The Effect of an Increase in Energy Efficiency on Embodied Energy use

A SCENARIO ANALYSIS FOR DUTCH RESIDENTIAL BUILDINGS

Master thesis by Anastasia Koezjakov

April 7th, 2017

Colophon

Author: Anastasia Koezjakov (5539064) - a.koezjakov@students.uu.nl

Programme: Sustainable Development, track energy and materials, Utrecht University

First supervisor: Wina Crijns-Graus – w.h.j.graus@uu.nl

Internship: 3SCEP Center at Central European University, Budapest, Hungary

Internship supervisor: Diana Ürge-Vorsatz – vorsatzd@ceu.edu

ECTS: 45

Abstract

Energy efficiency of heating and cooling (operational) energy use in buildings is currently a major global policy subject. But, the reduction potential of this energy use is decreasing, which leads to the shifting focus to material manufacturing (embodied) energy use. Therefore, this thesis investigates the relationship between this energy efficiency and embodied energy use, using Dutch residential buildings as a case study. The analysis is performed using three scenarios from an already existing building energy analysis model: the 3SCEP HEB (Center for Climate Change and Sustainable Energy Policy High Efficiency Buildings) model. Also, an Embodied Energy Database Management System (EEDMS) was created to analyse the embodied energy use, using 23 materials most common in Dutch residential construction; including material volumes and material energy intensities, for 25 Dutch building representatives. The building representatives are defined using the five types that occur most in the Netherlands: mid-terrace, end-of-terrace, detached, semi-detached and apartments. For every type representatives are chosen for five energy performance categories (low to high energy performance), based on construction period of the building type. The relevant parts of the 3SCEP HEB model are integrated in the EEDMS to model total embodied and operational energy use from 2015 to 2050 and create embodied-to-operational energy ratios.

The resulting embodied energy use in the 25 building representatives varies from 47 to 106 $MJ/m^2/y$, and the operational energy use from 124 to 682 $MJ/m^2/y$. The scenario analysis showed that a total energy use reduction potential of 40% can be reached in 2050, unfortunately this is accompanied by a 15% increase in embodied energy use. This increase is mainly caused by increasing use of insulation materials and aluminium in residential buildings. This research shows that the Dutch building representatives with the lowest embodied and operational energy - and therefore the most desired outcome - are buildings renovated into a home that is in line with the guidelines of a passive home and/or nearly Zero Energy Building (nZEB). The embodied to operational energy ratio range of this type is 0.39-0.55. This research shows that the relative importance of embodied energy use in total residential building energy use is increasing. Particularly in light of the goal to reach a maximum temperature increase of 2˚C by 2050 - taking into account the relative increase in passive homes and nZEB's in the future - it is important to include embodied energy use in future policy objectives.

Preface

This thesis is conducted as final step before graduating from the master Sustainable Development, track energy and materials, at Utrecht University. This research was partially executed in the Netherlands, and partially at the Central European University (CEU) in Budapest, Hungary. This research started with the aim to extend the 3SCEP HEB model of the CEU, but appeared to be so much more at the end. I am proud to say that this final report is my own original work, where I have built my own model that works independently from the 3SCEP HEB model. It was a long journey full of hard work and great experiences.

I would like to thank my supervisor at the CEU; Diana Ürge-Vorsatz, for giving me the opportunity to be part of the 3SCEP research team. This research opportunity did not only increase my scientific knowledge of building energy use, but I also learned to work in a different environment and cope with different cultures. I would also like to thank my supervisor at Utrecht University; Wina Crijns-Graus, for the constructive feedback on all chapters of this thesis. Our discussions really made me think and led to important insights.

I would also like to thank the interviewees that freed time in their busy schedule; Huibert Spoorenberg from OFME, Carl-Peter Goossen from BouwNext, Herman Broekhuizen from Heilijgers Bouw bv and Frans van Swam and Michel Eekert from Buildsight.

Finally I would like to thank all my friends and family for their support during this demanding period. Particularly Karlijn Scholtens deserves a special thanks: I would have not been able to finish this thesis without access to the SBR referencedetails she provided.

Amsterdam, April 2016
Anastasia Koezjakov

Table of Contents

Abbreviations 7
1. Introduction 8
1.1 Gap in the literature 9
1.2 Research aim 10
1.3 Relevance 11
2. Theoretical framework 12
2.1 Building on the 3SCEP HEB model 12
2.2 3SCEP HEB scenarios 14
2.3 Dutch buildings defined 17
2.3.1 Building vintages 17
2.3.2 Building types 19
2.3.3 Building representatives 23
2.4 Energy use 23
2.4.1 Defined boundaries 24
3. Method 25
3.1 Material composition and volumes 25
3.1.1 Material surface areas 26
3.2.2 Material thicknesses 27
3.2 Energy use 30
3.2.1 Materials 30
3.2.2 Embodied energy intensities 32
3.2.3 Embodied energy use 34
3.2.4 Operational energy use 36
3.3 Scenario analysis 37
4. Results 40
4.1 Energy use per building representative 40
4.1.1 Embodied energy use 40
4.1.2 Operational energy use 46
4.1.3 Embodied-to-operational energy ratios 46

4.2 Scenario analysis 48
4.2.1 Total energy use development 48
4.2.2 Embodied-to-operational energy ratios in the scenarios 52
4.3 Sensitivity Analysis 53
4.3.1 Gross floor area 53
4.3.2 Embodied energy intensities 54
4.3.3 Operational energy intensities 55
4.3.4 Building lifetime 56
4.3.5 Retrofit and demolition rate 57
5. Discussion 58
5.1 Theoretical implications 58
5.2 Reflection 58
5.3 Limitations 60
5.4 Further research 61
6. Conclusion 62
7. References 63
Appendix A: Calculations gross floor area building types 70
Appendix B: SBR Referencedetails 71
B.1 New vintage 71
B.2 Retrofit vintage 74
B.3 Advanced new vintage 76
B.4 Advanced retrofit vintage 79
Appendix C: Material volumes per building representative 81
C.1 Mid-terraced 81
C.2 End-of-terrace 86
C.3 Detached 91
C.4 Semi-detached 96
C.5 Apartment 101
Appendix D: Embodied Energy Database Management System 106
Appendix E: Embodied energy intensity values 109

Abbreviations

BVO	=	gross floor area
CBS	=	Dutch Central Bureau of Statistics
EBPD:	=	Energy Building Performance Directive
EEDMS:	**=**	Embodied Energy Database Management System
EE/OE ratio:	=	embodied-to-operational energy use ratio
EPC:	=	Building Energy Performance Coefficient
EPISCOPE:	=	Energy Performance Indicator Tracking Schemes for the Continuous Optimisation of Refurbishment Processes in European Housing Stocks
GBPN:	=	Global Buildings Performance Network
IEE:	=	Intelligent Energy Europe
IEEI:	=	initial embodied energy intensity in MJ/kg or MJ/m^3
IPCC:	=	Intergovernmental Panel on Climate Change
LCA:	=	Life Cycle Assessment
LCEA:	=	Life Cycle Energy Analysis
MF:	=	multi-family
NMD:	=	Dutch National Environment Database
nZEB:	=	nearly-Zero Energy Building
PH:	=	Passive House
PHI:	=	Passive House Institute
RVO:	=	Netherlands Enterprise Agency
3SCEP HEB:	**=**	Center for Climate Change and Sustainable Energy Policy High Efficiency Buildings
SF:	=	single family
TABULA:	=	Typology Approach for Building Stock Energy Assessment
TEEI:	=	transport embodied energy intensity in MJ/kg or MJ/m^3
TFEC:	=	Total Final Energy Consumption
Total EEI:	=	total embodied energy intensity (IEEI + WATEEI) in MJ/m^3
UNFCCC:	=	United Nations Framework Convention on Climate Change
WAFA:	=	weighted average floor area in m^2
WATEEI:	=	weighted average transport embodied energy intensity in MJ/m^3
WTW:	=	ventilation system with heat recovery

1. Introduction

According to Hopwood, Mellor & O'Brien (2005) the definition of the concept 'sustainable development' can differ amongst people with different worldviews. However, all studies seem to recognize that there is a link between environmental problems and socio-economic wellbeing (Hopwood et al., 2005; Kajikawa, 2008). Sustainable development can be achieved when economic development is intertwined with meeting the growing demand of human needs and desires, the conservation of natural resources and the capacity of Earth's environment to absorb stress (Kajikawa, 2008). The most commonly used definition of sustainable development is '*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*' (Butlin, 1989). Sustainable development became important in the middle of the 20th century when it became clear that anthropogenic activities are not compatible with the changing Earth system. These activities have led to life-threatening hazards that need to be managed. The Intergovernmental Panel on Climate Change (IPCC) (2014) is 95% certain that anthropogenic influence is the main cause of global warming. The more humans disrupt the environment, the greater the risks are of irreversible and severe impacts on ecosystems and societies - and on the longer term - on the whole climate system. Therefore, action needs to be taken now.

One of the largest global challenges to mitigate climate change is the conservation and enhancement of the current resource base (Butlin, 1989). Within this global challenge one of the most pressing issues is the burning of fossil fuels to produce energy, and its accompanying CO_2 emissions. Figure 1.1 shows the rapid global CO_2 emission increase, due to the burning of fossil fuels, cement and flaring, since 1850. Even though renewable energy use and more efficient energy production is increasing, fossil fuel combustion still happens on a large scale, worldwide. It is essential to decrease such burning, particularly to reach the goal of the maximum temperature increase of 2 ˚C by 2050 (Butlin, 1989; IPCC, 2014).

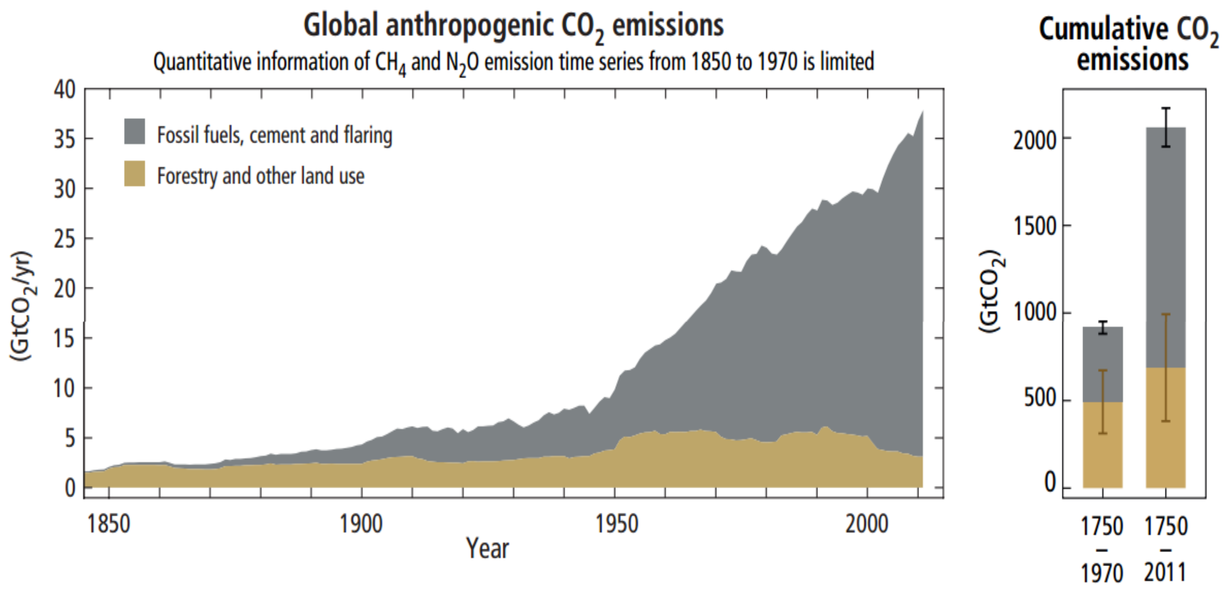


Figure 1.1: Rise of global CO_2 emissions in Gton $C0^2$/year since 1850 caused by burning of fossil fuels, cement and flaring (IPCC, 2014)

“Building energy is a major contributor to energy-related global challenges to sustainable development” (Urge-Vorsatz, Petrichenko, Staniec & Eom, 2013). Building heating and cooling leads to about 33% of the total final energy demand globally, which leads to about 30% of the global CO_2 emissions that are related to energy use (Urge-Vorsatz et al., 2012). Therefore, to mitigate climate change, greenhouse gas emissions from building energy use should be reduced fast.

Various studies are done on building energy use. According to Pérez-Lombard, Ortiz and Pout (2008), the global energy contribution from buildings have exceeded the contribution from industrial and transportation sectors. Population growth, increasing comfort levels, increasing demand for building services and the increasing time people are spending in buildings, will lead to a further increase of building energy consumption. Therefore, addressing the energy efficiency in buildings, is currently a major global policy subject.

Building energy use can be reduced in several ways (Ramesh, Prakash & Shukla, 2010). The operational energy (energy consumption) can be reduced by using active and passive technologies as for example; using the light of the sun during the day instead of artificial lighting, insulating the building to reduce heat losses or by installing a ventilation system with heat recovery (WTW). However, when the reduction in operational energy use is estimated, typically the energy consumption required to produce the building capital is neglected; which is referred to as the *embodied energy* (Sorrell, 2007). The reduction of operational energy use often leads to an increase in embodied energy use due to an increase in material use with higher energy intensities. Furthermore, the use of energy efficient equipment and installations in buildings is increasing nowadays, while at the same time insulation materials are becoming more advanced. The reduction potential of operational energy is therefore reduced, which leads to the shifting focus on embodied energy in buildings (Cabeza, Rincón, Vilariño, Pérez, & Castell, 2014).

1.1 Gap in the literature

Several studies have been done on the reduction of embodied energy use in buildings. In the study of Venkatarama Reddy and Jagadish (2003) was found that by using low-energy intensive materials and other construction techniques in residential buildings, 30-45% reduction in total embodied energy use can be obtained. Particularly in low-energy buildings, embodied energy contributes highly to the building life cycle energy; contribution can be up to 46% (Takano, Pal, Kuittinen & Alanne, 2015).

According to Langston & Langston (2008), measuring operational energy in buildings is more straightforward, while measuring embodied energy is more complex and time consuming. Trusty and Horst (2005) showed their preference for LCA (Life Cycle Assessment) tools like SimaPro and Athena for building energy analysis. However, the focus of such models is on the LCA approach, which does not provide an easy way to compare and possibly relate the different phases of energy use in buildings.

The embodied energy analysis’ that has been done until now, usually focussed on a specific country or location. For example in the research of Venkatarama Reddy & Jagadish (2003) embodied energy in buildings was investigated in the Indian context. Chen, Burnett & Chau (2001) investigated the embodied energy use profile in buildings in Hong Kong. Buchanan & Honey (1993) investigated the same energy use for New Zealand. Europe is advanced in increasing the energy efficiency of buildings compared to other continents. But, when the identified energy savings potential is examined more closely, it becomes clear that there is a lack of well-founded data on these potentials, on European and national level (Meijer, Itard &

Sunikka-Blank, 2009).

1.2 Research aim

From the previous sections can be derived that embodied energy use in buildings is an important factor to take into account when calculating building energy use. Also, the fact that an increase in energy efficiency (a decrease in operational energy) in buildings can lead to an increase in embodied energy use should not be ignored. Therefore the research framework of this thesis aims to analyse the relationship between energy efficiency and embodied energy use. By doing so, potential side-effects of increasing energy efficiency can be determined.

The Global Buildings Performance Network (GBPN) commissioned a study concerning the global potential for building related operational energy use and greenhouse gas emission mitigation, by performing a policy-based scenario analysis for the years 2005-2050. The results of this study provide insights in reaching low energy building consumption, using policy measures. This analysis started under guidance of the Fourth Assessment Report of the IPCC and was extended in cooperation with the GBPN in 2011 and 2012 (Urge-Vorsatz et al., 2013). To execute this analysis, the 3SCEP HEB (Center for Climate Change and Sustainable Energy Policy High Efficiency Buildings) model was developed. This particular model can determine the operational energy for a variety of countries, regions and even the whole world. It is most detailed amongst the global building energy use models, and provides a significant basis to model the operational energy use in buildings in this research.

Taking into account the timeframe of this thesis, it is only possible to determine the embodied- and operational energy use in buildings for one country. As previously mentioned; there is a lack of well-founded data concerning embodied energy in buildings in Europe. Therefore, an European country is chosen for the analysis; the Netherlands. The Netherlands is known for their building regulations on energy efficiency. Since 1995 building regulations were enforced to establish the required energy performance of new buildings (SenterNovem, 2005). The energy efficiency in residential buildings in the Netherlands is measured by the EPC (Building Energy Performance Coefficient) (RVO, 2016a). By introducing the EPC, the responsibility of choosing energy efficiency measures to realise a particular energy performance in a building, shifted towards the construction industry. This means that buildings can be built with the materials the developer prefers, as long as it meets the requirements given in the Dutch building regulations. The regulations also obligate the developer to include an environmental performance calculation of the building, when a new building is supplied. However, this calculation is meant to stimulate the developer to use sustainable construction materials, but is not forcing this. In conclusion, the Netherlands can benefit from the assessment of embodied energy use in residential buildings, because it can raise awareness amongst developers about the energy intensity of the used materials.

In the study of Pérez-Lombard et al. (2008) residential final energy consumption was higher than commercial consumption in every region that was analysed, (including the EU) and is therefore, more important to deal with. Taking this into account and the research timeframe; the embodied energy use analysis will only be performed for Dutch residential buildings, neglecting commercial buildings. The typical Dutch residential building representatives analysed in this research - taking into account building type and building energy performance - will be identified in the next chapter.

Based on above arguments, the research question is:

How does the embodied-to-operational energy use ratio develop for the main Dutch *residential building representatives, in three policy-based scenario's projected for the years 2015 to 2050?*

Sub-questions are:

1. What are important building representatives in the Netherlands that cover the whole building stock?
2. What is the embodied energy use of the building representatives in MJ/m^2/year, based on their material use and material volumes in m^3?
3. What is the operational energy use of the building representatives in MJ/m^2/year?
4. What is the total energy use development in Dutch residential construction in a scenario analysis over the years 2015-2050?

To analyse the embodied energy use, an Embodied Energy Database Management System (EEDMS) was created using Microsoft Access 2013. Later on, the relevant 3SCEP HEB model parts were integrated in the EEDMS to model the relationship between the two energy uses.

1.3 Relevance

By creating an EEDMS for Dutch residential buildings, and integrating parts of the 3CSEP HEB model, embodied energy use can be modelled next to the operational energy use in the Netherlands. Such an improvement in modelling knowledge will allow decision makers to take a step towards optimization of the performance of residential buildings by taking into account the relevance of the choice of construction materials. This will on its turn, contribute to the reduction of energy related CO_2 emissions (Stephan, Crawford & de Myttenaere, 2012). This is a significant step for society, considering it contributes to the mitigation of climate change.

The contribution of this thesis to the field of sustainable development is important for future energy policies and LCA-analysis. The creation of an EEDMS does not only lead to an increase in modelling knowledge and in data analysis; it also leads to availability of a new database of embodied energy data for Dutch residential buildings. Furthermore, this model provides the first step to model the complete energy life-cycle of buildings. Later on, the same method can be used to include other countries and eventually to model the whole world. The outcome of this research sheds light on the significance of embodied energy use in total building energy use. It helps policy makers to decide whether or not to include embodied energy use in buildings, in future policy goals.

2. Theoretical framework

This chapter defines and explains the boundaries of the research. First, the 3SCEP HEB model and scenario boundaries are explained. The 3SCEP HEB model provides the building blocks for the scenario analysis of embodied- and operational energy use, and gives modelling definitions that will be used throughout this thesis. Then the Dutch building representative definitions will be given, which leads to the answer on the first sub-question defined in section 1.2. At the end of this chapter, the boundaries of the terms *embodied energy use* and *operational energy use* are defined. These definitions determined the type of energy use data that was collected.

2.1 Building on the 3SCEP HEB model

The 3CSEP HEB model is a performance-oriented approach to the energy analysis of buildings (Urge-Vorsatz et al., 2012). In this model, the performance of whole systems is analysed and these performance values are inserted as inputs in three scenarios. These scenarios show the potential trends building energy use can follow when different decision regimes are possible. The goal of these scenarios is to emphasize the consequences of particular policy decisions, as information for policy makers. The modelling logic is shown in figure 2.1 and will be elaborated in this section.

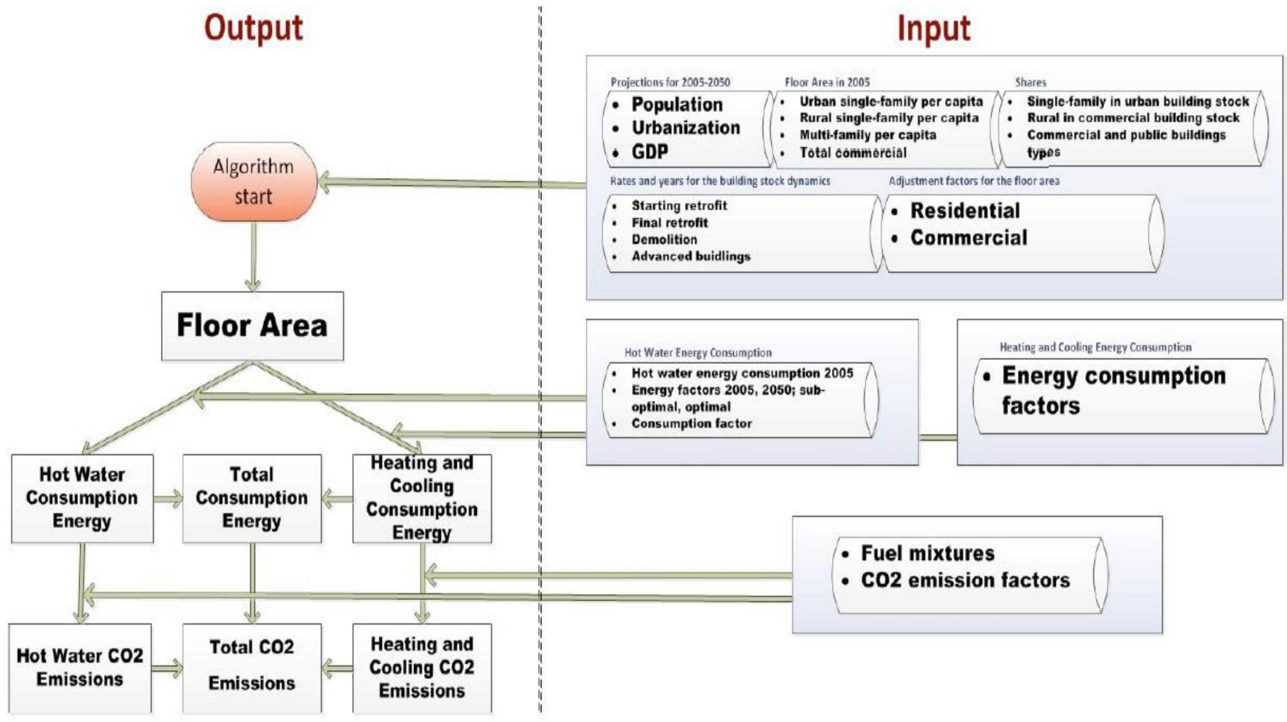


Figure 2.1: Modelling logic of the 3CSEP HEB model (Urge-Vorsatz et al., 2012)

The model is a bottom-up hybrid approach because it includes detailed information about individual buildings and the building sector, but also macroeconomic data like GDP, population growth, urbanization rate and floor area per resident. Output parameters of the scenarios are the Total Final Energy Consumption (TFEC) and the CO_2 emissions associated with this energy consumption. The timeframe of the scenarios is 2005-2050, because statistical data before 2005 was often not available, and the reliability of predictions after 2050 decreases drastically. Results are determined on a regional (where EU-27, China, India and USA are key regions in the model), on a country and on a global level.

