from an environmental and economic point of view. These results are made assuming a comparison with a starting situation with an R value of 2.5 m^2K/W, but a comparison with a starting situation with no insulation would give even more positive outcomes.

Applying a roofing membrane with no covering layer (ballast or reflective coating) is the best option in almost every case. The main goal of the covering layer is to prevent damages to the roofing membrane, but this benefit is not taken into account here. If a covering layer is necessary, gravel is the best option. Concrete tiles have a longer life span (i.e. 50 vs. 30 years), but gravel would still have lower impact scores, even considering two times its application.

Reflective coating and green roof have the highest impact scores, but their benefits are not taken into account.

For reflective coating, these benefits are:

- Reduction of indoor temperature and of energy consumption for cooling
- Reduction of roof temperature
- Extension of roof materials life span
- Reduction of the urban heat island effect
- Higher production of electric energy of PV panels installed on it

These would result in lower local air pollutant concentrations, decrease in greenhouse gases emissions and other indirect benefits (Xua, et al. 2011).

White bitumen leads to similar benefits as reflective coating, with the additional advantage that it doesn't require to be completely replaced every five years.

Green roof benefits are hard to quantify since heat transfer is affected by type of materials, climate, moisture of soil, type of vegetation, seasons and other parameters (Zinzi, et al. 2007). Thermal conductivity increases with soil density and decreases with increasing soil moisture content (Del Barrio 1997). Several researches have been conducted about benefits of green roof during summer in warm countries, but fewer are found on advantages during winter in countries with a Dutch-like climate. Del Barrio proposed a mathematical model to analyse green roofs cooling potential during summer. She also found that they have more effect on preventing heat gain than on preventing heat loss. This might be due to plant death in the fall and winter months, thereby reducing the amount of heat trapped by the green roof (Del Barrio 1997). Bass (2007) reported that the properties of green roofs in winter have a significant impact on old buildings, but the impacts are small in well-designed buildings for cold climates. Green roofs do not only reduce the energy demand for heating and cooling, but they also mitigate urban heat island effect, extend roofing membrane life span, improve air quality and enhance biodiversity. More research should be done on all these issues.

According with the results of this study, reflective coating and green roof should not be used from an environmental point of view. Nevertheless, there are no elements to exclude they can turn out to be environmentally friendly if their benefits are considered.

PV panels have higher impact scores than all other materials, but the electricity production leads to savings in the environmental impact scores of 18-19%, and in the primary energy demand of 16%. Because of the annual degradation of the modules, the contribution to the savings is higher in the first years. Therefore, the environmental and energy payback times are rather short (3 to 7 years). From an economic point of view, the investment is positive in every scenario. In economic calculations, the effect of modules degradation is mitigated by the increasing electricity price. The results for PV panels are assumed to be the same regardless of the roof type they are mounted on. This implies the assumption of technical feasibility in every case, and does not take into account potential benefits (i.e. increased electricity production) of mounting PV panels on a reflective coating or green roof.

Four “sustainable” scenarios are assessed, based on the results of the individual materials. Results found may vary significantly using materials with higher impact scores. The scenario with PIR (R = 5) and PVC mechanically fixed or the scenario with PIR (R = 5), PVC loose and gravel have the lowest impact scores.

Concerning energy consumption for heating, energy losses through the roof have a higher share in the impact scores than the production of material and maintenance activities together, ranging from 60 to 77%, even when an insulation layer with a high thermal resistance (5 m^2K/W) is used. The insulation is responsible for more than half of the total impact scores. Using lower amounts of insulating material would reduce this share, but this would result in higher heat losses through the roof and consequently in higher total impact scores for the whole roof. Maintenance is the part with the lowest contribution to the total impact scores, but a reduction can still be achieved with simple actions, such as scheduling annual activities at the same time for the different layers.

5 Conclusions

This research investigates the life cycle of roof constructions with the most common materials used in The Netherlands and some more innovative solutions as green roof and reflective coating. It indicates the materials with the lowest environmental impact scores. It shows in what extent each layer and each part of the life cycle are responsible for the total impact scores of roofs. It also shows the economic performance of the insulation materials and of PV panels.