In this model, building categories are distinguished by three factors; building type, building vintage and their location. Location differences are neglected in this research, as this is not relevant when only analysing the Netherlands. Residential buildings are split in single family (SF) and multi-family (MF) buildings and commercial/public buildings are divided in six categories. In this thesis, only the two residential building categories are relevant. Furthermore, there are five building vintages described in the scenarios, based on energy performance and construction period. *Standard* buildings are those that were already built before 2005; these are usually the least efficient. *New* buildings are constructed in the period 2005-2050. *Retrofit* buildings are buildings renovated between 2005 and 2050. The last two vintages are *advanced new-* and *advanced retrofit*, which have the same rules as new and retrofit, but with a lower specific energy use. When a building has reached a certain level of ambitious energy performance, which is typically about 70-90% reduction in energy use, this level is called 'the best practice'. Buildings that fit in this category are called 'advanced'. In this thesis, the same categories of building vintages will be applied.

The 3SCEP HEB model is built using Microsoft Access 2010[1]. Microsoft Access is a relational database management system, which allows the user to collect data, make relationships between data and arrange the data according to a fixed structure (Barrows, Stockman & Taylor, 2013). For the common user it is enough to use the form that is created to navigate the 3SCEP HEB model. A print screen of this form is shown in figure 2.2. In the left lower corner you can see all the input data used to do the calculations. When using the form, the retrofit rate and shift year has to be filled in (with 3% and 2020 as the default value, respectively). The shift year defines the year that certain building energy requirements will be mandatory (for example that all buildings have to reach a certain energy efficiency level in 2020). Then the version of the model is chosen; usually the newest version. Then, the scenario and the country/part of the world can be chosen. Finally, data can be calculated and exported to Microsoft Excel: the floor area development for a scenario, the heating and cooling energy and the hot water energy.

[1] When using the model in this research, the new version of Microsoft Access will be used: 2013.

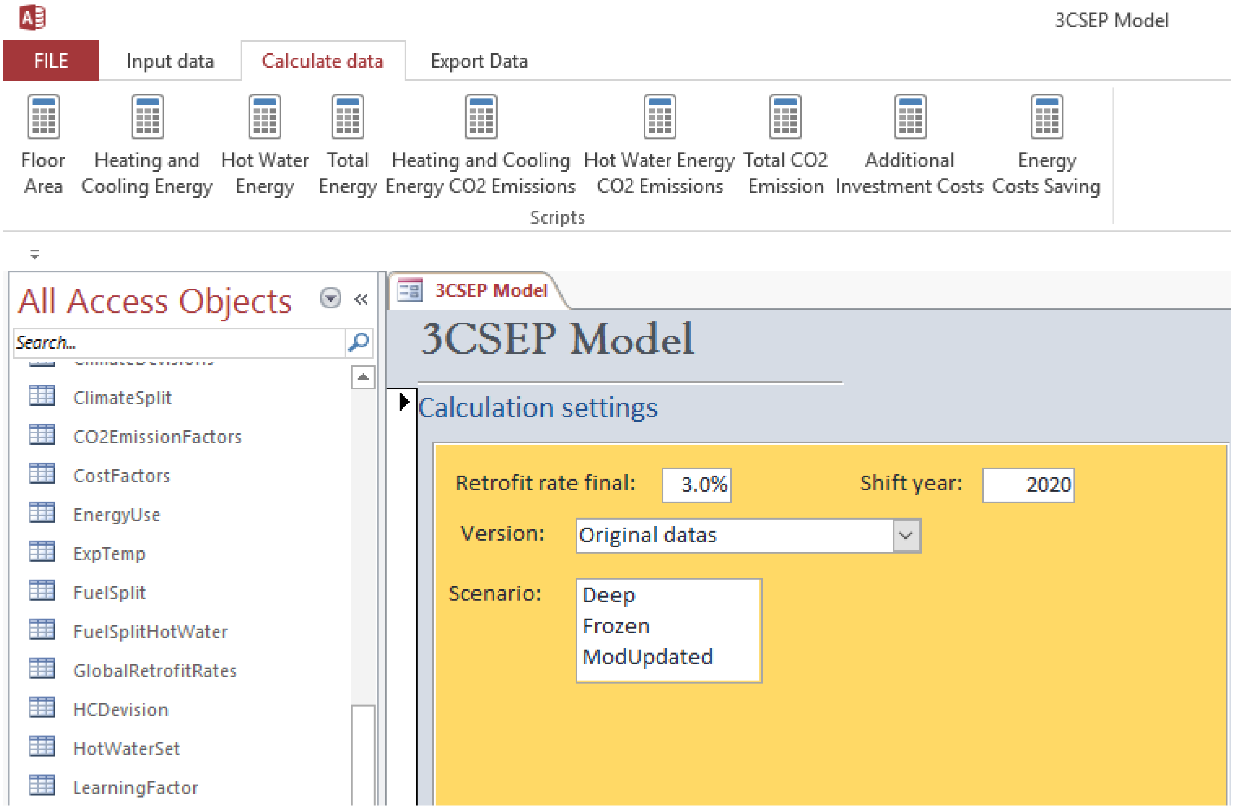


Figure 2.2: Form to use the 3CSEP HEB model in Microsoft Access

2.2 3SCEP HEB scenarios

The three scenarios in the 3SCEP HEB model are based on population projections and policy initiatives (Urge-Vorsatz et al., 2012). Every scenario follows certain rules which identify the floor area in m^2 in time. The calculated floor area can then be multiplied with a specific energy intensity to determine (embodied and/or operational and/or total) energy use over the years[2]. Figure 2.3-2.5 show an example outcome of floor area development in m^2 for every scenario. The scenarios of this model are based on a timeframe of 2005 to 2050, but only current projections will be shown, starting in 2015.

The *frozen efficiency* scenario assumes that energy use of new and retrofit residential buildings, will not change relatively to 2005 levels. Retrofit rates (the percentage of existing homes that are renovated every year) remain stable at 1.4% and the share of advanced new buildings does not change over time. Following these rules, the floor area in billion m^2 projection, for every vintage is shown in figure 2.3.

[2] **Note** that the data mentioned in this section is the basic data used in the model; later on, some of the input data is adjusted for the Dutch building stock and according to the current model timeframe (2015-2050).

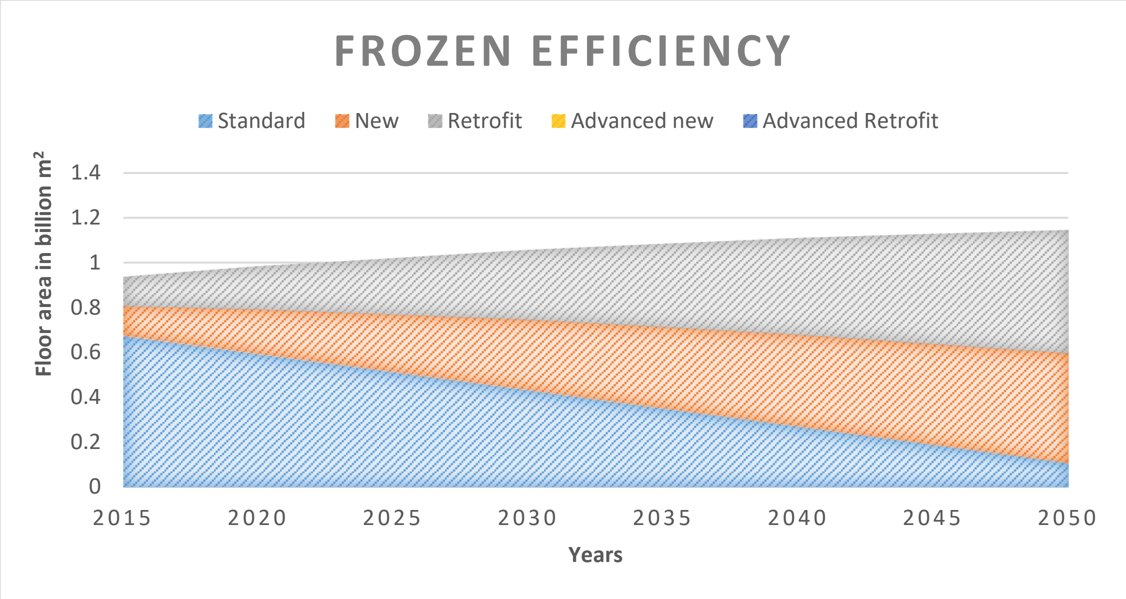


Figure 2.3: The total floor area in billion m² in the frozen efficiency scenario for Dutch residential buildings using the 3SCEP HEB data, with timeframe 2015-2050. For every vintage type (standard to advanced retrofit) the floor area development is shown.

The frozen efficiency scenario shows no (significant) advanced retrofit and advanced new homes over the years. The sharp decrease in standard homes makes room for an increase of new and retrofit buildings.

The *moderate efficiency* scenario is based on the Energy Building Performance Directive (EBPD), which was established in 2010 by the European Parliament and the Council of the European Union to reduce building energy consumption. This reduction is in line with the Kyoto protocol to the United Nations Framework Convention on Climate Change (UNFCCC) and will comply with the commitment to maintain the global temperature increase below 2 ˚C. This directive aims to increase the energy efficiency of buildings in the EU with 20% in 2020. Furthermore, all new residential buildings should be nearly-Zero Energy Buildings (nZEB's) by December 31st in 2020 (the shift year). A nZEB is defined as a building with an energy consumption close to zero. Other requirements are that a large part of this consumption should be produced by renewable energy sources, which should also be produced on the same location or nearby (European Parliament & EU Council, 2010).
To reach the goal of the EBPD, an accelerated renovation rate is assumed in the moderate efficiency scenario. This rate starts at 1.4% in 2005 and increases towards 2.1% in 2020 and remains the same afterwards (Urge-Vorsatz et al., 2012). All new buildings, starting in 2020 are then advanced new. The floor area development in billions m^2 is shown in figure 2.4 for this scenario.

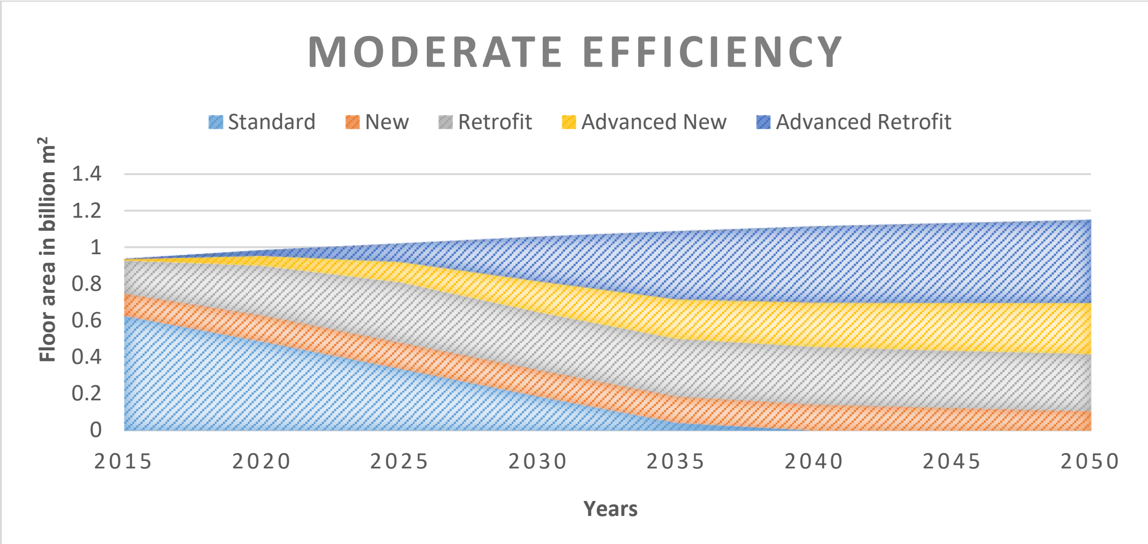


Figure 2.4: The total floor area in billion m^2 in the moderate efficiency scenario for Dutch residential buildings using the 3SCEP HEB data, with timeframe 2015-2050. For every vintage type (standard to advanced retrofit) the floor area development is shown.

Figure 2.4 shows that in the moderate efficiency scenario; standard homes decrease rapidly until 2040 to make room for the increase in advanced retrofit and advanced new homes. The amount of new and retrofit buildings decrease a bit, but remain rather stable over the years.

The *deep efficiency* scenario is based on a large share of homes with low final energy consumption. This scenario is an analysis of the techno-economic energy efficiency potential of operational energy (Urge-Vorsatz et al., 2012). The retrofit rate starts at 1.4% in 2005 and accelerates towards 3% in 2020 (Urge-Vorsatz et al., 2012). Between the years 2012 and 2022 the vintage categories new and retrofit buildings are replaced with advanced retrofit buildings; meaning that instead of building a new home or retrofitting a standard home, a standard home is advanced retrofitted. From 2022 onwards only advanced new and advanced retrofit buildings are added to the building stock. The floor area in billions m^2 projection is shown in figure 2.5 for this scenario.

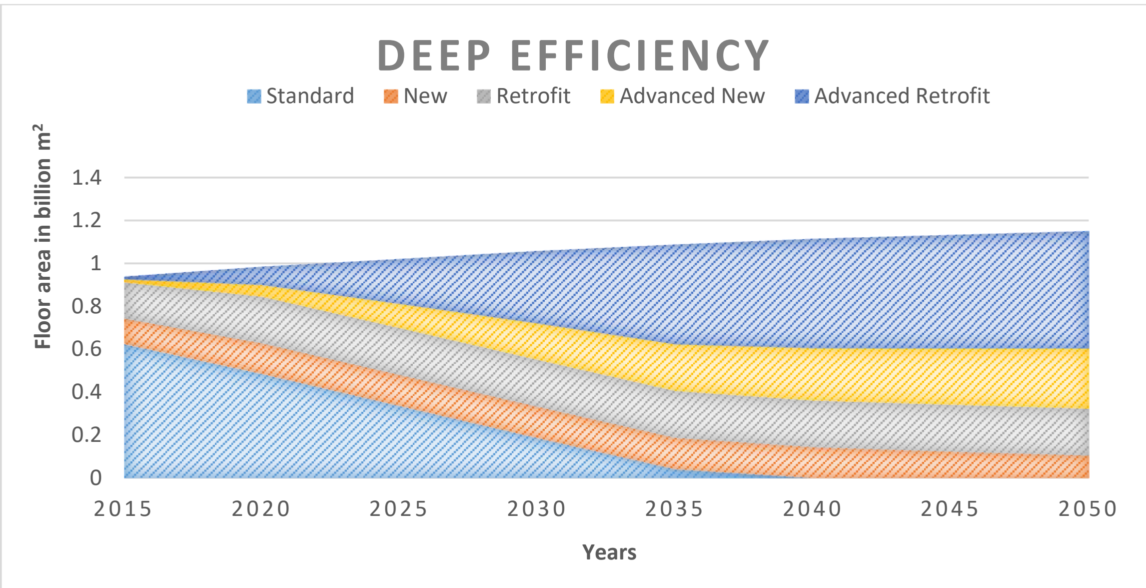


Figure 2.5: The total floor area in billion m^2 in the deep efficiency scenario for Dutch residential buildings using the using the 3SCEP HEB data, with timeframe 2015-2050. For every vintage type (standard to advanced retrofit) the floor area development is shown.

Comparing figure 2.4 and figure 2.5 shows that the largest difference between the moderate- and deep efficiency scenario is that the deep scenario has a much larger advanced retrofit building share, while moderate efficiency has a larger retrofit share.

2.3 Dutch buildings defined

This section explains how the previously mentioned vintages are adapted to the energy performance categories most common in the Netherlands, which building types will be used for this research, and how these types and vintages form the defined building representatives.

2.3.1 Building vintages

Every building vintage is an energy performance representative of an average Dutch home, based on the criteria of the particular vintages explained in section 2.1. The vintages are defined using Dutch building regulations: by using R_c- and U-values that correspond with a particular vintage (see table 2.1)

Table 2.1: R_c and U- values of the five different vintages (RVO, 2011; 2015a-e; SBRCURnet, 2015; Berghuis, 2016)

		Ground floor	**Roof**	**Facade**	**Windows**
Standard	Rc (W/m2K)	0.17	0.86	0.43	
	U (W/m2K)				5.2
New	Rc (W/m2K)	3.5	6	4.5	
	U (W/m2K)				1.3
Retrofit	Rc (W/m2K)	2.5	2	1.3	
	U (W/m2K)				2.2
Advanced New	Rc (W/m2K)	6.5	10	10	
	U (W/m2K)				0.8
Advanced Retrofit	Rc (W/m2K)	6.5	10	10	
	U (W/m2K)				0.8

The Dutch building regulations can be used to determine building requirements in the Netherlands over the years. The U-value shows the degree of insulation of a material. U is determined in W/m^2 K and expresses the amount of heat exchanged per second, per square meter and per degree temperature difference, between the two sides of a wall (Blok, 2009). Thus, the lower the U-value, the higher the degree of insulation. The R_c- value in W/m^2 K is the thermal resistance of a construction. So it is the thermal resistance of all materials used for a construction, added up (equation 2.1). Equation 2.2 shows that the thermal resistance of a material is equal to the thickness of the material in meters (d) divided by the thermal conductivity in W/mK (K). Equation 2.3 shows that the U-value can be calculated by taking the reciprocal of the thermal resistance.

(2.1) $R_c = R_{mat1} + R_{mat2} \dots + R_{insul1} + R_{insul2} + ..$

(2.2) $R = \frac{d}{k}$

(2.3) $U = \frac{1}{R_c}$

Vintage definitions

The *standard* building vintage is based on the building stock in the Netherlands, and defined as: built before 2015 and occur the most in 2015 compared to total building stock. This is the case for homes built in the years 1965-1975 according to CBS (Dutch Central Bureau of Statistics) data (2016a); see figure 2.6. Therefore, the standard vintage represents an average Dutch home that is built according to building regulations set between 1965 and 1975. This is a representation for an average embodied energy use, and an average operational energy use. This typical representation is chosen because it is not possible to differentiate between more than one standard vintage within the timeframe of this research. Furthermore, it is very difficult to find data about used building materials for more than one period; the differences between 10-year periods are expected to be insignificant.

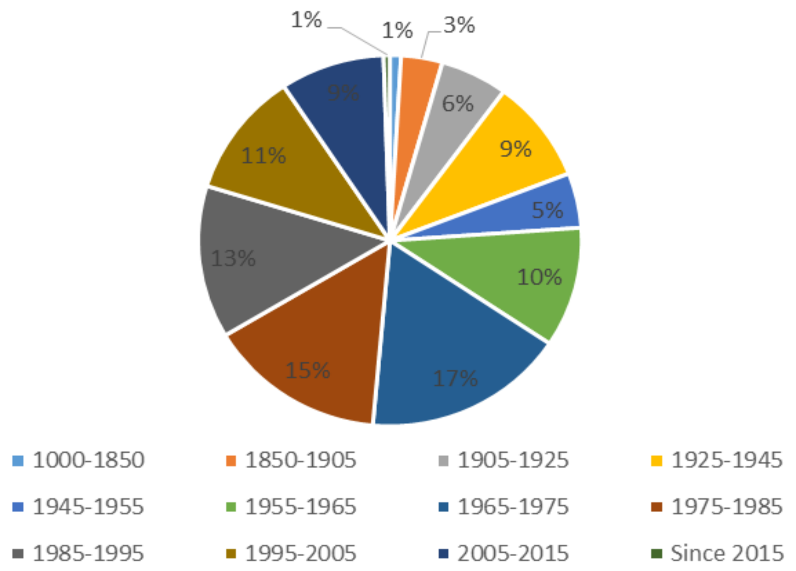


Figure 2.6: Percentage of the Dutch residential building stock in 2016 based on construction year (CBS, 2016a)

The *New* vintage represents an average home that is built according to building regulations set in 2015. The *Retrofit* vintage represent the adjustments necessary to convert a standard home to a more energy efficient home according to standard renovation requirements of the Netherlands Enterprise Agency (RVO). The definition is a 'partially renewal, change or enlargement of a structure' (RVO, 2016b). This vintage depends on the building regulations set in 2015, but for renovations.

Advanced new represents a building with requirements to reach the nZEB standard, which – in the 3SCEP HEB model and in this research - is a passive home. According to the Passive House Institute (PHI, 2015) and with support of the Intelligent Energy Europe (IEE) programme of the European Union (EU), a Passive House (PH) is an ideal basis to define a nZEB. This concept is ideal because it is applicable to all building types, includes high efficiency requirements and has excellent cost-benefit ratios if the lowering of overall energy costs is taken into account. This means that the PH concept fulfils the requirements of the EPBD standard. A PH has a stable indoor climate, where materials and installation equipment are optimized to reduce heat loss (SBRCURnet, 2015). *Passive* means that external heat is gained from solar radiation, and internal heat from light, equipment, machineries and occupants (Proietti et al., 2013). This heat should be sufficient to keep the home at a desired temperature during the period of heating. The most important guidelines are a maximum net energy use for heating of 15 kWh/m^2 per year, and a total primary energy demand of 120 kWh/m^2 per year (SBRCURnet, 2015). A PH consumes about 90% less heating energy than a conventional home, and about 75% less compared with an average European new constructed building (PHI, 2015).

However, based on personal communication with Goossen, C. (December, 6th, 2016) these guidelines are not most important when building a PH. Goossen is director and design manager at BouwQuest; an architecture firm that specializes in integrated design of homes. It seems to be more important to make sure the transmission losses are lower than 10 W/m^2. The lower the transmission losses, the easier it is to keep the temperature at the same level when using a WTW. The space in windows and window frames should never be lower than 17˚C. The usual PH concept is *massive passive*; which means that the building envelope should be one whole without any cracks. Due to the WTW present in a PH, material choice is not that important as long as the building is well insulated.

Advanced Retrofit represents the adjustments necessary to convert a standard home to a home that fits in the PH standards. These standards are more stringent than the current Dutch renovation standards. Considering the fact that the design of a PH is not significantly different from current homes, the energy efficient parts of the PH standard can easily be integrated in existing homes (Proietti et al., 2013).

2.3.2 Building types

According to the CBS (2016b) there are five main building types in the Netherlands. In 2015 42.5% of the Dutch population lived in a terraced home (corner or mid-terrace), 23% in a detached home, 20% in a semi-detached home, and 15% in an apartment. Terraced homes are usually built in rows of six homes, where two of the six homes are end-of terrace. This suggests that from total building stock, 28.3% is mid-terraced and 14.2% is end-of terrace. These types are defined as 'reference buildings' in reports of the Dutch government (Agentschap NL, 2011; 2013 & RVO, 2015a-e), which are developed based on policy requirements for Dutch housing over the years.

To get a complete overview of the Dutch building stock it is important to take all these types into account, even though the current 3SCEP HEB model only differentiates between SF and MF homes. It is expected that every type will differ in operational- and embodied energy use, and therefore all have to be analysed. The Dutch data sources (CBS, RVO, Agentschap NL) consider MF homes to be apartments, porch apartments and gallery homes. And SF homes are defined as detached, semi-detached and terraced homes. However, the 3SCEP HEB model considers terraced homes also to be MF homes. Fortunately, this does not influence the modelling results in this research because the 3SCEP HEB outcomes are used in totals.

A *standard terraced* home usually includes four to five rooms, divided over three floors (Agentschap NL, 2011). The residents are one- and two person households. Insulation measures were not significant around 1965-1975 and windows were single glazed. Interim improvements of these buildings with focus on insulation were measured in 2011. The single glass was replaced with 60% double glass and 18% HR glass. The closed façade was insulated for about 35% by that time, for the floor this was 8%, 17% of the inclined roof and 26% of the flat roof. The user surface on average is 106 m^2 and the amount of residents is on average three. The total primary energy use of a *standard mid-terrace* home is on average 129,904 MJ per year, and for a *standard end-of-terrace* home this is 164,751 MJ.

Since 2015 the EPC requirements became more stringent, which led to improvement of technical installations and the application of insulation measures to reduce energy consumption. Since 2015 the user surface is on average 124.3 m^2 and the primary energy consumption is on average about 26,352 MJ for a *new mid-terrace* home and about 28,340 MJ for a *new end-of-terrace* home per year (RVO, 2015a,b). Figure 2.7 and 2.8 show a sketch of an average Dutch mid-terrace home and end-of-terrace home, respectively.

Figure 2.7: Average Dutch mid-terraced home; front façade, rear, first-, second-, and third floor (Agentschap NL, 2013)

Figure 2.8: Average Dutch end-of-terraced home; front façade, rear, side, first-, second-, and third floor (Agentschap NL, 2013)

A *standard detached* home usually consist of four to six rooms, divided over two to four floors (Agentschap NL, 2011). The residents are usually two person households, with and without children. There is lack of insulation in these traditionally built homes. The improvement of these buildings measured in 2011 led to the replacement of single glass with 69% double glass and 14% HR glass. The closed façade was insulated for about 20% by that time, for the floor this was 15%, 20% of the inclined roof and 32% of the flat roof. The user surface on average is 144 m^2 and the amount of residents is on average three. The total average primary energy use of the *standard detached home* is 225,336 MJ/year.

Since 2015 the average user surface is 169.5 m^2 and the average primary energy consumption is about 39,324 MJ per year (RVO, 2015d). Figure 2.9 shows a sketch of an average Dutch detached home.

Figure 2.9: Average Dutch detached home; front façade, rear, side, first-, second-, and third floor (Agentschap NL, 2013)

A *standard semi-detached* home usually consist of four to five rooms, divided over three floors (Agentschap NL, 2011). The occupation is usually one- and two person households, with and without children. Just as was the case with the other building types; there is lack of insulation. The presence of insulation seems to depend on the construction year. The improvement of these buildings measured in 2011 led to replacement of single glass with 57% double glass and 18% HR glass. The closed façade was insulated for about 33% by that time, for the floor this was 10%, 11% of the inclined roof and 32% of the flat roof. The average primary energy consumption is 183,942 MJ per year. The user surface is on average 123 m^2 and the average amount of residents is three. Since 2015 the average user surface is 147.7 m^2, and the primary energy consumption is on average 33,380 MJ per year (RVO, 2015c). Figure 2.10 shows a sketch of an average Dutch semi-detached home.

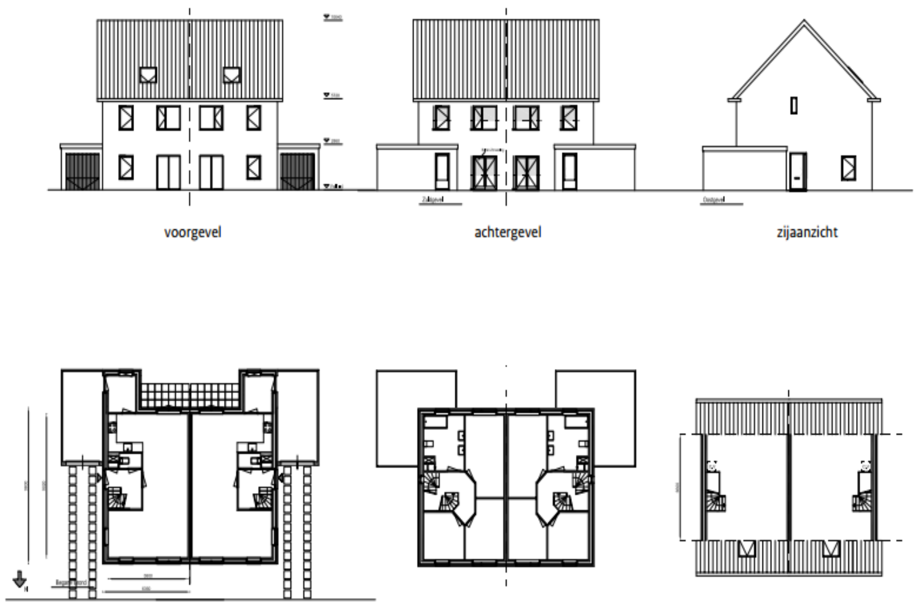


Figure 2.10: Average Dutch semi-detached home; front façade, rear, side, first-, second-, and third floor (Agentschap NL, 2013)

A *standard apartment* has usually two to four rooms and is part of a residential building with multiple floors (Agentschap NL, 2011). The residents are usually one- or two person households without children. Again there was lack of insulation when the building was traditionally built around 1965-1975. The improvement of these buildings measured in 2011 led to the replacement of single glazed windows with 52% double glass and 11% HR glass, and insulation of the closed façade with 12%. The user surface area is on average 77 m^2 and the average amount of residents is 2.8. Total average primary energy use of a *standard apartment* is 80,282 MJ per year. Since 2015 the average user surface is 102.1 m^2 and the yearly primary energy consumption is 21,543 MJ on average (RVO, 2015e). The user surface of the total building is on average 2756.2 m^2 in 2015 with 27 buildings on five different floors. Figure 2.11 shows a sketch of an average Dutch apartment building.

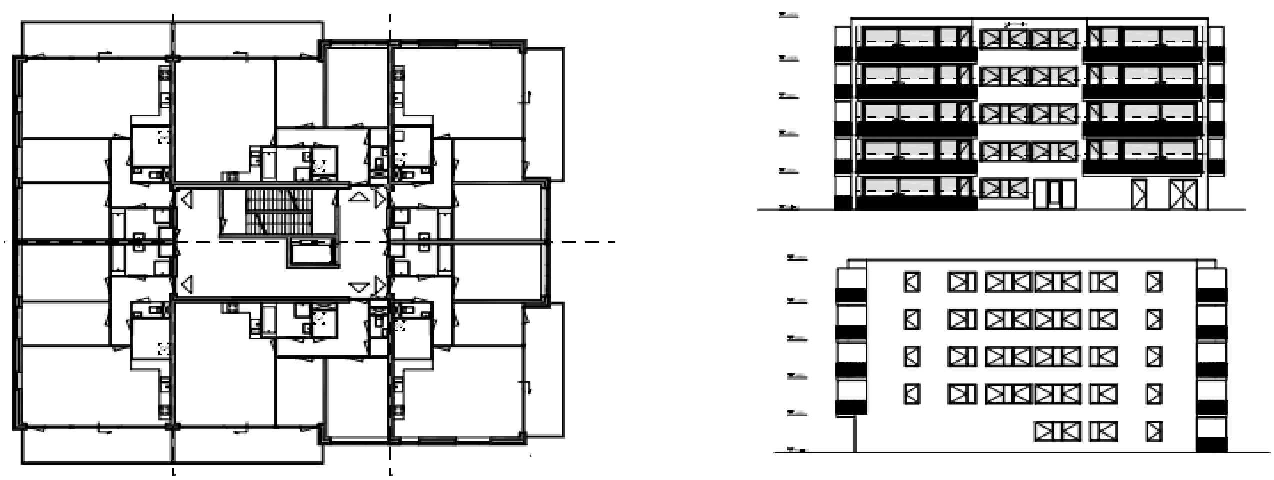


Figure 2.11: Average Dutch apartment building; intersection from above, front façade and rear (Agentschap NL, 2013)

2.3.3 Building representatives

In conclusion, the energy use is analysed for 25 building representatives: five building types multiplied by five building vintages. Table 2.2 shows the building representatives and the labels for these types that will be used throughout the thesis.

Table 2.2: The building representatives in Dutch residential construction and their labels. The representatives are defined using five building types and five building vintages.

	Building representative	**Label**
1	Mid-terrace home: Standard	MT.st
2	Mid-terrace home: New	MT.new
3	Mid-terrace home: Retrofit	MT.ret
4	Mid-terrace home: Advanced New	MT.anew
5	Mid-terrace home: Advanced Retrofit	MT.aret
6	End-of -terrace home: Standard	ET.st
7	End-of -terrace home: New	ET.new
8	End-of -terrace home: Retrofit	ET.ret
9	End-of -terrace home: Advanced New	ET.anew
10	End-of -terrace home: Advanced Retrofit	ET.aret
11	Detached home: Standard	D.st
12	Detached home: New	D.new
13	Detached home: Retrofit	D.ret
14	Detached home: Advanced New	D.anew
15	Detached home: Advanced Retrofit	D.aret
16	Semi-detached home: Standard	SD.st
17	Semi-detached home: New	SD.new
18	Semi-detached home: Retrofit	SD.ret
19	Semi-detached home: Advanced New	SD.anew
20	Semi-detached home: Advanced Retrofit	SD.aret
21	Apartment: Standard	A.st
22	Apartment: New	A.new
23	Apartment: Retrofit	A.ret
24	Apartment: Advanced New	A.anew
25	Apartment: Advanced Retrofit	A.aret

2.4 Energy use

To account for all energy inputs of a building, often Life Cycle Energy Analysis (LCEA) is used (Cabeza et al., 2014). In such an analysis the system boundaries are determined by three main phases: the manufacturing phase, the use phase and the demolition phase (Figure 2.12). The manufacturing phase energy use is referred to as *embodied energy*, and is defined as the energy necessary for the production of the building materials and the energy necessary to transport these materials to the building site. The energy put into the construction and renovation of the building are also included. The energy in the use phase is called the *operational energy*; which is the energy required for every day maintenance and maintaining comfort levels in buildings. This includes the energy for heating and cooling, ventilation, hot water heating, lighting and home appliances. The energy in the demolition phase includes the energy required to demolish the building at the end of its service lifetime and to transport the materials to recycling plants or landfill sites. Note that demolition energy is a part of the building embodied energy, as shown in figure 2.12.

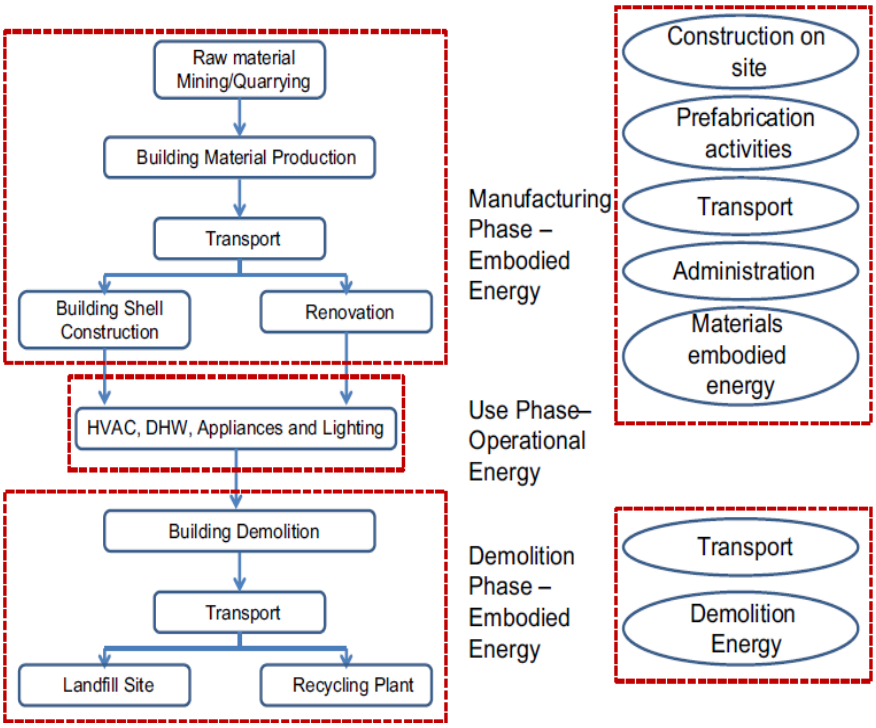


Figure 2.12: Three building energy use phases that represent the life-cycle building energy use (Ramesh et al., 2010; Dixit et al., 2010)

2.4.1 Defined boundaries

Stephan (2013) separates embodied energy in initial- and recurrent embodied energy. The *initial* embodied energy depends on the material choice in the building and the manufacturing processes that were needed to produce the material. Also, energy that is directly in association with this construction process, like the transport of materials to the factory site, is included in the initial embodied energy. *Recurrent* energy applies to the components of the building with a shorter lifetime than the service lifetime of the building. These are for example light bulbs, doors and carpets; these components will be replaced during the lifetime. Considering that recurrent energy is susceptible to consumer preferences - which makes it difficult to include these material choices in an overview of average building materials per building type - is chosen to exclude this energy in this research. Demolition energy is usually part of the embodied energy, but is also part of the end-of-life stage of a building (Weiler, Harter & Eicker, 2017). Therefore, the demolition energy is neglected; to make comparison of the initial embodied energy and operational energy valid. Thus, *embodied energy* in this research is defined as the initial embodied energy plus transportation energy to construction site.

The aim of this research is to compare the energy that is completely dependent on material choice. Varying materials in buildings, can have effect on the building operational energy: the heating and cooling requirements can change because every material has its own heat transmission characteristics (Blok, 2009). Therefore, *operational energy* is defined as the energy required for heating and cooling in Dutch residential buildings.

3. Method

This chapter explains the method used to answer the main research question. The structure is based on sub-question 2 to 4. The first section explains the data collection for the material composition and volumes used in the building representatives. In section 2 the data collection and calculations of embodied energy intensities of the materials, and total embodied energy use per building representative are explained. Section 3 explains the data collection of operational energy use of the building representatives, and section 4 the scenario analysis to model total energy use.

3.1 Material composition and volumes

The DGBC (2016) Materialentool 3.01 is used to determine the basic material characteristics of the building types and vintages. In the Dutch building regulations in 2012 it became mandatory to add an environmental performance calculation to every permit application for new residential buildings and offices with a communal surface area larger than 100 m^2, starting in 2013 (DGBC, 2016). This tool is developed by the DGMR (Engineers and advisors in Construction, Industry, Traffic, Environment and Software). This tool uses the NMD (National Environment Database) of the Netherlands to select the used products and materials. This tool was developed in 2013, but is updated based on current material use about every six months. The DGBC is the largest independent non-profit network organisation which aims to make the built environment more sustainable, in the Netherlands. This tool was recommended by Spoorenberg from OFME; a company that specializes in sustainable building advice in the Netherlands (Spoorenberg, H., personal communication, October 6, 2016). This tool calculates the average basic materials needed, for new Dutch residential buildings, based on building type and gross floor area in m^2.

The DGBC tool shows details of the building structure, the façade, inner walls, floors, roof, technical installations and interior design for two of the Dutch building types: detached and mid-terrace. Considering the fact that (1) interior design is highly dependent on the preference of residents and (2) technical installations are out of the scope of this research, only the building structure, façade, inner walls, floors and roof are analysed further.

The input in this tool is the BVO (Gross floor area). Unfortunately, the reports of the RVO always show the *user surface area* of a building type. The user surface area is the floor area of the space that can be used effectively (only areas that can be heated are included), while the gross floor area also includes stair area, installation space, closed gardens etc. (VROM, 2007). Therefore, based on table 3.1 the user surface area was converted in *gross floor area* (the calculations can be found in appendix A). This table is based on the older Dutch regulations standard NEN2580, because the most current standard NEN7120 did not include these values.

Table 3.1: User surface area with respect to the gross floor area in m² (VROM, 2007)

Terraced	User surface ≈ 0.79 * gross floor area
Detached	User surface ≈ 0.75 * gross floor area
Semidetached	User surface ≈ 0.76 * gross floor area
Apartment	User surface ≈ 0.90 * gross floor area

For every building type specific input values were used and assumptions were made based on the DGBC tool. The user surface in m² is obtained using reports of the Dutch government (Agentschap NL, 2011; RVO, 2015a-e). The standard, retrofit and advanced retrofit vintages are based on the user surface of the types built between 1965-1975. The new and advanced new vintages are based on the surface of new buildings, built since 2015. These floor areas are given in table 3.2.

Table 3.2: User surface per type and vintage in m² (RVO 2011; 2015)

	Standard	New	Retrofit	Advanced New	Advanced Retrofit
Mid-terrace	106	124.3	106	124.3	106
End-of-terrace	106	124.3	106	124.3	106
Detached	144	169.5	144	169.5	144
Semi-detached	123	147.7	123	147.7	123
Apartment	76.7	91.9	76.7	91.9	76.7

3.1.1 Material surface areas

The BVO input in the DGBC tool for *mid-terraced* homes in the new and advanced new vintage is 157.34 m². For *mid-terrace* standard, retrofit and advanced retrofit this is 134.18 m². For *detached* new and advanced new homes a BVO 226 m² of was used. For *detached* standard, retrofit and advanced retrofit the BVO is 192 m². The output is a series of materials, their surface areas in m² and sometimes other characteristics (thickness and R-values). Unfortunately, end-of-terrace homes, semi-detached homes and apartments were not covered by the DGBC tool; therefore assumptions had to be made. An *end-of-terrace* home has the same BVO's as a mid-terrace home. However, assumed is that the most important difference for the embodied energy use between a mid-terrace and end-of-terrace home is the fact that an end-of-terrace home has one house separating wall less, and one façade wall more. Adjustments in the surface areas of materials used for wall construction are made based on this assumption. The same assumption used for the end-of-terrace home applies to a *semi-detached* home. A *semi-detached home* is assumed to have one façade wall more and one house-separating wall less. Also, the BVO of a *semi-detached* home is larger than that of an *end-of-terrace* home. A new and advanced new semi-detached home have a BVO of 194.34 m2, and a BVO of 161.84 m2 for a standard, retrofit and advanced retrofit home.

Apartments are more complicated because a lot of materials and surfaces are shared. As explained in section 2.3.2: an average apartment building consist of 27 homes. To calculate the material surface of the foundation structure of an apartments building, the input in the DGBC tool was a BVO of 2757 m² for the new and advanced new vintage, and 2300 m² for the standard, retrofit and advanced retrofit vintage. This is the only part that is directly calculated by the tool and divided by 27 to get the outcome for an average apartment. The other building parts and their materials are determined using the tool outcomes of a mid-terraced home, and comparing these by using the ratio of the BVO size of an apartment relatively to the BVO size of a mid-terrace home. This was considered the best approach because the BVO size determined the material surface areas of the other types, and should be taken into account for apartments as well. Furthermore, the DGBC tool is the most detailed source found of material surface areas in all building types.

The data outcomes generated by the DGBC tool were not always sufficient. The following adjustments to material surfaces were necessary:

- The pole width in the foundation structure is given in diameter, therefore assumed is that the pole volume can be calculated using the standard volume equation for a cylinder. Here the $radius^2$ is 'thickness' and is equal to 0.4 m.
- Measurements of doors were not given in the tool, therefore standard measurements of 2.015 m^2 surface and 0.63 m thickness for the standard vintage and 2.315 m^2 surface and 0.93 m thickness for the new vintage are used (Skantrae, 2017).
- Only the length and diameter of the water drains are given in the tool. Thus, the surface area of the drain cloak is calculated by using the standard equation for a cylinder where $radius$ is 0.04 m.
- Only the length of the gutters is given in the tool. Thus, the surface area of the gutter cloak was calculated using the standard user surface equation for a cylinder where $radius$ is 0.042 m. The outcome is divided by two because a gutter is assumed to be about half of a cylinder.

3.2.2 Material thicknesses

The DGBC tool also generated data for material thicknesses. Unfortunately, this data was missing for some materials. Therefore, the first source used to complete the data was SBRCURnet, which provides details of standards in the Dutch construction industry. SBRCURnet is an independent agency with the focus on increasing building knowledge in the Netherlands (SBRCURnet, 2017a). Together with external building companies and professionals in GWW (Soil- road and water building) they collect building specific knowledge. This knowledge is captured in 'standards', and one of these standards are the reference details used in this research. The SBR reference details include drawings, recommendations and building physical parameters like thickness of materials (SBRCURnet, 2017b). The SBR reference details are used to differentiate between the vintages as well. These details are available in several categories: new standards, renovation standards, passive new standards and passive retrofit standards. Thus, every vintage is included except the standard vintage. The details for this vintage are derived from the renovation details by checking the thicknesses of materials before renovation. The specific SBR reference details were chosen for the R_c- values of the vintage in question, mentioned in section 2.3.1.

These carefully chosen SBR reference details can be found in appendix B. The assumptions derived from the SBR reference details are shown in table 3.3.