These results enable to give some practical guidelines to increase sustainability for roofers, housing associations, maintenance companies and other stakeholders. Energy consumption caused by heat losses through the roof is responsible for the highest share of impact score. This makes the insulation the most critical issue from an environmental point of view. Hence, a high thermal resistance value for the insulation layer (e.g. 5 m^2K/W) is preferable. Materials with low impact scores and enabling an economic return exist (e.g. PIR and EPS) and should be chosen. For the roofing layer, the bituminous membranes usually need to be applied in two layers, resulting in higher impact scores. The best option is PVC which can be fixed mechanically or applied loose with gravel as a ballast, resulting in similar impact scores. Gravel should be preferred to concrete tiles if a ballast is applied. In most of the cases the materials with a lower weight per m^2 have lower impact scores as well. This should not be considered a rule, but it might be a taken into account if no other element is available. PV panels have positive outcomes from an environmental and an economic point of view and should be mounted in every possible situation. Their price is decreasing and new technology is available. This might lead to even better outcomes. Maintenance activities are responsible only for a small share of the total impact scores, but here the assumption is that activities take place at the same time for different layers. This approach should be chosen or kept.

Due to the number of variables, many assumptions needed to be made, but indications on a wide cluster of options are given. As a general recommendation, a holistic approach should be kept for further research, due to the number of interconnections between the results of the environmental impact assessment of the different layers and phases. Further research should investigate the benefits of green roof and reflective coating. The results should state if these are environmentally friendly or if the high impact scores they cause are not balanced by their benefits. In order to assess this, the energy consumption for cooling should be considered. A comparison between countries with different climates would suggest which solutions are more appropriate in which situations. Moreover, an analysis of uncertainties should be carried out to strengthen the conclusions reported here.

Considering the relative impact of the housing sector and the age of the majority of European buildings, large scale improvements can be done in this sector to reduce our damage on the environment. A first important step could be to reduce heat losses in old houses with a bad insulation, which would lead to high savings in the short term from both an environmental and economic point of view, to have a better quality of life and lower expenses.

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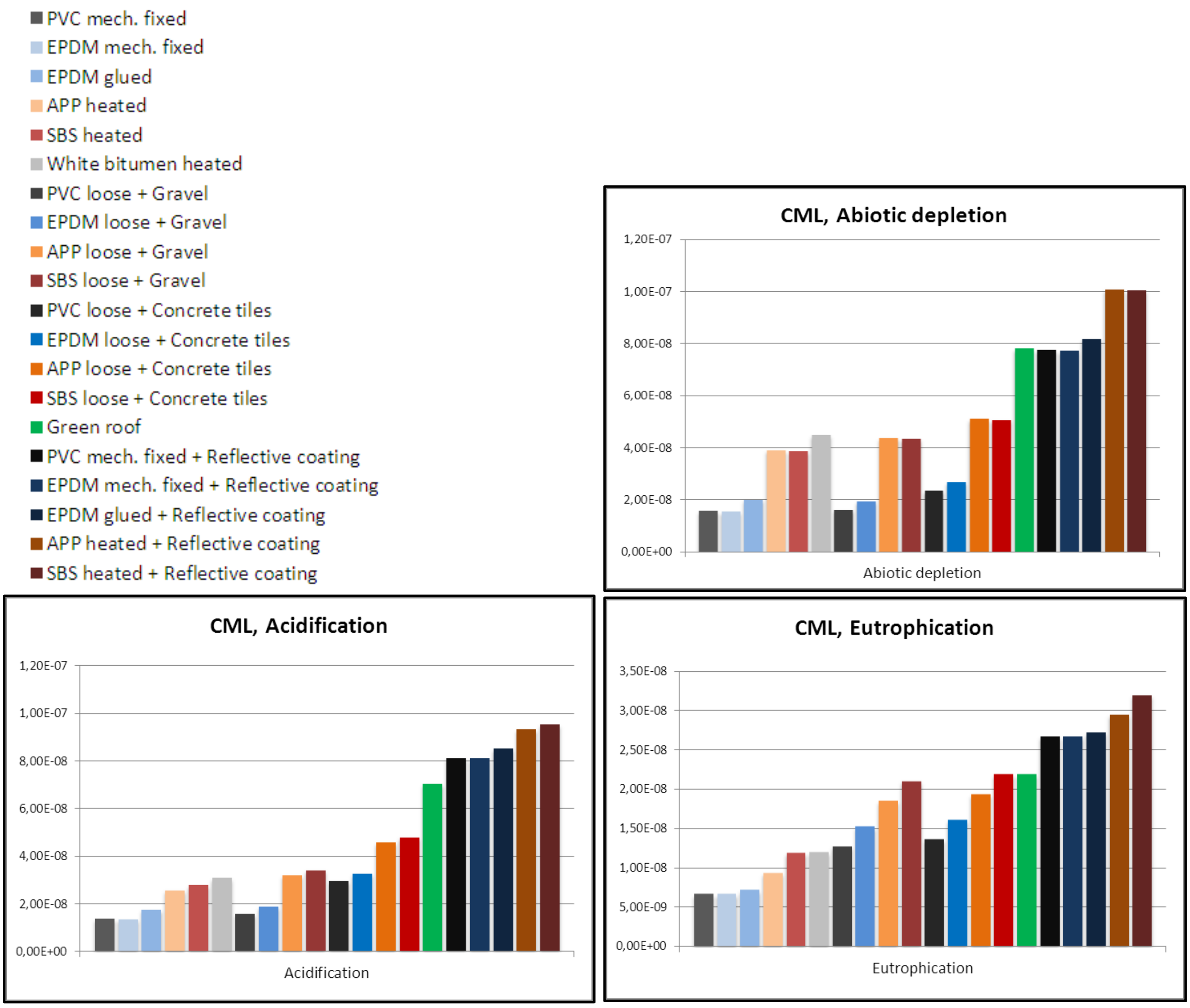
Appendix A **Environmental comparison of roofing and covering layer with CML 2001 and ReCiPe midpoint methods**

Figures A1 and A2 show the impact scores of the combinations of roofing and covering layers with CML 2001 and ReCiPe midpoint methods respectively. Results were similar to those obtained with ReCiPe endpoint method as presented in section 3.2.2.