Table 3.3: Assumptions derived from the SBR reference details in appendix B

Appendix	Detail	Assumptions
B.1 – new	a	• mineral wool of 140 mm thick is applied in the façade • the upper screed is 60 mm thick • the cantilevered hollow core slab floor is 200 mm thick • the floor insulation is EPS of 120 mm thick • it confirms that the inner and outer leaf of the façade wall is 100 mm thick
	b	• the window frames are 62 mm thick
	c	• the roof insulation is mineral wool of 270 mm thick
B.2 – retrofit	a	• insulation applied after construction in façade walls is mineral wool of 50 mm thick • insulation applied after construction in cantilevered floors is PUR foam of 100 mm thick
	b	• insulation applied after construction in roofs is mineral wool of 100 mm thick
B.3 – advanced new	a	• the cantilevered foundation floor is insulated on all sides using an EPS insulation box • the façade wall consists of facade siding of 19 mm thick, wood fibreboard of 20 mm thick, and mineral wool of 350 mm + 50 mm thick • the cantilevered hollow core slab floor is insulated with XPS of 180 mm thick
	b	• the door is insulated with PUR of 30 mm thick
B.4 – advanced retrofit	a	• insulation applied after construction in façade walls is mineral wool of 270 + 30 mm thick • insulation applied after construction in the foundation cantilevered floor is EPS of 240 mm thick • insulation applied after construction in cantilevered floors is mineral wool of 240 mm thick
	b	• insulation applied after construction in roofs is PUR of 275 mm thick

When DGBC and SBRCURnet data was not sufficient, this was mended with additional literature- and internet sources. These additional sources and other relevant assumptions are listed below:

- The amount of doors a building type has was based on the basic appearance of the type, sketches of the appearances were introduced in section 2.3.2. This is assumed to be 2 façade doors in all types. The amount of inside doors in the building types are: mid-and-end-of-terraced 11, detached 14, semi-detached 12 and apartments 7.
- HR glazed windows are given in the DGBC tool (11 mm). Single glazed windows are 6 mm thick and the thickness of argon filled space in HR ++ windows is 13 mm (Bosschaert, 2009).
- Ceramic floor and wall tiles are assumed to be 10 mm (Veronove, 2017).
- Concrete roof tiles are assumed to be 21 mm (Monier, 2016)
- Gutter thickness is assumed to be 203 mm (zinkbouwmarkt.nl, 2017)

For the standard, retrofit and advanced retrofit vintage matters were more complicated. To obtain data of average material use during the years 1965-1975 for all building types, interviews were held with experts in building construction. Unfortunately, it appeared that building companies and building consultants (Heijlijgers Bouw bv and Buildsight) found it hard to give an average material use, because in their opinion: every home is different (personal communication: van Eekert, M., July 12, 2016; van Swam, F., September 21, 2016;

Broekhuizen, H., September 29, 2016). Therefore, the information gained from the interviews is mended with other literature- and internet sources shown in table 3.4. This table lists the assumptions of the main differences between the standard and new vintage.

Table 3.4: Assumptions about the difference between the standard and new vintages and their sources.

Assumption	Source
New buildings have a foundation structure with wooden poles, while standard homes have concrete poles.	• DGBC (2016) • Gemeente Rotterdam (2017)
Window frames and façade doors consist of aluminium in the new vintage, while these are made of softwood in the standard vintage.	• DGBC (2016) • Gemeente Rotterdam (2017)
Internal walls are made of aerated concrete in the new vintage, while this is gypsum in the standard vintage.	• DGBC (2016) • Gemeente Rotterdam (2017) • p.c. Broekhuizen, H. (29-09-2016)
In the new vintage often hollow core slab cantilevered floors are applied; while in the standard vintage it is common to find a 'kwaaitaal' floor on the ground floor and wide slab floors on the higher floors, particularly in apartments. All three floors are made of precast concrete, with reinforcement at the ground floor.	• DGBC (2016) • Liebregts & Persoon (2011) • p.c. Broekhuizen, H. (29-09-2016) • SBR Reference details appendix B
In the standard vintage there was no (significant amount of) insulation applied in all building parts.	• Agentschap NL (2011)

As mentioned in section 2.3.1: the U-value of the window glazing for the standard vintage is 5.2 W/m^{2}K, for the new vintage 1.3 W/m^{2}K, for the retrofit vintage 2.2 Wm^{2}K, and for advanced new/retrofit 0.8 Wm^{2}K. Using these U-values and table 3.4, the window glass types are determined.

Table 3.4: Type of glass according to U-value (Tremco Illbruck, 2017)

Glass type	U-value
Single glazed	5,7 W/m^{2}K
Double glazed	± 3 W/mK^2
HR glazed	1,6 - 2,0 W/m^{2}K
HR+ glazed	1,2 - 1,6 W/m^{2}K
HR++ glazed	< 1,2 W/m^{2}K

The assumptions for window glazing types are as follows:

- the windows in the standard vintage are on average single glazed
- the windows in the new and retrofit vintage are on average HR glazed
- the windows in the advanced new/retrofit vintage are on average HR ++ glazed

To finally calculate the material volumes in m^3 for every type, simply the material surfaces in m^2 were multiplied with the corresponding thickness in m, and summed per type. In appendix C the detailed overview of the material characteristics for every building representative can be found - within the categories structure, façade, inside walls, floors and roof - including; material type, its surface in m^2, thickness in m and the corresponding volume in m^3. This data can also be found in the EEDMS.

3.2 Energy use

3.2.1 Materials

Every building material included in this research is explained shortly in this section. Some materials are described more detailed than others, because details specific for the Netherlands, were not always available.

Concrete

Concrete is a mixture of cement, sand, water and aggregates (Goggins, Keane & Kelly, 2010). When concrete is reinforced, steel is added to the concrete to deal with high pressures. The addition of steel increases the embodied energy intensity of concrete with about 1.04 MJ/kg (Circular Ecology, 2011). The cantilevered floors in Dutch residential buildings (all representatives) consist of *reinforced concrete* with a strength of 30/37 MPa (DGBC, 2016). The embodied energy intensity is based on reinforced concrete with a strength of 32/40 MPa in the ICE database, because this came closest to the value of 30/37 MPa. This type of concrete is also used in house separating walls. *Precast (prefabricated) concrete* is used in all the analysed parts of the building; foundation structure, façade, inside walls, floors and roof. This type of concrete increases the average embodied energy intensity of virgin concrete with 0.45 MJ/kg (Circular Ecology, 2011).

Aerated concrete is a light material produced from limestone, cement and sand (Xella Group, 2017). This type of concrete has a large amount of closed cells that contain air, which makes it possible to use this type of concrete for numerous construction opportunities. This air in combination with concrete makes the aerated concrete blocks a significant thermal insulator. In this research the aerated concrete is in the shape of blocks (Xella-Ytong is used in the DGBC tool), used in the inside walls of the new and advanced new vintage in all building types.

Wood

Wood is used in all Dutch building representatives. In the new and advanced new buildings, poles of *hardwood* are used in the foundation structure. *Softwood* is – in contrast to hardwood – often used if the construction is non-bearing (Centrum Hout, 2005). It is used in doors and window frames in the standard vintage, and in the pitched roof of all vintages. *Plywood* (multiplex) is a composite material of wooden plates that consist of several layers of thin veneer and is often used for doors and floor coverings (Bot, 2009). In this research plywood is used for inside doors, floor coverings and flat roofs of all vintages. The softwood and plywood used, are both European wood from sustainable forestry (DGBC, 2016).

Insulation materials

Insulation materials are used to reduce heat flow between walls and rooms, to increase the energy efficiency of a home. The typical K-value defines the degree of insulation (heat transmission) of the material. These values vary with mass density, temperature and moisture content (Bjørn Petter, 2011).

Expanded Polystyrene (EPS) is an insulation material made from crude oil (small spheres of polystyrene) that contains an expansion agent, which expands when heated (Bjørn Petter, 2011). Typical K-values of this material are between 30 and 40 W/mK, with 36 W/mK at 0%

moisture content. This material is often used to insulate cantilevered floors in Dutch residential buildings.

Extruded Polystyrene (XPS) is also produced from crude oil, but from melted polystyrene (instead of using the small spheres of polystyrene) by adding an expansion gas (Bjørn Petter, 2011). The structure is that of closed pores, while EPS has a partly open structure. The typical K-value of XPS is the same as that of EPS. However, the thermal conductivity of XPS starts lower (34 W/mK at 0% moisture content) than that of EPS. This material is often used to insulate cantilevered floors in Dutch residential advanced new buildings.

Mineral wool is the collective name for glass wool and rock wool, which can be produced in boards, mats and as filling material (Bjørn Petter, 2011). The soft and light variants of mineral wool are applied in the framework of homes and in structures that have cavities. Mineral wool boards with higher mass densities are applied when the insulation has to carry loads, like in roofs and floors. Glass wool is a product of borosilicate glass and rock wool of melted stone. Oil and phenolic resin is added in both cases to bind the fibres together and improve the properties of the product. Typical K-values are between 30 and 40 W/mK, with 37 W/mK at 0% moisture content.

Polyurethane (PUR) is formed in a chemical reaction between polyols and isocyanates (Bjørn Petter, 2011). PUR can be used as board and as an expanding foam. The foam is used to fill cavities and to seal around doors and windows. In this research, PUR boards are used in roofs of advanced new/retrofit buildings and PUR foam in floors of retrofit buildings. The K-values are typically between 20 and 30 W/mK, with 25 W/mK at 0% moisture content. This value is significantly lower than that of the insulation materials mentioned until now.

Others

Aluminium is recovered from bauxite in an open-pit mine and processed locally (Worrell et al., 1994). Aluminium is a lightweight material, has high strength and is easy to recycle; it is the most widely used material in the world after iron (Moors, 2006). This material is commonly applied in building construction and vehicles. In this research, aluminium is used in doors and window frames of new and advanced new buildings of all building types. Recycling of aluminium is applied on large scale in Europe; the recycling rates are about 85% in the building sector (Moors, 2006). Furthermore, the aluminium used in the DGBC tool is VMRG aluminium, which is 47% recycled. The embodied energy intensity value chosen in this research depends on this share of recycled material.

Primary glass is used in all windows, its volume amount differs per type and vintage. *Argon* is a colourless noble gas used in HR++ glass windows. Filling of the window gaps with argon leads to a higher insulation value, compared to the usual filling with air (Arasteh, Selkowitz & Wolf, 1989). This gas is included in this research to differentiate between the embodied energy intensity of single glazed, double glazed, HR glazed and HR++ glazed windows.

Bitumen is a viscous fluid recovered from crude oil. About 85% of all bitumen that is produced, is used in the production of asphalt (Geertsma, 2014). About 10% of the production of bitumen is used for roof covering. This material is very suitable for roofing because of its waterproofing qualities. In this research, bitumen is used for roof covering of all building representatives. *Gravel* is used as a finish on the roof.

The outer leaf of the masonry walls of the new, standard and retrofit homes consist of *clay brick*. This type of brick is commonly used in the construction of buildings (Venkatarama Reddy & Jagadish, 2005). In the Netherlands, such walls are made out of river clay gained from the floodplains of the big Dutch rivers since the beginning of the 90's (KNB, 2013). This clay is then mixed with additives like sand, and then casted and dried (Worrell et al., 1994). The inside walls of standard, retrofit and advanced retrofit homes consist of *gypsum blocks* (Gemeente Rotterdam, 2017). This is a mineral that almost entirely consist of calcium sulphate. The material *Ceramics* is defined as a wall or floor finish in this research. The material is produced when two materials are heated, sometimes under pressure (CvAE, 2017). Examples are porcelain and vitrified clay.

Sand is used as a soil supplement in the foundation structure. S*and cement* is a mixture of sand, cement and aggregates, and is used as screed in all building representatives (Circular Ecology, 2011). *Polyvinylchloride (PVC)* is a plastic used for rainwater drains and the gutters are made of the metal *zinc*. Both occur in all building representatives.

3.2.2 Embodied energy intensities

To get the initial embodied energy intensities, the Inventory of Carbon and Energy (ICE) (Circular Ecology, 2011) was used as a leading database. This database contains estimates of embodied energy intensities of about 200 materials, where the intensities are determined from cradle to gate. The definition of cradle to gate according to the database builders is '*All activities starting with the extraction of materials from the earth (the cradle), their transportation, refining, processing and fabrication activities until the material or product is ready to leave the factory gate'* (Circular Ecology, 2016). The intensities are given in MJ/kg, thus multiplying it with the corresponding material density in kg/m^3 will give the desired initial embodied energy intensity (IEEI) in MJ/m^3. This database includes a discussion of the data sources that were used to define the embodied energy intensities. This increases the reliability of the data collected.

The downstream processes (transportation to site and storage areas) are not included in this database. Therefore, transport energy to the construction site is estimated using a report of the CE Delft ((Bijleveld, Bergsma, Krutwagen, & Afman, 2015). CE delft is an independent consultancy and research agency, specialized in developing solutions for sustainability issues (CE Delft, 2016). The average transport distance of a load of building materials in the Netherlands from factory to site (including import of materials from other countries used in the Dutch construction industry) is key to calculating the transport embodied energy intensity in MJ/m^3. The two main transport vehicles for building materials in the Netherlands are truck and ship, and therefore both are included.

The following equations are used to calculate the transport embodied energy intensity (TEEI):

(3.1)

$$TEEI\ (\frac{MJ}{kg}) = \frac{\left(avg\ fuel\ use\left(\frac{L}{km}\right) * avg\ transport\ distance\ (km)\right) * \ energy\ content\ fuel\ \left(\frac{MJ}{L}\right)}{avg\ load\ (kg)}$$

(3.2)

$$WA\ TEEI\ building\ material\ \left(\frac{MJ}{kg}\right) = \left(TEEI\ road\ transport\ \left(\frac{MJ}{kg}\right) *\ share\ transported\ by\ truck\right) + \left(TEEI\ ship\ transport\ \left(\frac{MJ}{kg}\right) * share\ transported\ by\ ship\right)$$

The TEEI is calculated for road and ship transport separately by using equation 3.1. The average fuel used by trucks in the Netherlands is diesel, with an average usage of 0.32 L/km (IRU, 2009). The average transport distance by truck estimated for an average building material in the Netherlands, including import from other countries, is 96 km (Bijleveld et al., 2015). The energy content of diesel is 36 MJ/L (Blok, 2009). The maximum average truck load is 40 tons (RDW, 2012). Thus, filling in these variables in equation 3.1 leads to a TEEI of road transport in the Netherlands of 0.028 MJ/kg.

The fuel used in material transport by ship is also diesel, thus the same energy content is applicable as for road transport. Specific diesel oil usage of an inland ship is 6500 L/km (Backer van Ommeren, 2011). The average transport distance for average freight (average building material was unfortunately not available) in the Netherlands by ship, including import from other countries, is 123 km (Bijleveld et al., 2015). The average maximum ship load in the Netherlands is 1200 tons (EICB, 2017). Thus, filling in these variables in equation 3.1 leads to a TEEI of ship transport in the Netherlands of 0.21 MJ/kg.

Next, equation 3.2 is used to calculate the weighted average transport embodied energy intensity (WATEEI) per unit of building material. The share of building materials in the Netherlands, transported by truck is 72% and transported by ship is 28% (Bijleveld et al., 2015). This leads to a weighted total TEEI of 0.08 MJ/kg for every material when not accounting for density.

Table 3.5 shows the 23 materials most often used in the Netherlands, their labels that will be used throughout this thesis, their initial embodied energy Intensity (IEEI) in MJ/kg, the total embodied energy intensity (Total EEI[3]) (which is the IEEI and WATEEI added up), and the corresponding density in kg/m^3. The table is sorted by total EEI: from highest intensity to lowest.

[3] **Note** that TEEI is transport embodied energy intensity and Total EEI total embodied energy intensity.

Table 3.5: Most common Dutch residential building materials, their labels, initial embodied energy intensity (IEEI), total embodied energy intensity (Total EEI) and density; sorted by total EEI from high to low.

Material name	**Label**	**IEEI (MJ/kg)**	**Total EEI (MJ/kg)**	**Density (kg/m^3)**
Aluminium	Al	108.6	108.68	2700
Polyurethane foam	PUR	101.5	101.58	45
Expanded polystyrene	EPS	88.6	88.68	27.5
Extruded polystyrene	XPS	87.4	87.48	37.5
Polyvinylchloride	PVC	67.5	67.58	1380
Zinc	Zi	53.1	53.18	7000
Bitumen	Bi	51	51.08	2400
Mineral wool	MW	16.6	16.68	140
Wood fibre	WF	16	16.08	750
Plywood	Pl	15	15.08	540
Primary glass	PG	15	15.08	2500
Ceramics	Ce	12	12.08	2000
Hardwood	HW	10.4	10.48	750
Softwood	SW	7.4	7.48	560
Argon	Ar	6.8	6.88	1.66
Aerated concrete	AC	3.5	3.58	750
Gypsum plaster	Gy	3.48	3.56	1120
Brick, clay	Br	3	3.08	1700
Reinforced concrete	RC	2.07	2.15	2300
Precast concrete	PC	1.27	1.35	2200
Sand cement	SC	0.99	1.07	2200
Gravel	Gr	0.083	0.16	2240
Sand	Sa	0.0081	0.01	2240

3.2.3 Embodied energy use

The first part of the Embodied Energy Database Management System (EEDMS) was created using the data described in the previous sections. The inputs are the IEEI, the WATEEI, the material densities, and the material surfaces and thicknesses (which define the material volumes) in all building representatives. The detailed explanation of this model and how to use it can be found in appendix D.

For every building type representative the materials are identified. For every material its volume, density, IEEI and WATEEI are included in the EEDMS. Then equation 3.3 is used (in the model) to sum up the embodied energy outcomes for every material that occurs in a building representative.

(3.3) $$Total\ EEU\ building\ representative\ (MJ) = \sum \left(EEI_x \left(\frac{MJ}{kg}\right) * density\ material_x \left(\frac{kg}{m3}\right) * volume\ material_x\ (m3) \right)$$

Equation 3.3 calculates the total Embodied Energy Use (EEU) of a building representative by multiplying the total embodied energy intensity (Total EEI) of the material (x stands for one of the 23 materials shown in table 3.5) with its corresponding density and specific volume. To make sure the building representatives can be compared, the outcome of equation 3.3 for every type is divided by the corresponding floor area in m^2, which leads to the total embodied energy in MJ/m^2. This floor area is the *user surface area* mentioned in section 3.1. The reason for using this instead of the BVO is because most of the Dutch data and reports (Agentschap NL, RVO, CBS) use the *user surface area* too, which makes comparison with these sources easier. This outcome is divided by building lifetime to make sure comparison with operational energy in MJ/m^2/year is valid. Figure 3.1 illustrates this.

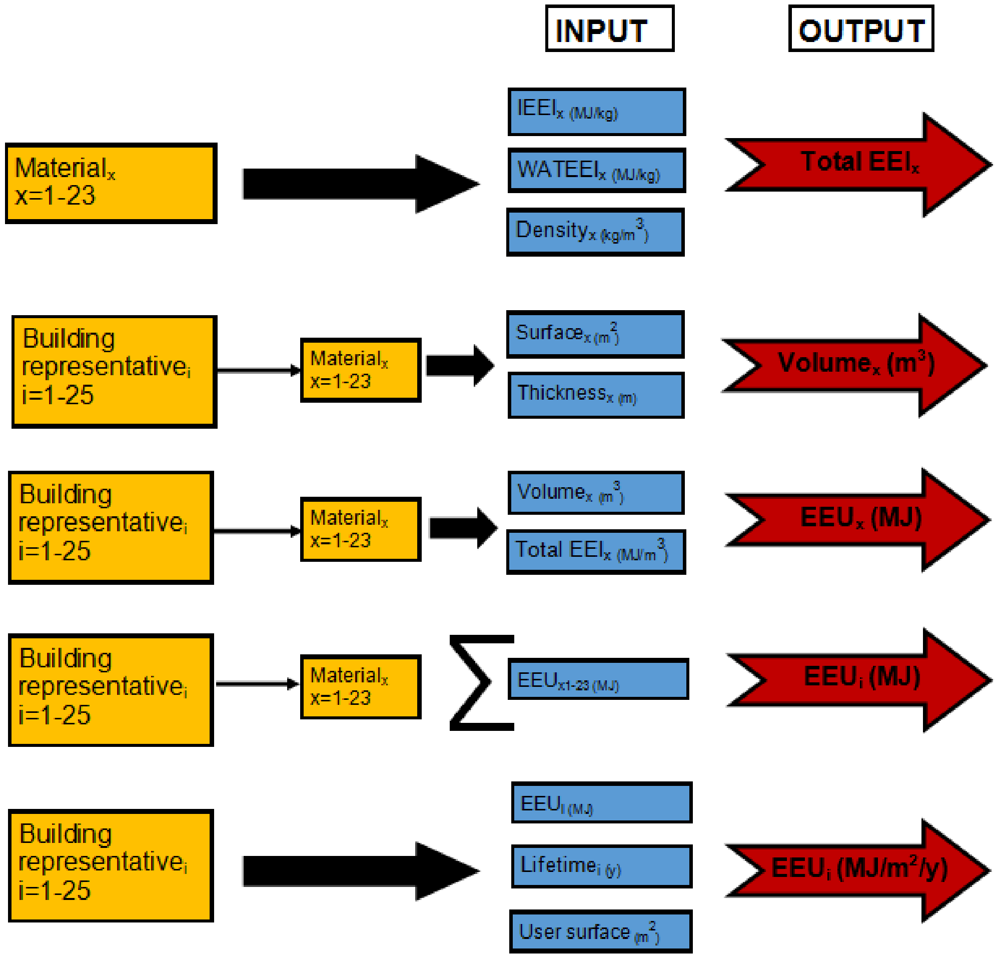


Figure 3.1: Illustration of the method used to calculate embodied energy use in MJ/m^2/y per building representative i (1 to 25), by inserting the corresponding material x (1 to 23). IEEI is initial embodied energy intensity, WATEEI is the weighted average transport embodied energy intensity, Total EEI is the total embodied energy intensity per material and EEU is the total embodied energy use.

Building lifetime

The building stock in the Netherlands is continuously changing: buildings are demolished, but are also adapted to the current needs of the Dutch population and can live for centuries. Statistics show that on average, 97% of the residential buildings reach a lifetime of 50 years, 77% a lifetime of 75 years and 57% a lifetime of 100 years (SEV, 2004). However, when differentiating between SF and MF homes: only 30% of the MF homes reach a lifetime of 100 years, while this is 80% in SF homes. Taking a weighted average of the building lifetime based on these statistics leads to an average lifetime of SF homes of 73.3 years, and for MF homes of 66.8 years. In the 3SCEP HEB model is assumed that a building life cycle of 30 years corresponds with a retrofit rate of 3.3% per year (Urge-Vorsatz et al., 2013). This implies that the retrofit rate used in this research of 1.4% corresponds with a building life cycle of about 71 years. Thus an average of 73.3 for SF and 66.8 for MF seems reasonable.

This building life time is used to calculate the yearly embodied energy. Therefore, it is important to differentiate between retrofitted and non-retrofitted homes. A simple renovation often increases the lifetime with 15 years (Timmermans, 2014). Therefore, the lifetime included in the EEDMS is; for *retrofit* and *advanced retrofit* SF homes 73.3 years; and for MF homes 66.8 years. For *standard, new* and *advanced new*: 73.3-15= 58.3 years for SF homes and 66.8-15= 51.8 years for MF homes. Even though Goossen, C. (personal communication, December 12, 2016) was sure that passive homes (advanced new and advanced retrofit) can reach a lifetime of about 100 years because the moisture and condensation issues in the materials are minimal, unfortunately no scientific proof was found that this was indeed the case. Therefore, this longer lifetime is not taken into account in the EEDMS, but a variation in building lifetimes is included in the sensitivity analysis in section 4.3.