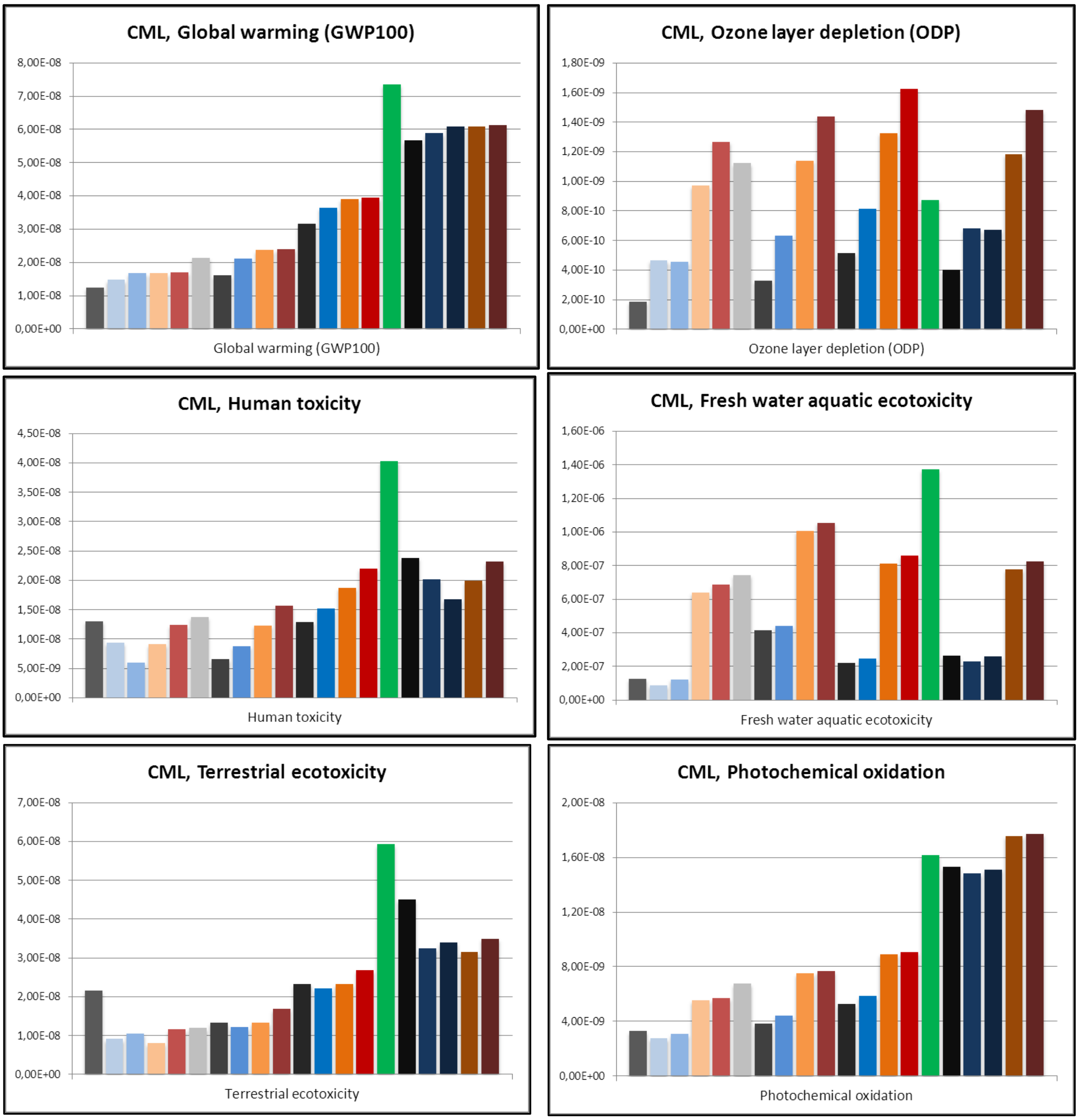
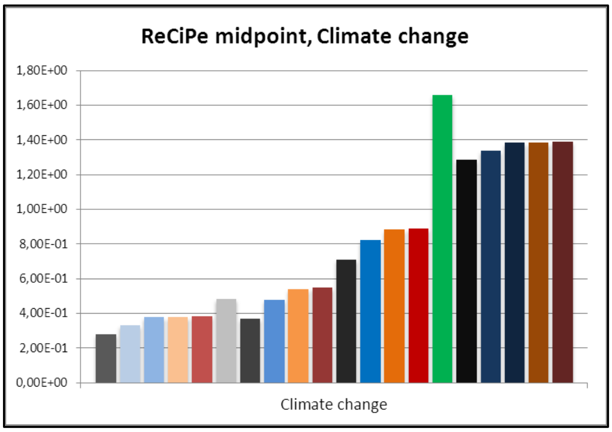
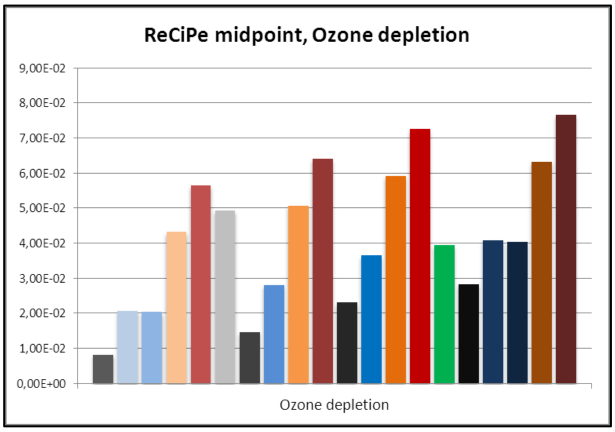
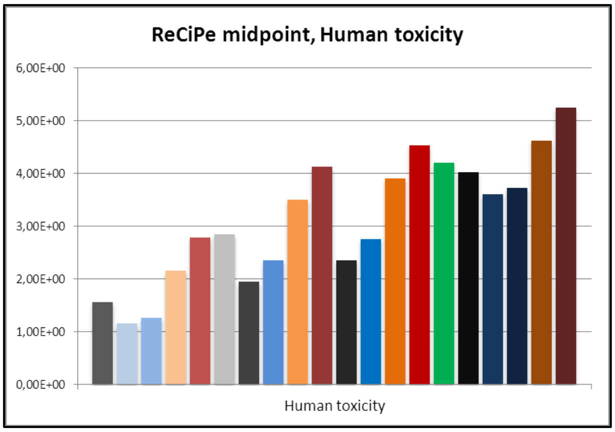