3.2.4 Operational energy use

The operational energy intensities are based on the required heating and cooling amount in Dutch residential buildings in kWh/m^2/year obtained from the TABULA web tool. In April 2013 the European project EPISCOPE (Energy Performance Indicator Tracking Schemes for the Continuous Optimisation of Refurbishment Processes in European Housing Stocks) was launched as a follow up project TABULA (Typology Approach for Building Stock Energy Assessment) (Institute Wohnen und Umwelt GmBH, 2016). Both projects are part of the IEE Program of the EU. The TABULA project developed residential building typologies for 13 countries in Europe. The EPISCOPE project used this TABULA concept and extended it including building stock models for the assessment of refurbishment processes and to project the future energy consumption. The energy performance of the building types is calculated using a TABULA reference calculation method; these calculations can be retrieved in charts of the specific building type, which increases the reliability of the source . Furthermore, this data is available for all building types and vintages, which is very convenient for this research. For the Netherlands this data is collected by TU Delft (2015).

Considering there is not much cooling necessary in the Netherlands, the data only includes heating demand. The TABULA heating data is given in primary energy terms, and is shown in table 3.6, sorted by the building representative with the highest operational energy to the lowest. This data is converted into MJ/m^2/year to make comparison valid with the embodied energy use in MJ/m^2/year.

Table 3.6: Operational energy intensities in common Dutch residential building types and vintages (TU Delft, 2015)

Type	**Operational energy (kWh/m^2/y)**
D.st	189.5
ET.st	174
SD.st	173
MT.st	153
A.st	133
D.ret	96
ET.ret	92
SD.ret	91
MT.ret	87
A.ret	81
D.new	62
ET.new	58
SD.new	55
MT.new	52.5
D.aret	51.8
A.new	51
ET.aret	46.8
SD.aret	46.2
MT.aret	41.2
D.anew	39.8
ET.anew	37.5
A.aret	37
SD.anew	36.4
MT.anew	34.9
A.anew	34.4

3.3 Scenario analysis

To calculate the total floor area growth in Dutch residential construction over the years 2015-2050 the 3SCEP HEB model was used. The floor area input data is rather simple; the population development over the years 2015-2050 is multiplied with the average floor area in m^2 per person. The data in the current model is updated; the changes in the model are shown in table 3.7.

Table 3.7: Data changes in the 3SCEP HEB model.

Old data	New data	New data source
Forecasted population between 2005-2015 in the Netherlands	Observed population development in the Netherlands between 2005 and 2015	• Ministry of Internal Affairs and Kingdom relations (2016) • CBS (2017)
Forecasted population between 2016-2050 in the Netherlands	Forecasted population between 2016-2050 based on Dutch forecasts	• Ministry of Internal Affairs and Kingdom relations (2016)
European average demolition rate (0.5%)	Demolition rate specifically calculated for the Netherlands (0.16%)	• Ministry of Internal Affairs and Kingdom relations (2016)
European average new construction rate (0.5-1%)	New construction rate specifically calculated for the Netherlands (0.64%)	• Ministry of Internal Affairs and Kingdom relations (2016)
Average floor area per person for OECD countries (43.41 m^2)	Average residential floor area per person in the Netherlands (56.94 m^2)	• Agentschap NL (2011) • RVO (2015a-e)

The new data in table 3.7 is further explained in this section. The forecasted population data in the Netherlands is based on abf Research data. abf Research consist of experts in statistical analysis and quantitative research, and deliver reports concerning statistical developments in the residential sector to the Ministry of Internal Affairs and Kingdom relations (abf Research, 2016). The fact that this Ministry uses this data, increases the reliability of the source. The population development data (2005-2050) is shown in figure 3.1. The population is expected to grow with about 7% until 2050, relative to 2015.

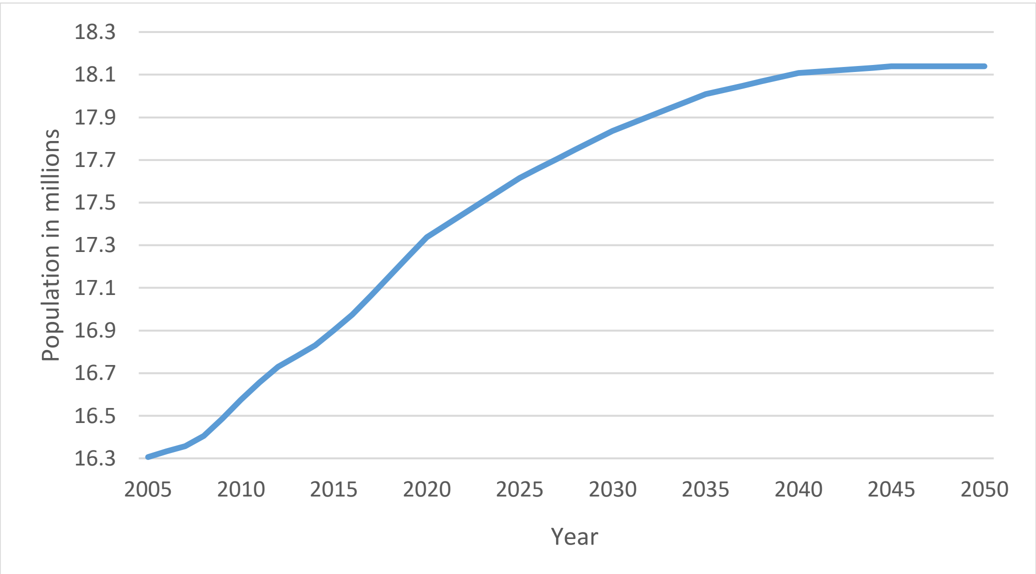


Figure 3.1: Population development prediction in the Netherlands (CBS, 2017; Ministry of Internal Affairs and Kingdom relations, 2016)

The demolition rate is the percentage of residential buildings that are demolished every year in the Netherlands and the new construction rate is the percentage of buildings that are newly constructed annually. The specific data used to calculate the new construction and demolition rate are shown in table 3.8 and 3.9. The model calculates the amount of new buildings constructed yearly, based on the new construction rate and the population growth. Demolition rates in the Netherlands appear to be quite low, considering the demolition rates used in the 3SCEP HEB model vary between 0.3 and 1%, with for EU regions on average 0.5%.

Table 3.8: New construction rate Dutch residential buildings (Ministry of Internal Affairs and Kingdom relations, 2016)

Year	Total building amount	Total new built	New construction rate
2012	7386700	48.700	0.664%
2013	7449300	49.300	0.666%
2014	7535300	45.200	0.603%
2015	7588000	47.900	0.635%
		Average	**0.642%**

Table 3.9: Demolition rate Dutch residential buildings (Ministry of Internal Affairs and Kingdom relations, 2016)

Year	Total building amount	Total demolished	Demolition rate
2012	7386700	13700	-0.185%
2013	7449300	12900	-0.173%
2014	7535300	11000	-0.146%
2015	7588000	11300	-0.149%
		Average	**-0.163%**

The retrofit rate is kept as it is in the current model on 1.4%. The reason for this is that there is no data about the amount of homes renovated every year in the Netherlands, and to what extent. The retrofit rate of 1.4% is seen as a normal retrofit rate in developed countries (Urge-Vorsatz et al., 2012). Furthermore, according to Meijer et al. (2009) the retrofit rate is twice the new construction rate. When assuming this, if the new construction rate in the Netherlands is 0.64%, the retrofit rate should be about 1.3%. Hence, a retrofit rate of 1.4% is plausible.

It was not clear where the average floor area per person data, that was used in the model, came from. Therefore, own calculations were conducted to make sure this data was significant. First of all, a weighted average of the floor area's (WAFA) in the building types and vintages was determined based on the occurrence of the building types amongst all Dutch residential buildings. These shares of occurrence are shown in percentages in table 3.10.

Table 3.10: Shares of occurrence (shown in % of Dutch residential building types (CBS, 2016b)

Mid-terrace	28.3%
End-of-terrace	14.2%
Detached	23.0%
Semidetached	20.0%
Apartment	15.0%

The WAFA per building is 127.81 m^2. Then equation 3.4 was used to calculate the floor area per person in m^2. In this equation, the total building amount in year x (2012-2015) is multiplied with the WAFA (which gives the total floor area) and divided by the total population amount in the Netherlands in that particular year. Finally, an average for the years 2012-2015 was derived, which leads to an average floor area in m^2 per resident of 56.94 (see table 3.11)

(3.4)

$$Floor\ area\ per\ resident\ in\ year_x\ (m2) = \frac{WAFA * total\ building\ amount\ year_x}{population\ year_x}$$

Table 3.11: Floor area per resident in m^2 for Dutch residential buildings (Ministry of Internal Affairs and Kingdom relations, 2016)

Year	**Building amount**	**Total floor area in m^2**	**Floor area per resident in m^2**
2012	7386700	944086740	56.43
2013	7449300	952087584	56.74
2014	7535300	963079158	57.22
2015	7588000	969814692	57.38
		Average	**56.94**

The model assumes that floor area per person will not change until 2050, thus, the same is assumed in this research.

Some other small adjustments were necessary in the scenario rules. In the deep efficiency scenario, the transition period wherein advanced buildings were proliferating widely, is changed from 2012-2022 to 2018-2028. This is done because it is already 2017, so a ten-year transition period can now only start in 2018. All other scenarios were adjusted to start in 2016, instead of 2015. The shift year remains unchanged, because this is linked to the EBPD, which requires all new buildings to be nZEB, starting from 2020.

The updated floor area projections for 2015-2050 obtained from the 3SCEP HEB model are inserted in the EEDMS and multiplied with the embodied energy intensity (MJ/m^2/year) and the operational energy intensity (MJ/m^2/year) to get two projections of these energy uses for every building representative. Lastly, the embodied- to operational energy ratios are calculated and the most favourable ratios are determined.

Data analysis is crucial in this research; and when working with a large amount of data, mistakes can easily be made. Therefore, to reduce the probability of mistakes; a sensitivity analysis is executed to check the robustness of variables in section 4.3. Also, modelling outcomes are compared with scientific literature and reports on the same topic in section 5.2.1.

4. Results

The structure of this chapter is based on sub-question 2 to 4. Section 4.1 shows the most important results concerning energy use, specified per building representative; subdivided in embodied energy use, operational energy use, and the embodied-to-operational energy use ratios (EE/OE ratios). Section 4.2 shows the scenario analysis results; the results are presented in the same order as the previous section, but for the total energy use development of Dutch residential construction. Lastly, section 4.3 provides the results of the performed sensitivity analysis.

4.1 Energy use per building representative

4.1.1 Embodied energy use

Figure 4.1 below shows the outcomes of the embodied energy use per building representative in MJ/m^2/year, sorted from high to low embodied energy, varying from 47 to 106 MJ/m^2/year. Total embodied energy use per building representative in GJ varies from 232 to 1042 GJ, and per m^2 it varies between 3 to 6.2 GJ/m^2 (when building lifetime is not taken into consideration). The building *vintages* all have their own colour to make it easier to distinguish one vintage from another. The advanced new vintage (green) is on average the most embodied energy intensive vintage, and retrofit (yellow) the least energy intensive. When only comparing building *types*: it is clear that apartments have the lowest embodied energy use and mid-terraced homes have the highest.

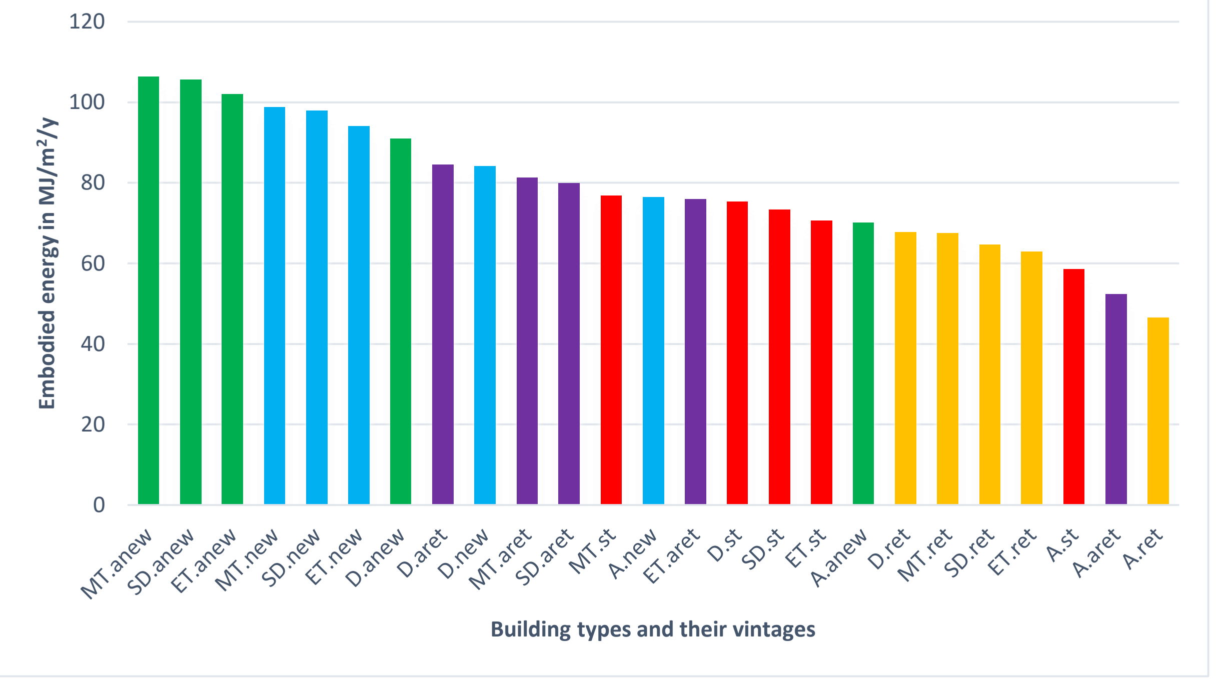


Figure 4.1: The total embodied energy in MJ in the common building representatives in the Netherlands per m^2/year. The vintages have their own colour: green is advanced new, blue is new, purple is advanced retrofit, red is standard and yellow is retrofit.

The order of the magnitude of the embodied energy use in the building representatives can be explained by the material choice, material volumes, the specific embodied energy intensities of these materials and building life time. These contributing factors are discussed next.

Embodied energy use differences discussed

Figure 4.2 shows an overview of the contribution of the materials to the total embodied energy use in the building representatives in percentages. It displays the seven materials that have the highest share in the embodied energy use: precast concrete (RC), reinforced concrete (RC), softwood (SW), polyurethane insulation (PUR), aluminium (Al), mineral wool (MW), clay brick (Br), plywood (Pl), gypsum (Gy), bitumen (Bi), primary glass (PG) and sand cement (SC). Figure 4.3 illustrates this contribution in absolute values, in order to visualize the absolute differences. Table 4.1 shows material intensities and volumes in m^3 of all 23 materials, for the three building types: mid-terrace, detached and apartments, since these three building types differed most significantly. The volumes of end-of-terrace and semi-detached can be found in appendix C. The data in table 4.1 is ordered by the material with average highest volume in a building representative to lowest.

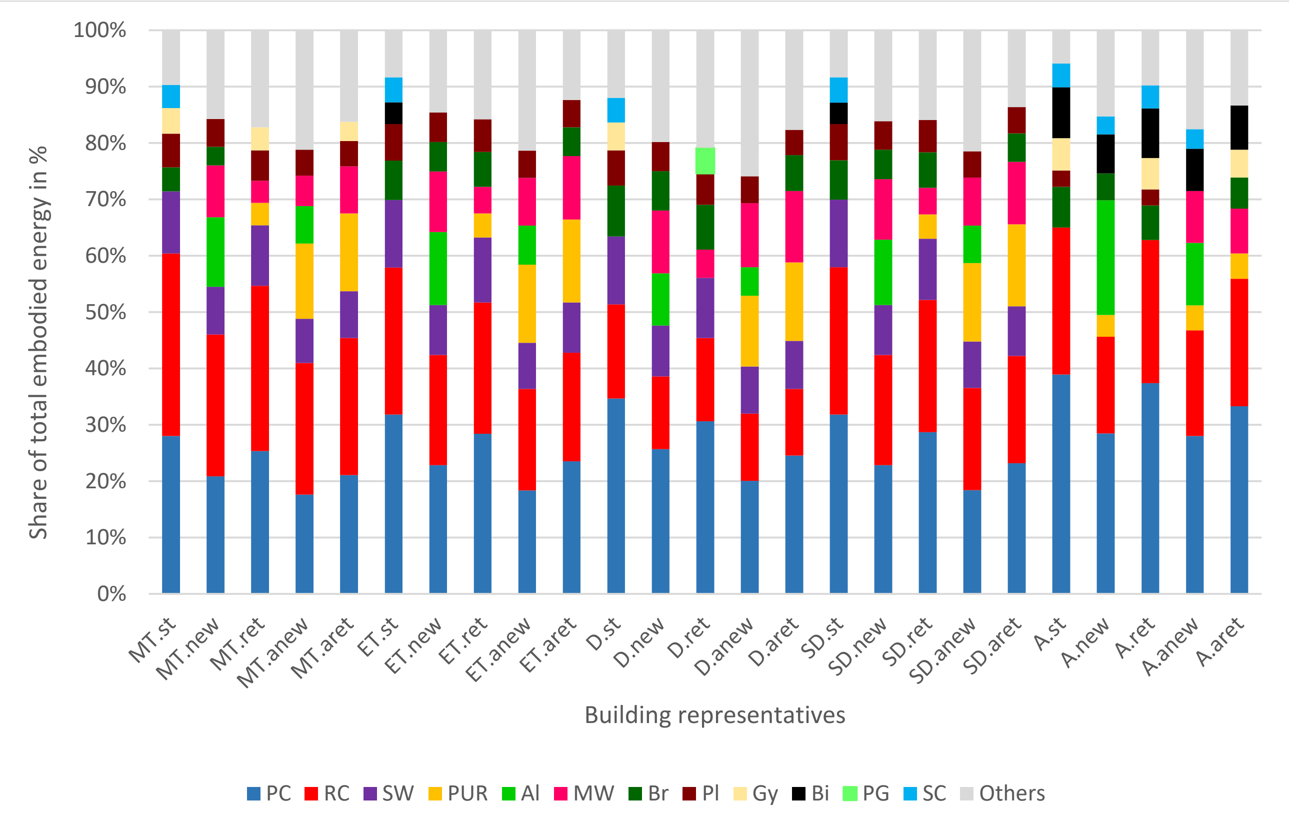


Figure 4.2: The contribution of the most important materials in Dutch residential building representatives. The contribution of a material is shown in percentage of the total for that building representative. A building representative is a building type (mid-terrace to apartments) and its vintage (standard to advanced retrofit).

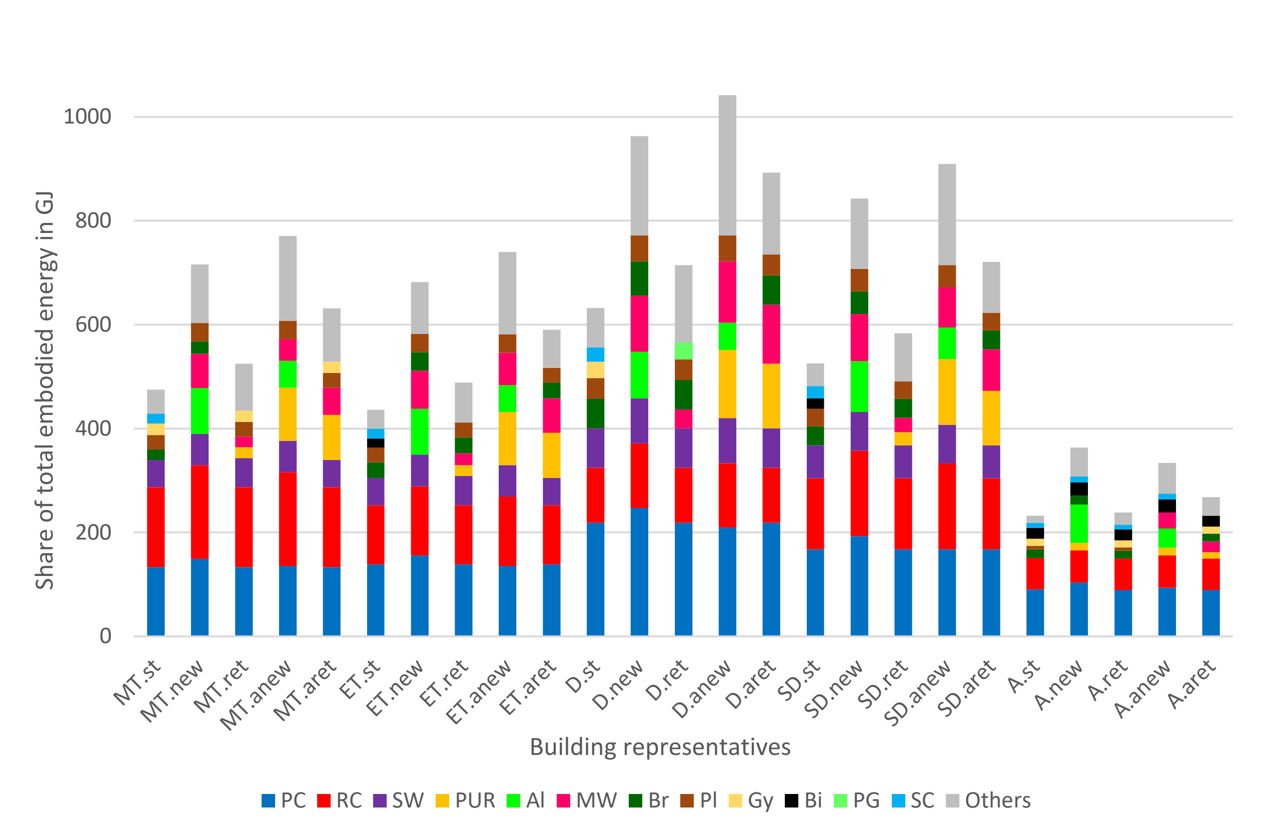


Figure 4.3: The contribution of the most important materials in Dutch residential building representatives. The contribution of a material is shown in absolute values in GJ of the total for that building representative. A building representative is a building type (mid-terrace to apartments) and its vintage (standard to advanced retrofit).

Table 4.1: The 23 materials most used in Dutch residential construction, their embodied energy intensities in GJ/m^3, and the volumes present of these materials in the building representatives in m^3. The materials are ordered with on average highest volume, to lowest volume.