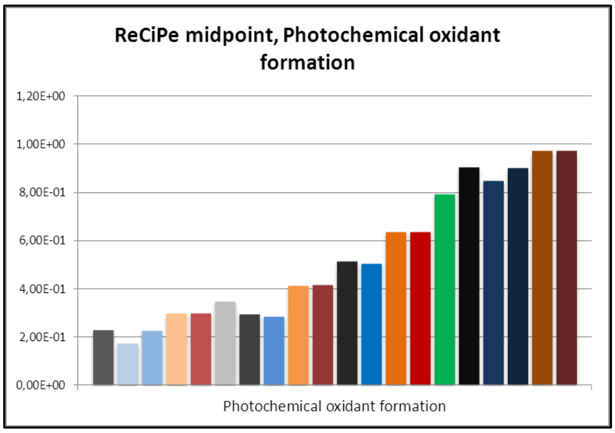
Figure A1: Normalized impact scores of feasible combinations of roofing and covering layer, calculated with the CML 2001 method

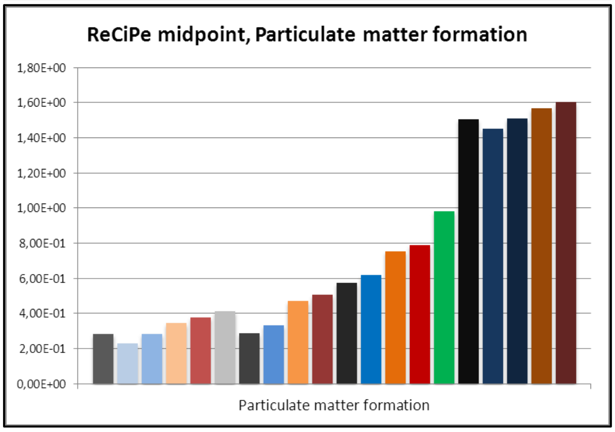
- ■ PVC mech. fixed
- ■ EPDM mech. fixed
- ■ EPDM glued
- ■ APP heated
- ■ SBS heated
- ■ White bitumen heated
- ■ PVC loose + Gravel
- ■ EPDM loose + Gravel
- ■ APP loose + Gravel
- ■ SBS loose + Gravel
- ■ PVC loose + Concrete tiles
- ■ EPDM loose + Concrete tiles
- ■ APP loose + Concrete tiles
- ■ SBS loose + Concrete tiles
- ■ Green roof
- ■ PVC mech. fixed + Reflective coating
- ■ EPDM mech. fixed + Reflective coating
- ■ EPDM glued + Reflective coating
- ■ APP heated + Reflective coating
- ■ SBS heated + Reflective coating

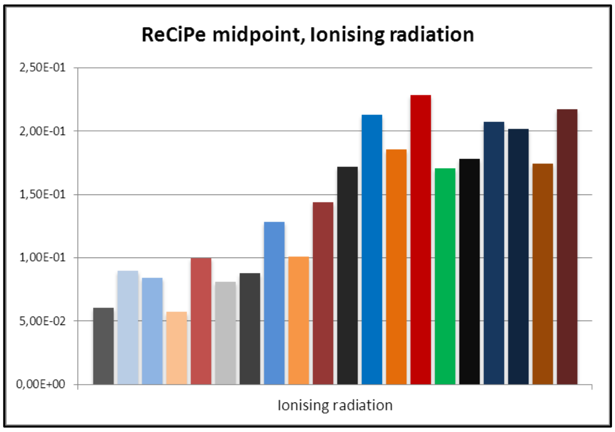

ReCiPe midpoint, Climate change

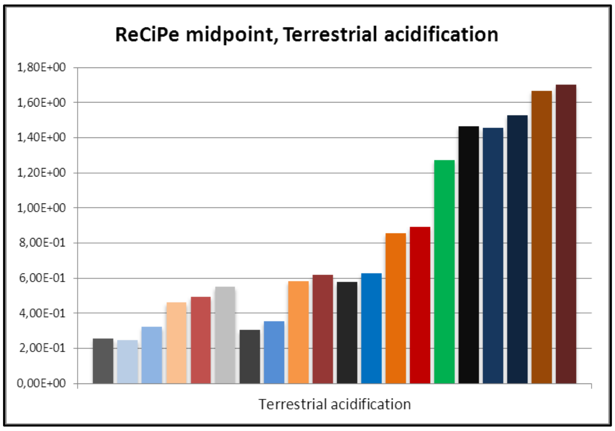

ReCiPe midpoint, Ozone depletion

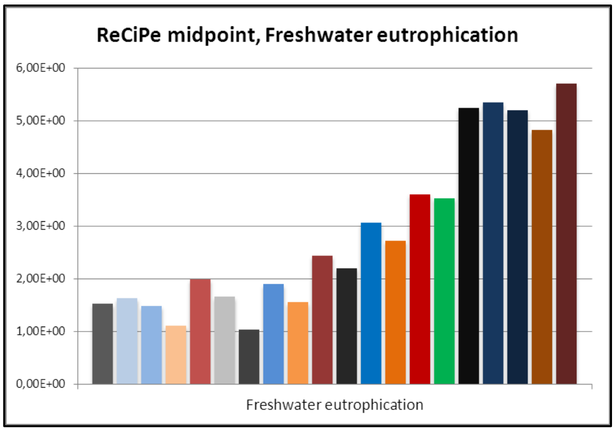

ReCiPe midpoint, Human toxicity

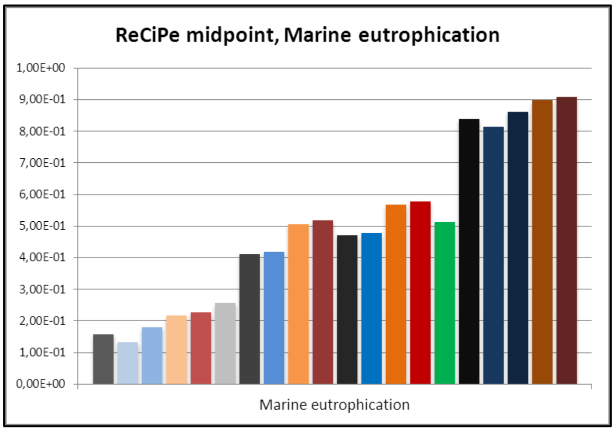

ReCiPe midpoint, Photochemical oxidant formation

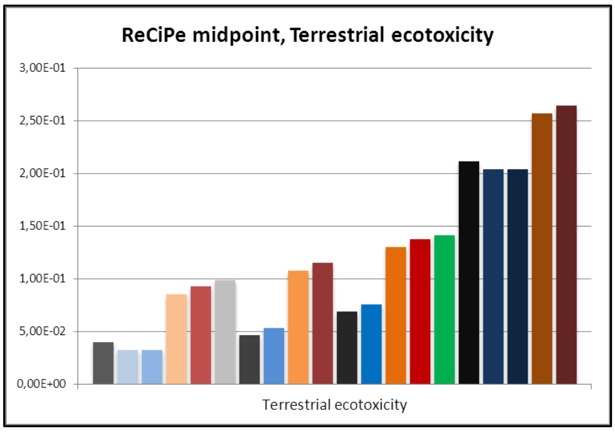

ReCiPe midpoint, Particulate matter formation

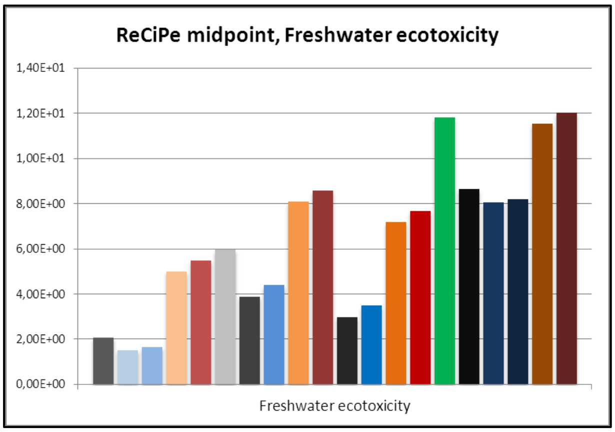

ReCiPe midpoint, Ionising radiation
2,50E-01
2,00E-01
1,50E-01
1,00E-01
5,00E-02
0,00E+00
Ionising radiation

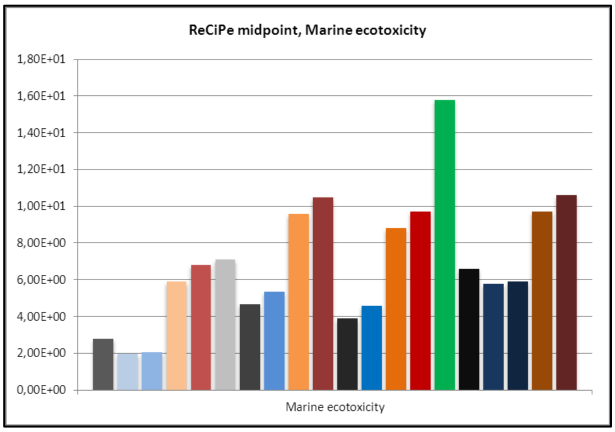

ReCiPe midpoint, Terrestrial acidification
1,80E+00
1,60E+00
1,40E+00
1,20E+00