		Volume in m^3														
Material	**Total EEI (GJ/m^3)**	**MT.st**	**MT.new**	**MT.ret**	**MT.anew**	**MT.aret**	**D.st**	**D.new**	**D.ret**	**D.anew**	**D.aret**	**A.st**	**A.new**	**A.ret**	**A.anew**	**A.aret**
PC	2.97	44.24	50.22	44.79	45.69	44.79	73.73	83.28	73.73	70.46	73.73	21.34	34.82	30.04	31.49	30.04
Sa	0.20	34.26	40.16	34.26	41.24	34.26	49.02	57.70	49.02	57.70	49.02	21.75	26.07	21.75	26.07	21.75
RC	4.94	31.10	36.46	31.10	36.46	31.10	21.35	25.13	21.35	25.13	21.35	12.26	12.63	12.26	12.63	12.26
MW	2.34		28.24	8.85	17.89	22.56		45.96	15.35	50.65			4.66	2.35	13.15	9.14
PUR	4.57			4.57	22.43	19.03			6.54	28.65	27.23		3.07	0.31	3.25	2.62
SW	4.19	12.53	14.44	13.42	14.44	12.53	18.17	20.75	18.17	20.75	18.17	0.17		0.17		0.17
SC	2.35	8.27	9.69	8.27	9.69	8.27	11.83	13.93	11.83	13.93	11.83	4.12	4.91	4.12	4.91	4.12
XPS	3.28				9.64					13.85					0.67	
AC	2.68		6.36		6.36			9.14		9.14			3.34		3.34	
EPS	2.44		6.43		3.57	1.83		9.23		5.13	2.61		0.45		0.58	1.16
GY	3.99	5.42		5.42		5.42	7.76		7.76		7.76	3.34		3.34		3.34
Br	5.24	3.86	4.53	0.99	0.86	3.86	10.89	12.82	10.89	2.44	10.89	2.79	3.33	2.79	0.63	2.79
Pl	8.14	3.47	4.36	2.70	3.45	3.47	4.89	6.11	4.89	6.11	4.89	0.83	1.16	0.83	1.16	0.83
HW	7.86		1.65		1.65			2.56		2.56			1.07		1.07	
WF	12.06				0.91					2.56					0.67	
Gr	0.36	0.38	0.45	0.38	0.45	0.38	0.54	0.64	0.54	0.64	0.54	0.48	0.57	0.48	0.57	0.48
Ce	24.16	0.38	0.44	0.38	0.44	0.38	0.54	0.64	0.54	0.64	0.54	0.20	0.24	0.20	0.24	0.20
Zi	372.26	0.27	0.32	0.27	0.32	0.27	0.03	0.04	0.03	0.04	0.03	0.00	0.01	0.00	0.01	0.00
Al	293.43		0.30		0.17			0.30		0.18			0.25		0.13	
Ar	0.01				0.18	0.16				0.72	0.61				0.11	0.10
Bi	122.59	0.14	0.16	0.14	0.16	0.14	0.20	0.23	0.20	0.23	0.20	0.17	0.20	0.17	0.20	0.17
PG	37.70	0.10	0.13	0.22	0.13	0.22	0.41	0.53	0.86	0.53	0.86	0.06	0.08	0.13	0.08	0.13
PVC	93.26	0.004	0.004	0.004	0.004	0.004	0.005	0.006	0.005	0.006	0.005	0.001	0.001	0.001	0.001	0.001

Building types

For most of the building types precast concrete is the most important contributor to the embodied energy use, and reinforced concrete is of second importance (figure 4.2 & 4.3). The average shares of total embodied energy use amongst the building representatives are 26.6% precast concrete and 21% reinforced concrete. Only in mid-terraced homes this is the other way around. This can be explained by pointing out that an end-of-terrace home (for example) has one façade wall more than a mid-terrace home; which results in more use of brick and precast concrete. When a home has one house separating wall more, there is more use of reinforced concrete walls and the corresponding inside walls (aerated concrete or gypsum). Precast and reinforced concrete are used in large volumes in the building types as seen in table 4.1. The larger volume of precast concrete compared to reinforced concrete seems to have a larger impact than the larger Total EEI of reinforced concrete (37.7 GJ/m^3) relative to precast concrete (8.14 GJ/m^3).

In all building types except apartments, softwood is the third largest contributor to the embodied energy use. The high contribution of this material is mainly caused by the large volume; considering the Total EEI is low (2.68 GJ/m^3). This volume is much smaller in apartments. Mineral wool has large impact in all building types, but this impact is significantly lower in apartments. This lower impact is clearly caused by the lower volume of this material in apartments relatively to other types. Bitumen has a clear impact in apartments, whereas this material's contribution is significantly lower in other building types. The impact of sand cement is also more present in apartments than in the other building types. When apartments are compared with the other building types, it is evident that the share of ply- and softwood is replaced by bitumen and sand cement in apartments. This low amount of wood present in apartments is because of the flat roof. A flat roof consists of concrete, bitumen and gravel, while an (partially) inclined roof also consist of ply- and softwood.

When comparing the building type with highest embodied energy use (mid-terrace) and the type with lowest embodied energy use (apartments) the main differences are found in the shares of softwood, PUR, plywood and bitumen. In mid-terrace homes these shares are on average: softwood 9.3%, PUR 10.4%, plywood 5,1% and bitumen 3%. In apartments, these shares are on average: softwood 0.3%, PUR 4.3%, plywood 2.7% and bitumen 8%. Even though bitumen has a high embodied energy intensity (122.6 GJ/m^3) and a relatively high volume in apartments, the higher volumes of the other materials in mid-terraced homes (and in the other building types) are predominant and lead to higher embodied energy use.

Vintages

In the standard vintage, the building materials gypsum, clay brick and sand cement play an important role according to figure 4.2 & 4.3. When gypsum is present in the vintage (standard, retrofit and advanced retrofit) this material is a large contributor to the embodied energy use. Interesting is that aerated concrete - the replacement of gypsum in the new and advanced new vintage - did not appear in figure 4.2 & 4.3. The reason for this is the lower Total EEI of aerated concrete (2.97 GJ/m^3) compared to gypsum (4.19 GJ/m^3). The standard vintage has low embodied energy use compared to the new vintage, due to several reasons:

1. This vintage has the least amount of materials, mainly due to the lack of insulation.
2. The new vintage uses aluminium for the window frames and façade doors, which is a high energy intensive material (293.43 GJ/m^3) compared to the softwood (4.19 GJ/m^3) used for the

same purposes in the standard vintage. When aluminium is present (new and advanced new homes) it is always a large contributor to the embodied energy use. Table 4.1 shows that the volume amount of aluminium is small in these vintages; therefore the main reason of its large contribution can be ascribed to its high Total EEI.
3. The foundation poles in the new vintage consist of hardwood with a Total EEI of 7.86 GJ/m^3, whilst these poles consist of precast concrete with an lower intensity of 2.97 GJ/m^3 in the standard vintage.

The retrofit vintage consists of the same materials and volumes as the standard vintage, but with new additional materials to increase the energy efficiency of the home. The single glass in the standard vintage is replaced by HR glass in the retrofit vintage, which leads to a higher primary glass volume in this vintage. Remarkable is that primary glass in the detached retrofit home is a larger contributor than PUR, which is the other way around in the other building representatives. Detached homes have the most window glass of all types, which can be the cause of this difference. A retrofit home is additionally insulated with mineral wool and PUR. When PUR is present in the building vintage (retrofit, advanced new and advanced retrofit) it is usually an important contributor, as shown in figure 4.2 & 4.3. This is mainly caused by the large volume used of this material (table 4.1) because the Total EEI is rather low (2.34 GJ/m^3). The additional insulation and replacement of window glass should lead to a higher embodied energy use in the retrofit vintage compared to the standard vintage. But, this is not the case due to the longer lifetime of the retrofit vintage (73.3 years) compared to the standard vintage (58.3 years).

The advanced retrofit vintage also consists of the basic materials used in the standard vintage, but there are more additional materials, with higher volumes. It is noteworthy, that a new home seems to be on average more embodied energy intensive than the advanced retrofit home. Table 4.1 shows that particularly the volume amount of PUR is huge in the advanced retrofit vintage. Even though the volume of EPS (Total EEI of 2.44 GJ/m^3) and mineral wool (Total EEI of 2.34 GJ/m^3) is larger in a new home, this does not offset the enormous amount PUR in the advanced retrofit home, which is also more energy intensive (Total EEI of 4.57 GJ/m^3). Thus, the longer lifetime of advanced retrofit homes compared to new homes, plays a vast role in this outcome.

The advanced new vintage has the highest embodied energy use relative to the others; from table 4.1 can be derived that this is mainly caused by the large PUR and XPS volume. PUR is incorporated in the roof and used as door insulation (which none of the other vintages have). The floor is insulated with XPS (with a Total EEI of 3.28 GJ/m^3), which is more energy intensive than mineral wool or EPS. Furthermore, the façade structure is completely different compared to the other vintages; it consists of mineral wool of 400 mm thick and wood fibreboard (details see appendix C). Even though mineral wool is less energy intensive than the traditionally used clay brick (Total EEI of 5.24 GJ/m^3) and precast concrete (Total EEI of 2.97 GJ/m^3), the high volume amount of mineral wool, together with medium intensive wood fibreboard (Total EEI 12.06 GJ/m^3) leads to a higher embodied energy use of the building façade.

Figure 4.3 shows that the vintage type with lowest embodied energy use is standard, but when converting the total embodied energy use; in embodied energy use in $MJ/m^2/y$, the retrofit vintage has the lowest outcome. Considering the fact that the low embodied energy use in

MJ/m^2/y in retrofit homes is caused by the higher lifetime of these buildings compared to non-retrofitted homes, standard homes are seen as the least embodied energy intensive vintage. When comparing standard homes with advanced new homes, the main differences are found in insulation materials. Standard homes have no insulation materials at all, while advanced new has on average 11.4% PUR, 7.9% mineral wool, 4.1% XPS and 1.1% EPS. Moreover, a standard home does not have aluminium, while an advanced new home includes 7.8% of this high energy intensive material on average. Even though the average shares of precast- and reinforced concrete (33% and 25.5% respectively) in standard homes are larger than in advanced new homes (20.6% and 19.6% respectively), the absence of insulation materials and aluminium are the reason why standard homes are very low- embodied energy intensive compared to advanced new homes.

4.1.2 Operational energy use

The operational energy use of the building representatives is shown in MJ/m^2/y - to match the embodied energy use outcomes - in figure 4.4. It is sorted from highest (682 MJ/m^2) to lowest (124 MJ/m^2).

The operational energy use is clearly highest in the standard vintage and lowest in the advanced new vintage (which was the other way around for embodied energy use). Detached homes have the highest energy use while apartments have the lowest. Heating space area and the sharing of walls seem important factors when measuring operational energy use.

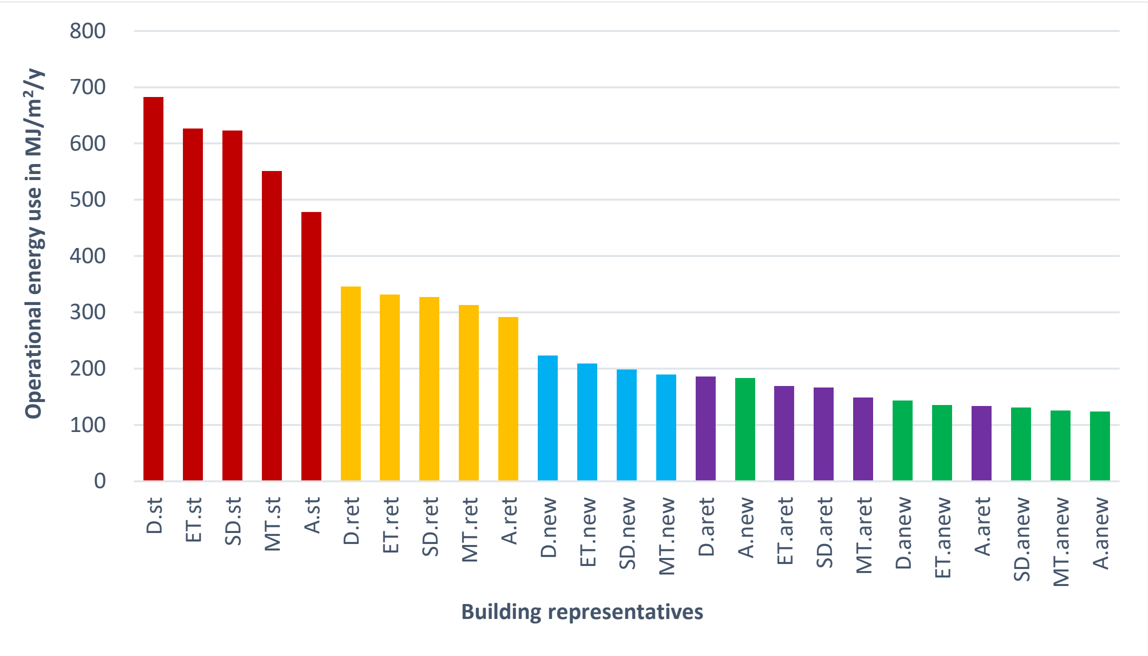


Figure 4.4: The operational energy in MJ/m²/y in the common Building representatives in the Netherlands. The vintages have their own colour: green is advanced new, blue is new, purple is advanced retrofit, red is standard and yellow is retrofit.

4.1.3 Embodied-to-operational energy ratios

Figure 4.5 shows the yearly embodied energy use plus the yearly operational energy use for the building types and vintages, varying from 186 to 758 MJ/m^2/y. Cleary the operational energy use determines the order of magnitude. The embodied energy use in standard homes is about 10-12% of the total energy use. This is 28-46% in advanced homes.

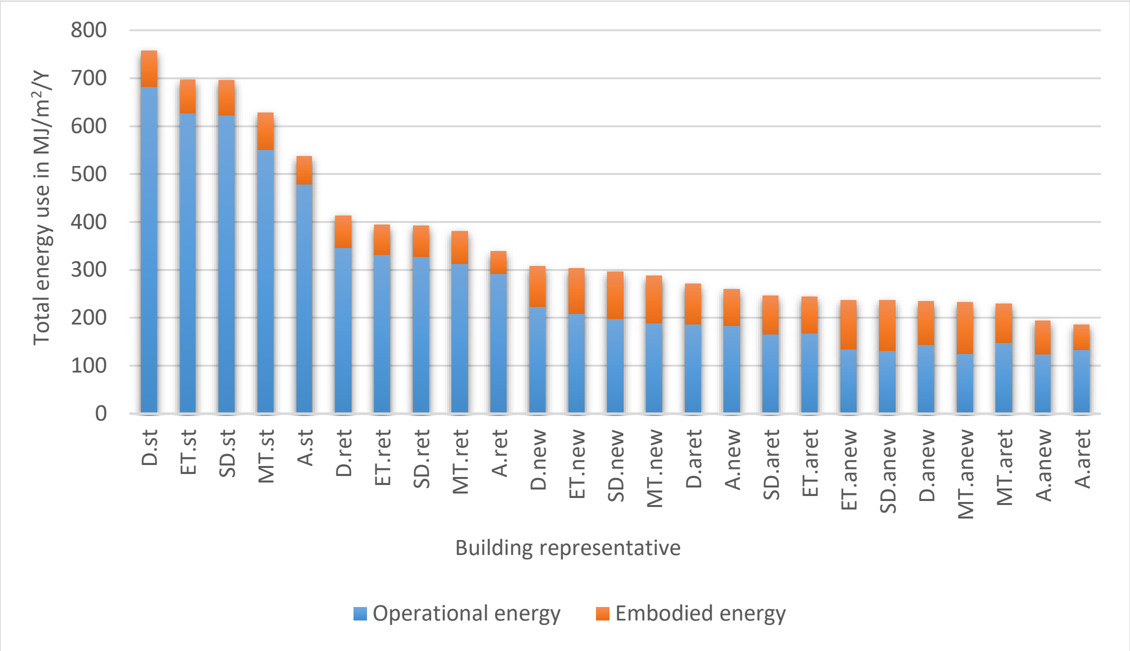


Figure 4.5: The total energy use in MJ/m²/y in the common residential building representatives in the Netherlands, subdivided in operational and embodied energy use.

When considering the operational energy use, embodied energy use and total energy use of the building representatives, EE/OE ratios can be determined (figure 4.6). Figure 4.6 is sorted from highest total energy use to lowest (to make comparison with figure 4.5 easier). It becomes clear that the standard vintage has the lowest ratio (min 0.11), and advanced new the highest ratio (max 0.85).

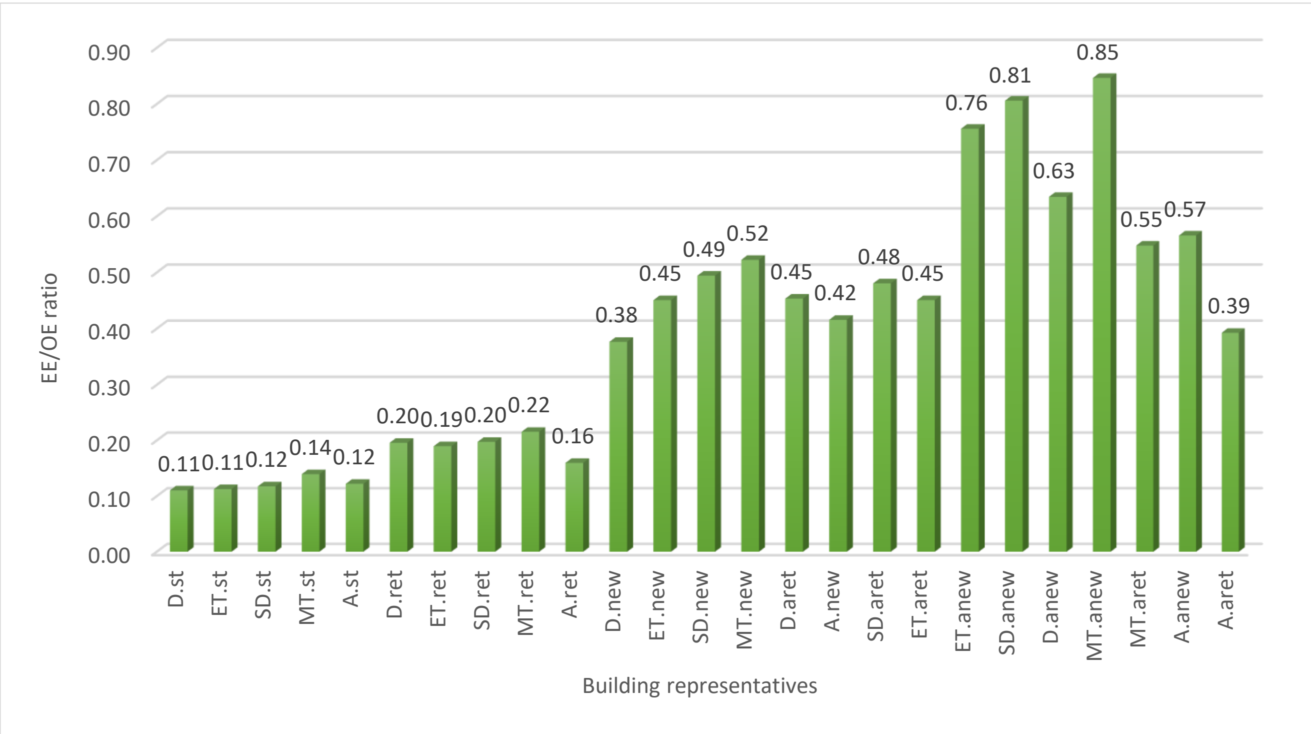


Figure 4.6: Embodied-to-operational energy ratio's (EE/OE ratio's) in the common residential building representatives in the Netherlands.

On average, it seems that the higher the EE/OE ratio, the lower the total energy use of a building. Detached standard homes have the lowest ratio and highest total energy use. Whilst, advanced retrofit apartments have lowest total energy use, but not the highest ratio. This implies that a high ratio does not necessarily mean that it is the most desired outcome. When taking into account lowest operational energy and lowest embodied energy in one building vintage: advanced retrofit seems to be the best option, and is therefore the most desirable outcome. The ratio range of the most desirable outcome is then 0.39-0.55.

4.2 Scenario analysis

This section shows the most important results concerning the total energy use development in Dutch residential buildings, in three scenarios, over the years 2015-2050. In the first section, the total energy use development is shown: divided in floor area development obtained from the 3SCEP HEB model, and a discussion of every scenario separately. Then, the EE/OE ratios in the three scenarios are discussed.

4.2.1 Total energy use development

Floor area

Figure 4.7, 4.8 and 4.9 show the floor area development for the years 2015-2050 for the frozen, moderate and deep efficiency scenario, respectively. The differences in floor area development in the scenarios are already discussed in section 2.2. The changes that occurred as result of data updates in the 3SCEP HEB model are discussed in this section.

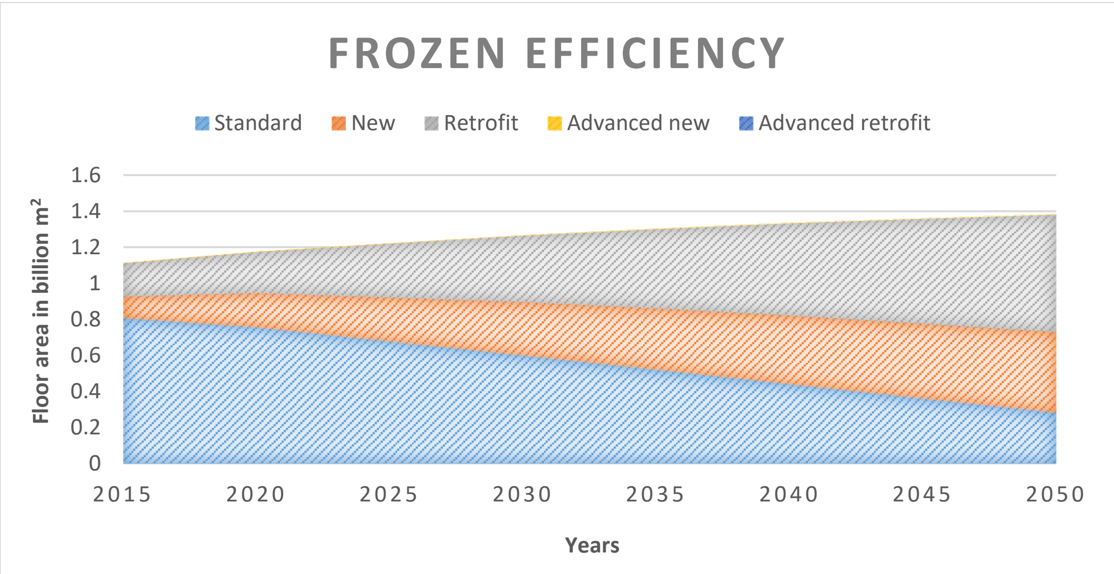


Figure 4.7: The total floor area in billion m^2 in the frozen efficiency scenario for Dutch residential buildings using the 3SCEP HEB model (with data updated for the Netherlands), with timeframe 2015-2050. For every vintage (standard to advanced retrofit) the floor area development is shown.