1,00E+00
8,00E-01
6,00E-01
4,00E-01
2,00E-01
0,00E+00
Terrestrial acidification

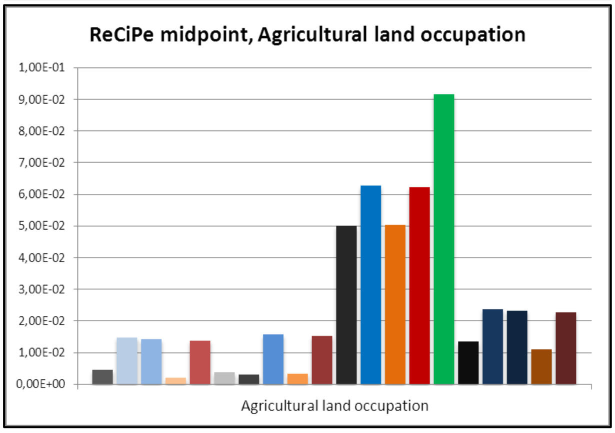

ReCiPe midpoint, Freshwater eutrophication
6,00E+00
5,00E+00
4,00E+00
3,00E+00
2,00E+00
1,00E+00
0,00E+00
Freshwater eutrophication


ReCiPe midpoint, Marine eutrophication
1,00E+00
9,00E-01
8,00E-01
7,00E-01
6,00E-01
5,00E-01
4,00E-01
3,00E-01
2,00E-01
1,00E-01
0,00E+00
Marine eutrophication


ReCiPe midpoint, Terrestrial ecotoxicity
3,00E-01
2,50E-01
2,00E-01
1,50E-01
1,00E-01
5,00E-02
0,00E+00
Terrestrial ecotoxicity


ReCiPe midpoint, Freshwater ecotoxicity
1,40E+01
1,20E+01
1,00E+01
8,00E+00
6,00E+00
4,00E+00
2,00E+00
0,00E+00
Freshwater ecotoxicity


ReCiPe midpoint, Marine ecotoxicity
1,80E+01
1,60E+01
1,40E+01
1,20E+01
1,00E+01
8,00E+00
6,00E+00
4,00E+00
2,00E+00
0,00E+00
Marine ecotoxicity


ReCiPe midpoint, Agricultural land occupation
1,00E-01
9,00E-02
8,00E-02
7,00E-02
6,00E-02
5,00E-02
4,00E-02
3,00E-02
2,00E-02
1,00E-02
0,00E+00
Agricultural land occupation

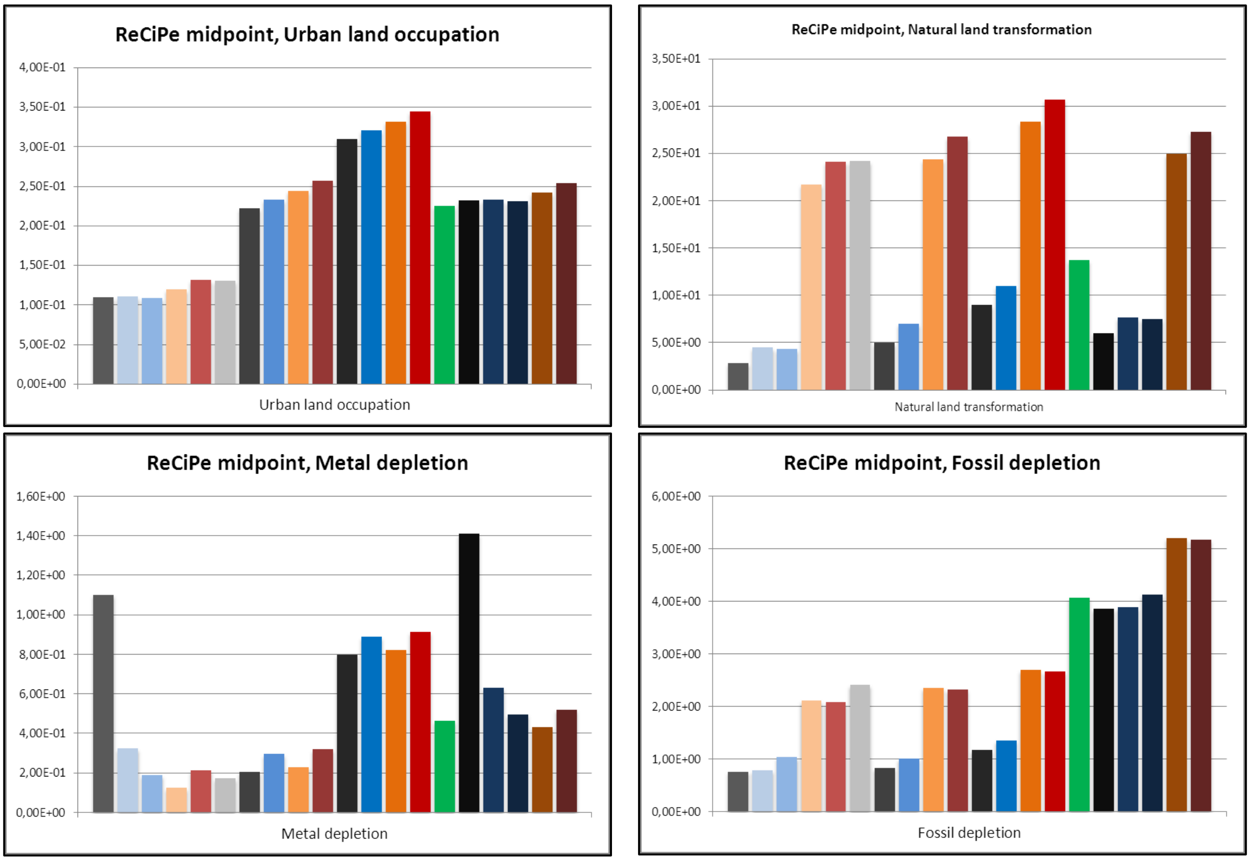


Figure A2: Normalized impact scores of feasible combinations of roofing and covering layer, calculated with the ReCiPe midpoint method

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