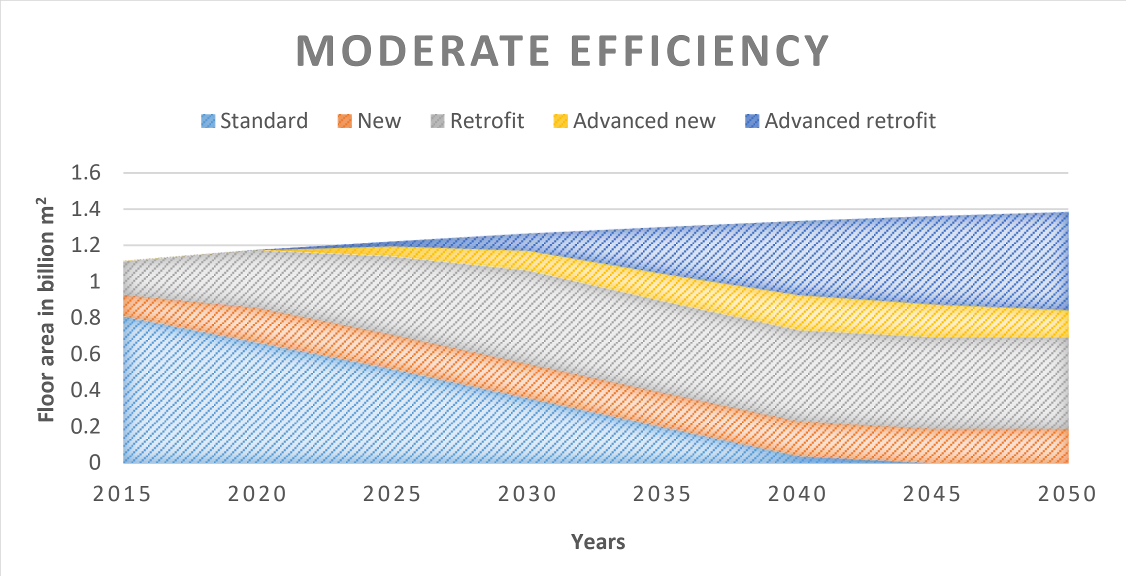


Figure 4.8: The total floor area in billion m^2 in the moderate efficiency scenario for Dutch residential buildings using 3SCEP HEB model (with data updated for the Netherlands), with timeframe 2015-2050. For every vintage (standard to advanced retrofit) the floor area development is shown.

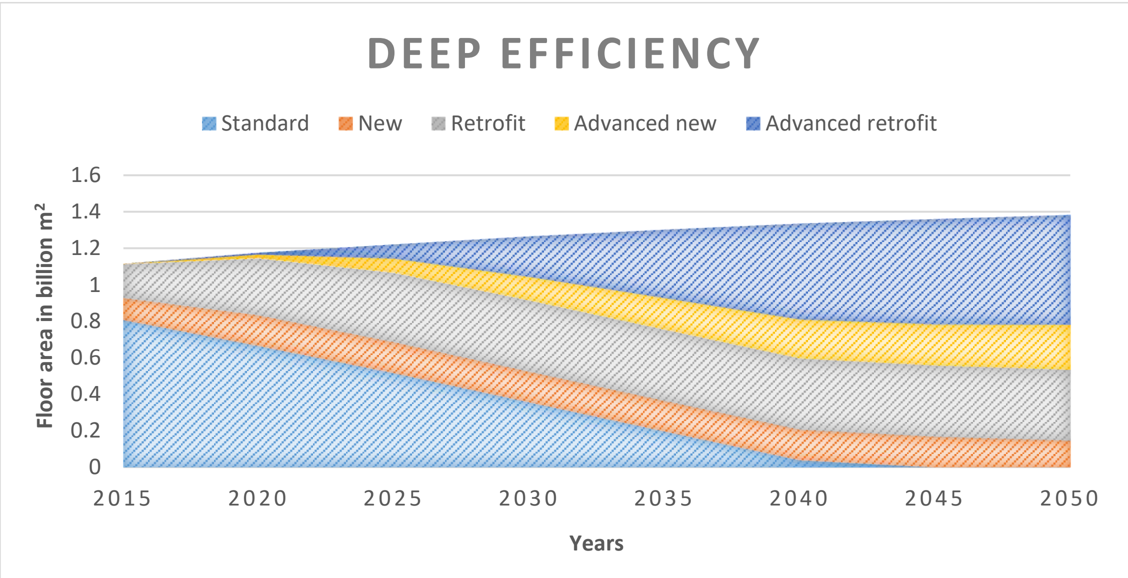


Figure 4.9: The total floor area in billion m^2 in the deep efficiency scenario for Dutch residential buildings using 3SCEP HEB model (with data updated for the Netherlands), with timeframe 2015-2050. For every vintage (standard to advanced retrofit) the floor area development is shown.

When comparing the floor area development shown in figure 4.7-4.9 (with updated data) and the development in figure 2.3-2.5 (3SCEP HEB data) it becomes clear that the decrease in standard buildings is slower after updating the data. Furthermore, the total amount of floor area starts and ends higher in figure 4.7-4.9, but the total growth is the same. The slower decrease of standard buildings can be explained by the lower demolition rate used for the Netherlands. Overall, the advanced new and advanced retrofit homes start to develop later after updating, with the largest share of these low energy homes in the deep efficiency scenario.

Total energy use - frozen efficiency

Figure 4.10 shows the development of the total energy use of residential buildings in the Netherlands, in the frozen efficiency scenario. The impact of the vintages on the total energy use is distinguished in the figure. The total decrease is 11.6%, which decreases gradually towards 2050. The total change is small, which makes sense, because the frozen efficiency scenario does not include any future policy actions. The standard vintage determines the largest part of the total energy use in the first few years. Towards the end, the largest share of the standard buildings is retrofitted. The share embodied energy in total energy use increased from 12.6% in 2015 to 18% in 2050; mainly caused by the increasing share of new homes (272% floor area increase between 2015 and 2050).

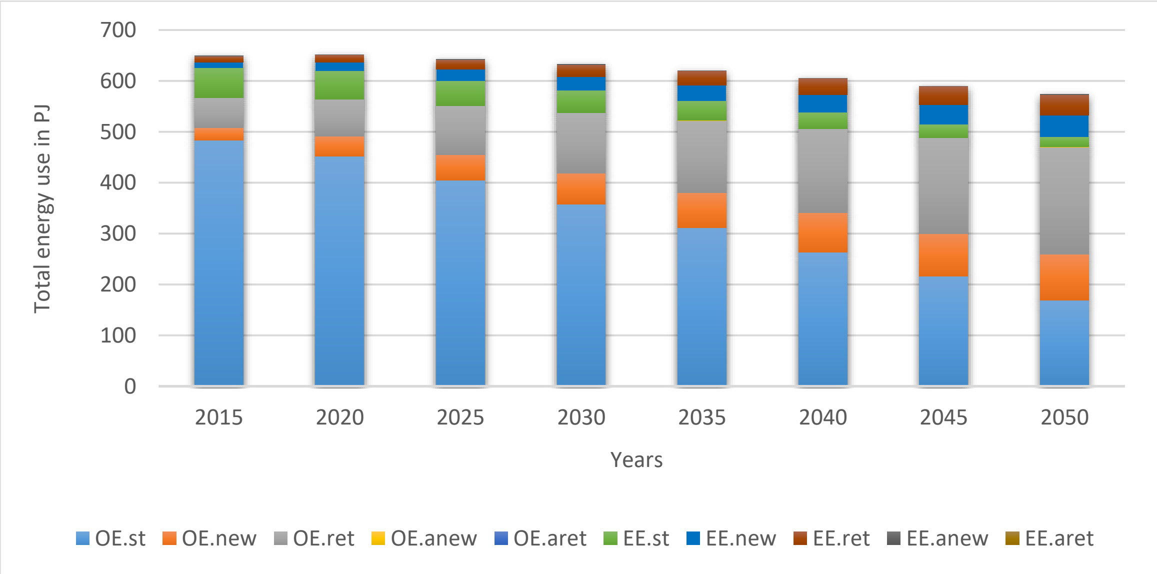


Figure 4.10: The total energy use development in PJ in the Dutch residential sector, in the frozen efficiency scenario, over the years 2015-2050. The build-up is according to vintage: OE = operational energy and EE = embodied energy.

Total energy use - moderate efficiency

Figure 4.11 shows a total decrease in energy use between 2015 and 2050 of 38% in the moderate efficiency scenario, which is much more significant than in the frozen efficiency scenario. Figure 4.11 shows that the total decrease is more rapid until 2040, and stays stable afterwards. The standard homes are much faster replaced by retrofits in this scenario, compared to the frozen efficiency scenario. Also, advanced retrofit homes increase fast after 2030, which leads to a large share of this vintage in the total energy use in 2050. Since 2020 there is an increase in advanced new homes observed, at the cost of new homes. This is in line with the EBPD policy, which states that all new homes have to be nZEB (advanced) from 2020 onwards. The share embodied energy in total energy use increased from 12.6% in 2015 to 25.3% in 2050; mainly caused by increasing advanced retrofit homes (542% floor area increase between 2015 and 2050).

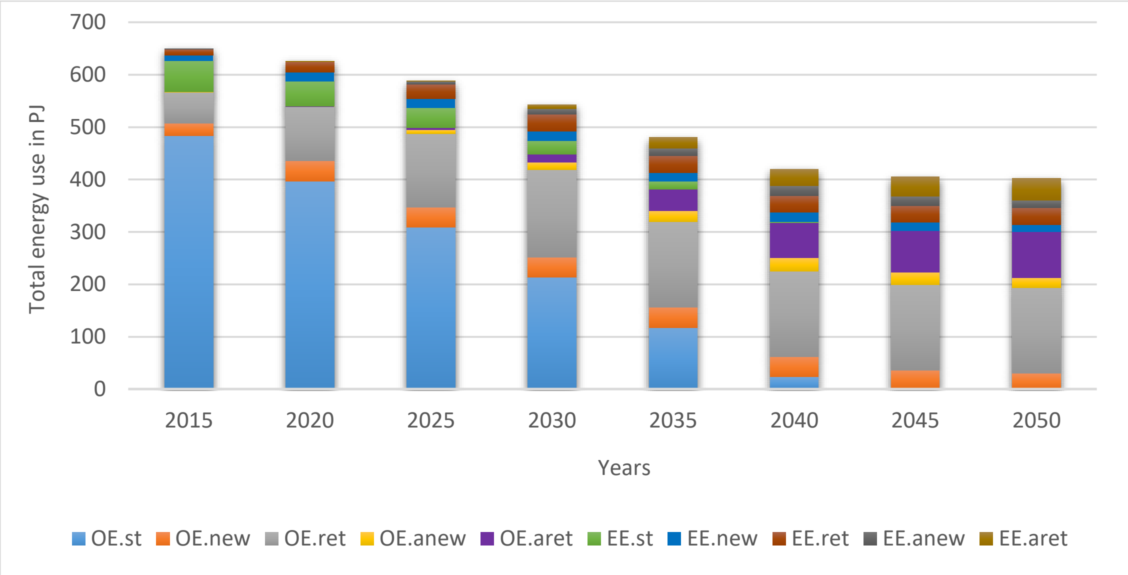


Figure 4.11: The total energy use development in PJ in the Dutch residential sector, in the moderate efficiency scenario, over the years 2015-2050. The build-up is according to vintage: OE = operational energy and EE = embodied energy.

Total energy use - deep efficiency

The decrease in total energy use in the deep efficiency scenario is comparable with the moderate efficiency scenario, shown in figure 4.12. The main difference is the larger and more rapid decrease (40.2%) in the deep efficiency scenario. Furthermore, the increase of advanced retrofit homes leads to a smaller share of new and retrofit homes between 2025-2050. This is caused by the 10-year period (2018-2028) where advanced homes are proliferating. The share embodied energy in total energy use increased from 12.6% in 2015 to 27.6% in 2050; mainly caused by increasing advanced retrofit homes (591% floor area increase between 2015 and 2050), as in the moderate scenario.

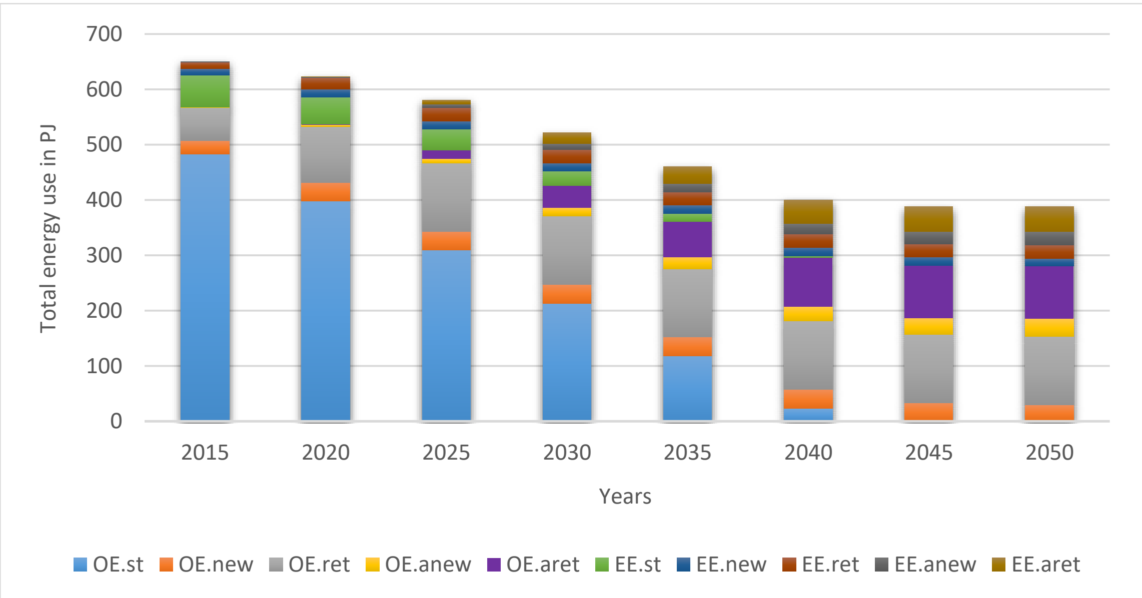


Figure 4.12: The total energy use development in PJ in the Dutch residential sector, in the deep efficiency scenario, over the years 2015-2050. The build-up is according to vintage: OE = operational energy and EE = embodied energy.

Remarkable is, that there seems to be a slight increase in total energy use in 2050 compared to 2045 in both the moderate and deep efficiency scenario. It appears that the disappearance of standard homes in 2045, together with the increase of advanced homes in the last years, leads to the increase in total energy use around 2050.

When comparing the three scenarios can be concluded that standard homes play a huge role in total energy use in the Dutch residential sector. In the frozen efficiency scenario, the total energy use is gradual, with standard homes always present over the years. In the moderate and deep efficiency scenario the standard homes disappear around 2045, and afterwards the total energy use remains stable at first, and then increases in 2050. Around 2045, the new and retrofit homes remain stable, but advanced new and advanced retrofit homes increase. Under these circumstances, the relative operational energy use remains stable while the embodied energy use increases, which leads to an overall increase in building energy use.

The moderate efficiency scenario shows that if the EBPD policy goals are met, a decrease of 38% of total residential building energy use in the Netherlands can be reached. Accelerating the share of advanced new and advanced retrofit homes in these buildings even more, as is done in the deep efficiency scenario, can lead to an additional total energy use decrease of 2.4%.

4.2.2 Embodied-to-operational energy ratios in the scenarios

Figure 4.13 shows the development of the EE/OE ratio in the three scenarios. The ratios all start at 0.144, and reach their maximum around the year 2045. In the frozen efficiency scenario it increases until 0.22, in the moderate scenario until 0.34, and in the deep scenario until 0.38.

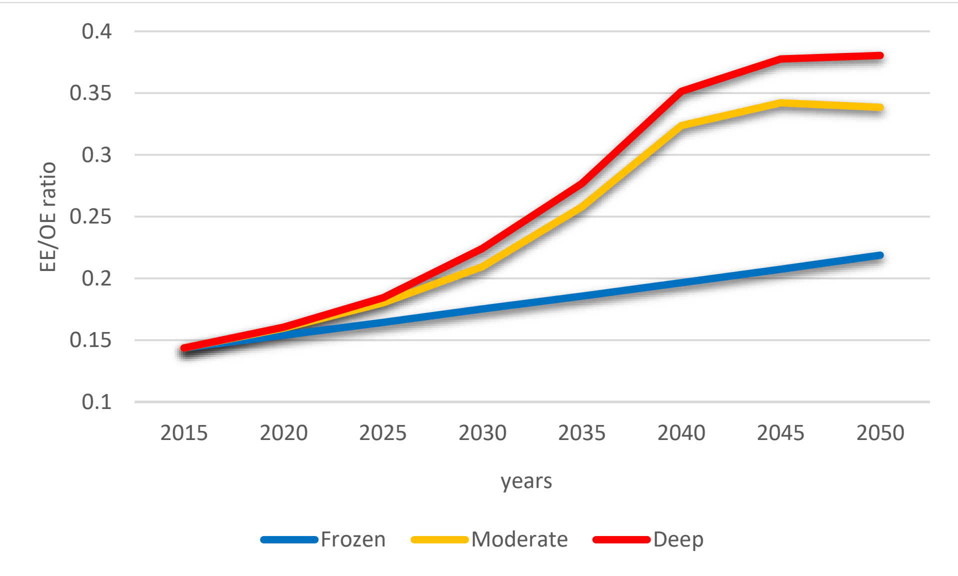


Figure 4.13: The development of the embodied-to-operational energy use ratio (EE/OE ratio) in the frozen, moderate, and deep efficiency scenario in 2015-2050.

The EE/OE ratio is equal to 1 when the operational energy use and embodied energy use are equal. In all three scenarios the share operational energy decreases over the years, while the share embodied energy increases: this leads to an overall EE/OE ratio increase.

In the frozen efficiency scenario, the development of the EE/OE ratio is a straight line, because the decrease in total energy use, and thus the improvement, is gradual. In the moderate efficiency scenario, the EE/OE ratio development looks a lot different compared to the development in the frozen efficiency scenario. The ratio increases much faster; mainly due to the fast decrease of operational energy use. The same applies to the deep efficiency scenario, but with a faster ratio increase. In both the moderate- and deep scenario around 2040 the increasing ratio starts to decline and flattens out around 2050.

Section 4.1.3 mentioned that advanced retrofit homes have the most optimal EE/OE ratio range of 0.39-0.55. Figure 4.13 shows that the highest ratios in the deep and moderate scenario are reached around 2045: 0.38 and 0.34 respectively. When looking closely at the building shares that determine these ratios, interesting facts are observed. In 2045 in the moderate scenario: 37% of the homes is retrofit, 35.8% advanced retrofit, and the remainder is evenly distributed over new and advanced new homes. In 2045 in the deep scenario, 28% is retrofit, 43.3% is advanced retrofit, 16.5% advanced new and the remainder is new. When taking into account the fact that in the deep scenario the EE/OE ratio is higher, and total energy use is lower, it can be argued that this is a more optimal situation compared to the moderate scenario in 2045. From these facts can be concluded that advanced retrofit homes are the most important vintage to consider when reducing total building energy use, and advanced new is second-best.

4.3 Sensitivity Analysis

A sensitivity analysis is important to check robustness of variables. It shows the local response of the output when varying input factors one at a time, while holding the others fixed (Saltelli, Tarantola & Chan, 1999). The results of this analysis are shown for the moderate efficiency scenario, considering this scenario is most representative for Dutch policy in the future.

4.3.1 Gross floor area

The BVO is used as input in the DGBC tool to calculate material volumes in the building types. This value can have impact on the results because the input BVO is not directly proportional to the user surface value of the particular building type. For example apartments have a large conversion value (0.9) and therefore have a proportionally smaller BVO value compared to the user surface value, while detached homes, with a much smaller conversion value (0.75), have a proportionally larger BVO value than the user surface area. In this research is chosen to use the user surface values (mentioned in section 3.1) for the calculation of the embodied energy use per m^2 of the building representatives because the user surface is also used to calculate the operational energy use in m^2, and many of the Dutch data sources (e.g. RVO and CBS) use the same approach.

Figure 4.14 shows the total- and embodied energy use in Dutch residential construction for both the BVO and the user surface area. There are indeed proportional differences between the energy use; both the total energy use and embodied energy use are 21% lower when using the BVO. The impact on the EE/OE ratio is: the value starts higher at 0.183 and ends higher at 0.43 (which was 0.144-0.34) in the moderate scenario. All outcomes differ proportionally when using the BVO, and therefore there will be no impact on the overall conclusion of this research.

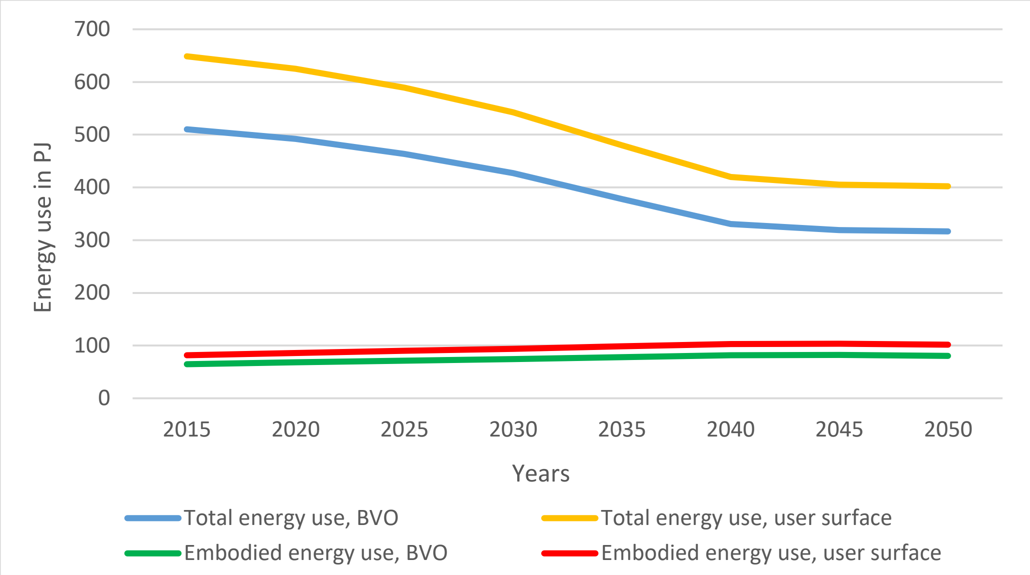


Figure 4.14: Total and embodied energy use development in Dutch residential construction in 2015-2050. The outcomes when using user surface values of the buildings and gross floor areas (BVO) are compared.

4.3.2 Embodied energy intensities

The embodied energy intensity values of the materials in this research are carefully chosen to fit within the 'cradle to gate' definition. However, these values can vary according to their specific manufacturing processes, which often depends on technological progress. To cover the whole range, the sensitivity analysis is based on the lowest and the highest possible embodied energy intensities. These intensities are based on the range given in the ICE database (Circular Ecology, 2011). For the detailed intensity range of all 23 materials, see appendix E.

Figure 4.15 shows the total and embodied energy use in Dutch residential buildings, for the embodied energy intensity range. The total energy use is 8.2% lower when the intensity values are at their lowest, and 19.8% higher when the values are at their highest. For embodied energy this range is much higher; between -32.5% and 78.4%. This shows that it is very important to choose the embodied energy intensity values carefully: particularly the 78% increase is striking. When taking the total possible deviation of the embodied energy intensities into account, the range of EE/OE ratios is: in 2015 0.097 to 0.027, and in 2050 0.23 to 0.6 (which was 0.144 in 2015 and 0.34 in 2050). This deviation can lead to differences in overall results, which particularly applies to high impact materials such as aluminium and PUR. However, the values in this research where chosen as specific as possible for the Netherlands (especially for the high impact materials), therefore a significant deviation is unlikely.

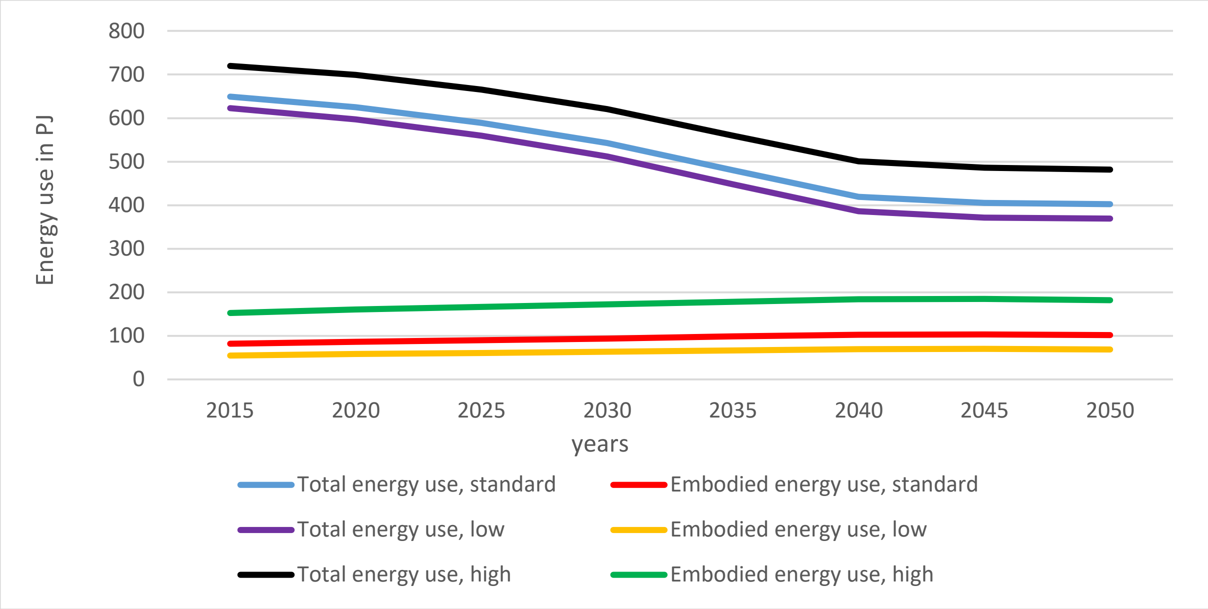


Figure 4.15: Total and embodied energy use development in Dutch residential construction in 2015-2050. The development is shown for standard, low and high embodied energy intensity values.

4.3.3 Operational energy intensities

The operational energy intensities used in this research are introduced in section 3.2.4, and based on averages of the building representatives. These intensities however, can differ due to climate specifications of the location of the building, specific building characteristics and behaviour of residents, amongst other things. Therefore the effect of this variation in operational energy intensities on total energy use is presented in this section. Figure 4.16 shows the outcome when the standard intensities are used, and 10% below and 10% above this amount. This deviation is chosen randomly to illustrate the effect on total energy use when using different intensities. Also, larger deviations are not expected because the data source (TU Delft, 2016) is considered to be reliable.

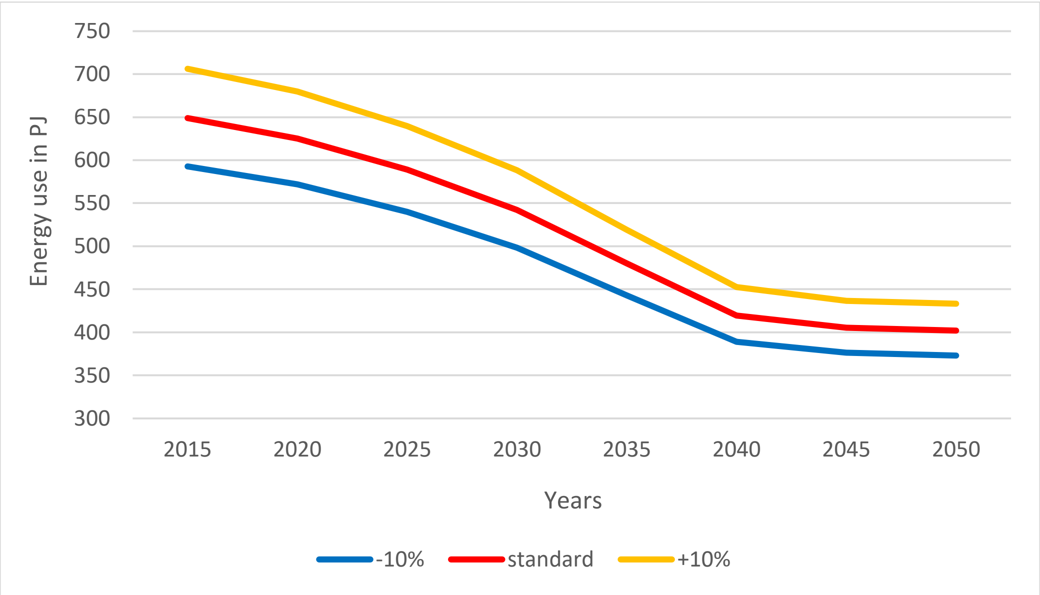


Figure 4.16: Total energy use development in Dutch residential construction for the years 2015-2050. The development is shown for standard operational energy intensities, intensities that are 10% higher and 10% lower.

Figure 4.16 shows that around the year 2015 the deviation of total energy use is larger when applying the operational energy intensity range, than in 2050. This can be explained by the increasing floor area towards 2050. The smaller the floor area, the higher the impact on total energy use if operational energy intensities are wrongly chosen. The EE/OE ratio range including the operational energy intensities deviation is 0.13-0.16 in 2015 and 0.31-0.38 in 2050. This is a small deviation compared to 0.144 in 2015 and 0.34 in 2050, and therefore the impact on the overall conclusion is expected to be insignificant within this range.

4.3.4 Building lifetime

Building lifetimes can have significant influence on the total and embodied energy use outcomes of building types. Figure 4.17 shows the outcomes of these two energy uses for a building lifetime of 50 years, which is currently the Dutch building technical lifetime (Netherlands Enterprise agency & Ministry of Internal Affairs and Kingdom Relations, 2012) and 100 years for all building representatives. This is compared to the standard: for retrofit and advanced retrofit SF homes 73.3 years and for MF homes 66.8 years; for standard, new and advanced new SF homes 58.3 years and 51.8 years for MF homes.

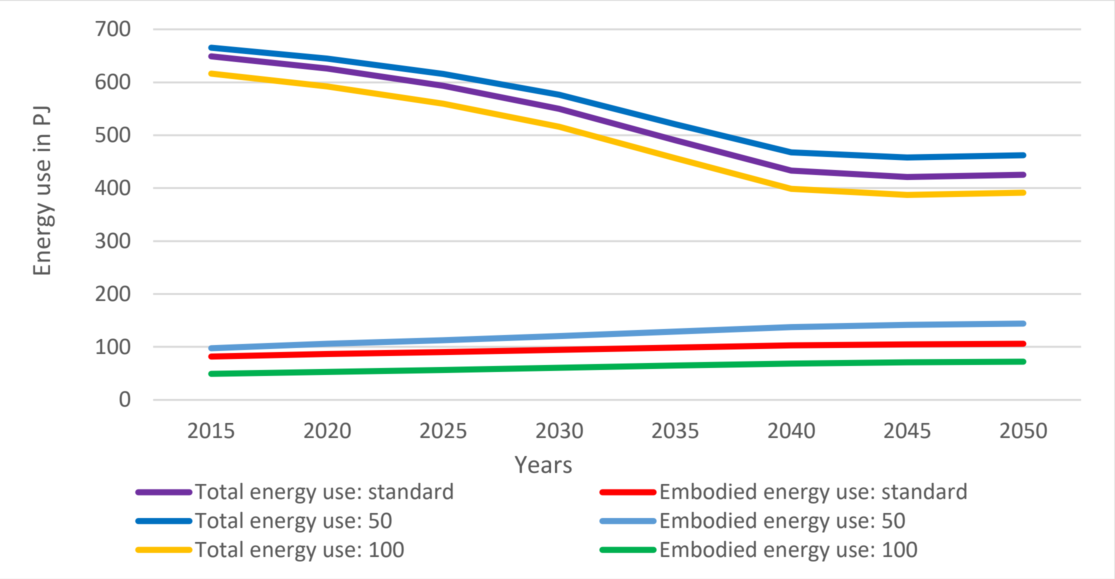


Figure 4.17: Total and embodied energy use development in Dutch residential construction in 2015-2050. The development is shown for the standard building lifetime, and a lifetime of 50 and 100 years.

Figure 4.17 shows that if a building lives a long lifetime (100 years) the total energy use decreases with 8% compared to the standard lifetime. When a building lives shorter than assumed in this research (50 years) the total energy use increases with 8.8%. Thus, the effect of building lifetime on the total energy use of a residential building is small. However, the embodied energy use decreases with 32% at a lifetime of 100 years, and increases with 36% at a lifetime of 50 years, compared to the standard. A longer lifetime decreases the EE/OE ratio and a shorter lifetime increases it. The range of the EE/OE ratio when including these lifetimes is 0.09 to 0.17 in 2015, and 0.23 to 0.45 in 2050 (which was 0.144 in 2015 and 0.34 in 2050). Choosing the right building lifetime is therefore very important when calculating embodied energy use, and can have impact on the overall conclusion of this research. Particularly the relative lifetimes of the building representatives are important: the lower embodied energy of the retrofit and advanced retrofit vintages are for a large part caused by the lower lifetime.

4.3.5 Retrofit and demolition rate

In the 3SCEP HEB model a retrofit rate of 1.4% is assumed, with a range of 0.7% to 2% possible in developed countries (Urge-Vorsatz et al., 2012). The retrofit rate is incorporated in the 3SCEP HEB model as one of the factors that determines the development of the floor area shares of retrofit and advanced retrofit homes, and thus indirectly also determines the development of the other vintage floor areas. However, this model is also based on rules to reach certain policy goals, determined for every scenario separately. Therefore, it is hard to decompose the effect of the retrofit rate on the conclusion of this research. Particularly because of its changing nature in the moderate (increase until 2.1% in 2020) and deep efficiency scenario (increase until 3% in 2020).

However, based on scientific expertise can be argued that using a higher retrofit rate (compared to the 1.4%) can lead to a larger share of retrofit and advanced retrofit homes every year. This can eventually lead to a lower total energy use in 2050 considering the fact that (advanced) retrofit homes are less (total) energy intensive than standard and new homes. When using a lower retrofit rate compared to the 1.4%; the share of (advanced) retrofit homes can increase slower over the years. It is expected that this will lead to a less optimal situation with a higher total energy use in 2050. Fortunately, the outcomes of using a lower and higher retrofit rate are not expected to have influence on the overall conclusion because 1) advanced retrofit homes are still considered the best option, and 2) and the deep efficiency scenario is still preferred over the moderate efficiency scenario. The only effect can be that a higher retrofit rate might lead to a higher EE/OE ratio around 2045/2050, and that a lower retrofit rate can impede the reaching of policy goals set in the moderate and deep efficiency scenario, because of the higher total energy use at the end of 2050.

In the 3SCEP HEB model a demolition rate of 0.5% was used (with a possible variation of 0.3 to 1%), which is higher compared to the demolition rate in this research (0.16%). In section 4.2.1 was already mentioned that a higher demolition rate can lead to a faster decrease of standard buildings, compared to a lower demolition rate. Based on scientific expertise can be argued that a faster decrease in standard buildings can force a faster increase in (advanced) new buildings because the demolished buildings have to be replaced. This will lead to a relatively lower amount of (advanced) retrofit homes in 2050 and therefore a less optimal situation with higher total energy use. When using a lower demolition rate compared to the 0.5%; the decrease in standard homes is expected to be slower, and therefore the increase in (advanced) new homes is expected to be slower. This can eventually lead to a more optimal situation (as long as all standard homes are replaced by 2050) with lower total energy use in 2050 because the relative share of (advanced) retrofit will be higher. Retrofitting seems to be a less energy intensive option than demolishing and constructing a new building.

5. Discussion

This chapter is divided in three parts. Section 5.1 presents the theoretical implications of the results of this research. Section 5.2 compares the results of this research to other studies and section 5.3 discusses limitations. Lastly, section 5.4 gives recommendations for further research.

5.1 Theoretical implications

Section 1.3 already introduced the relevance of this research. The difference between this research and other studies focussing on embodied energy use in residential buildings, is the detailed analysis for the Netherlands. The EEDMS contains detailed information about average material use in Dutch residential buildings and the characteristics of these buildings. 25 building representatives are distinguished which make up the whole Dutch residential construction industry. A model like this did not exist before, and can function as a well-grounded base for the analysis of embodied energy use in other countries. This EEDMS can also be expanded with even more building types and building materials, or can be perfected for one particular building. The 3SCEP HEB model used for the scenario output of floor area development is fine-tuned in this research for the Netherlands. This model can also be fine-tuned for other countries. The EEDMS and 3SCEP HEB model together have increased the modelling opportunities of embodied and operational energy analysis in residential buildings.

The EEDMS shows the importance of the choice of building materials in a residential building. Materials and their embodied energy intensities can be varied in the model to determine the effect on the embodied energy use, which provides a step towards the optimization of life cycle energy use in buildings. Increasing optimization of building energy use can lead to a decrease in the combustion of fossil fuels, which contributes to the mitigation of climate change and can help to reach the goal of the maximum 2˚C temperature increase by 2050. Furthermore, determining the development of EE/OE ratios in Dutch residential buildings shows the effect of the different building vintages on total energy use.

5.2 Reflection

It is important to compare the results obtained in this research with other studies focussing on operational and embodied energy use in residential buildings. Often case studies executed for this topic differ in type of residential building, climate zone and data sources (Sartori & Hestnes (2007). Comparison in absolute numbers between the case studies is therefore not possible. Consequently, the embodied and operational energy use outcomes of other studies will be compared in relative terms with the outcomes of this research. Furthermore, case studies for the Netherlands were unfortunately not available. Therefore first, literature reviews that show averages based on multiple case studies are discussed, and second; case studies focussing on one country are presented.

5.2.1 Literature reviews

Sartori & Hestnes (2007) analysed 60 case studies on this topic and found that operational energy indeed represents the largest part of the total energy use in a residential building. Low-energy buildings are more energy efficient, but have higher embodied energy use, which is also confirmed in this research. According to the research of Balaras, Droutsa, Dascalaki & Kontoyiannidis (2005), the European average of annual heating consumption is 174.3 kWh/m^2, which is comparable with the operational energy used for an average end-of-terrace home in this research (174 kWh/m^2/y). An end-of terrace home can be considered as an average representative of a Dutch home in energy terms, and therefore can be concluded that the operational energy used in this research is in line with literature.

Chastas, Theodosiou & Bikas (2016) conducted a literature review on LCEA studies in residential buildings. In this review is confirmed that when a conventional home is transformed in a passive/low energy home (from standard to advanced), the share of embodied energy in total building energy use increases, even though total energy use decreases. In LCEA studies on conventional buildings the share of embodied energy was between 6 and 20%, while the range of the share measured in standard homes in this research is 10-12%.

5.2.2 Case studies

The outcomes of this research seem comparable with outcomes of literature reviews. Next, a comparison is made using case studies for a country comparable with the Netherlands; Sweden, and a country disparate from the Netherlands; India.

Adalberth (1997) studied the embodied- and operational energy use in three low energy use dwellings in Sweden. The average embodied energy was 833 kWh/m^2, which is about 3 GJ/m^2. The embodied energy range in this research was 3-6.2 GJ/m^2, thus the 3 GJ/m^2 measured in Adalberth (1997) is within this range. Furthermore, the average embodied energy compared to total building energy in this research is about 23%, while this is 15% in Adalberth (1997).

Debnath, Singh & Singh (1995) analysed three types of residential buildings in India on their embodied energy use. The energy consumption of the built-up area is estimated to be 3 to 5 GJ/m^2 (which is 3-6.2 GJ/m^2 in this research). The major conclusion in this study is that brick, steel and cement are the three major contributors to the embodied energy use. This is in line with this research: the two major contributors identified are precast and reinforced concrete. Precast concrete contains cement and reinforced concrete contains both cement and steel. Venkatarama Reddy & Jagadish (2003) also executed an embodied energy analysis in residential buildings in India. In this study was confirmed that aluminium doors and windows can contribute highly to the total energy output of a building, just as in this research. The total embodied energy was measured for three types of buildings, from which the first two are comparable with the Dutch building types analysed in this research. The first house has a reinforced concrete structure with burnt clay brick masonry walls with embodied energy of 4.21 GJ/m^2 and the second one has load bearing brickwork with a reinforced concrete slab floor and mosaic floor finish with embodied energy use of 2.92 GJ/m^2. These results are comparable with the 3-6.2 GJ/m^2 range in this research.

5.2.3 Scenario outcomes

In the report of Urge-Vorsatz et al. (2012) the same scenario analysis was executed for the operational energy use for four key regions (explained in section 2.1), from 2005 to 2050, using the 3SCEP HEB model. The mitigation potential for heating and cooling for Europe was 8% for the frozen efficiency scenario, 61% for the moderate scenario and 69% for the deep scenario. This was, 17%, 47% and 50% respectively, in this research. The differences in outcomes are caused because of different data sources and heating and cooling boundaries, different demolition/new construction rates and the use of a different timeframe for the analysis (start in 2005 instead of 2015). Furthermore, the outcome of this research is valid for the Netherlands, not necessarily for Europe. In conclusion, establishing a standard research framework for this sort of analysis' is essential to make comparison between studies possible.

5.3 Limitations

Even though the assumptions and data used in this research are chosen as carefully as possible, there are limitations in this research.

When defining the embodied energy use in this research, is chosen to exclude recurrent and demolition energy. These two energy uses did not fit within this research framework, and according to Crowther (1999) and Stephan, Crawford, & de Myttenaere (2012) the energy required for demolition, represents about 1% of the total life cycle energy of the building. Even though the impact of including these two energy uses is expected to be small, including these in future research of embodied energy will capture the complete embodied energy use.

Other limitations mostly concern embodied energy intensities of the materials. The sensitivity analysis showed a possible deviation range of -32.5% to + 78.4%, which is quite high. To get precise numbers, the actual degree of recycling and reuse of every material should be known, because producing virgin materials leads to higher embodied energy intensity than when producing recycled and/or reused materials. It was not always possible to account for this. Furthermore, future embodied energy intensity can be lower due to technological progress, which is not taken into account in this research due to time constrictions. Also, the sample size of the embodied energy intensities in the ICE database differed in some cases which undermines the reliability of this data. For the calculation of transport intensity very rough numbers were used, and volumes and material choice are largely based on assumptions, not observations/exact measurements. These limitations are important to consider, but, the data collection in this research was as thoroughly checked as was possible within the research timeframe.

The results of the EEDMS are expected to differ for other countries. As mentioned in the sensitivity analysis the operational energy intensities can also deviate. These intensities do not only depend on location (climate zones) but also on the behaviour of occupants. In countries with a warmer climate than in the Netherlands, the cooling operational energy is expected to be higher, and the average material use is expected to differ, for example due to higher humidity levels. In countries with a colder climate, the necessary heating energy is expected to be higher and/or the insulation levels are expected to be higher. Furthermore, the average material use in residential buildings also depends on the prosperity of a country. Therefore, the EEDMS can only be used as a relational database structure for other countries, the average material use input should be determined for every country separately.

The sensitivity analysis revealed the importance of building lifetime on the EE/OE ratios. Other variables are expected to have small or even insignificant impact on the conclusion of this research. Unfortunately, the combined uncertainty of the variables used in the EEDMS and 3SCEP HEB model is not validated due to time constrictions, which is a limitation that should be taken into account.

5.4 Further research

Recommendations for further research on this topic focus on optimization of residential building LCEA analysis for the Netherlands. A large limitation of embodied and operational energy use analysis is that every researcher chooses its own boundaries, measurements and units. Therefore, is recommended that a framework is developed with rules for measuring embodied and operational energy in a residential building. This will lead to easier comparison of case studies between countries and between buildings types.

Furthermore, the EE/OE ratios in this research were developed as a first step towards optimization of residential building energy use in the Netherlands. The next step can be a conversion of the embodied and operational energy use in CO_2 emission equivalents to the determine the environmental impact of the building types. Furthermore, a cost-analysis of the materials and appliances in a building can be performed to include costs in the optimization.

6. Conclusion

The purpose of this research was to show the effect of increasing energy efficiency on the embodied energy use in Dutch residential buildings. The analysis is executed using the already existing 3SCEP HEB model, and the newly built Embodied Energy database Management System (EEDMS). Three scenarios showed the embodied and operational energy use development for Dutch residential buildings between 2015 and 2050, from which EE/OE ratios resulted. 25 Dutch building representatives were defined using most common Dutch building types and vintages (based on energy performance and construction period).

The resulting embodied energy use in the 25 building representatives varies from 47 to 106 MJ/m^2/y. Of the building types, apartments have the lowest embodied energy use and mid-terraced homes, the highest. The higher shares in mid-terrace homes of softwood (9.3%), PUR (10.4%) and plywood (5,1%) are the reason of this higher embodied energy use. In apartments these shares are on average: softwood 0.3%, PUR 4.3% and plywood 2.7%. Of the building vintages, advanced new homes are most energy intensive, and standard homes are least energy intensive. Advanced new has on average 11.4% PUR, 7.9% mineral wool, 4.1% XPS, 1.1% EPS, and 7.8% aluminium, while standard homes have none of these materials. Precast- and reinforced concrete contribute most to the embodied energy in all building representatives, with on average 26.6% and 21% respectively.

The resulting operational energy use in the Dutch building representatives varies from 124 to 682 MJ/m^2/y. Of the building types, apartments have the lowest operational energy use and detached homes the highest. Of the building vintages, standard homes are most energy intensive, and advanced new homes are least energy intensive. The vintage that is most desirable, hence has the lowest operational energy and embodied energy use; is advanced retrofit. The ratio range of this building vintage is 0.39-0.55.

The scenario analysis showed a total energy use decrease in the frozen efficiency scenario of 11.6%, in the moderate efficiency scenario of 38% and in the deep efficiency scenario 40.2%. This is accompanied by an embodied energy increase of 5.4%, 12.7% and 15% respectively. In all scenarios the embodied to operational energy ratios start at 0.144 and increase to their maximum around 2045, which is 0.22 in the frozen scenario, 0.34 in the moderate scenario and 0.38 in the deep scenario. In the moderate and deep scenario, the increase in embodied energy use is mainly caused by an increase in advanced retrofit homes. Advanced retrofit homes are the most important vintage to consider when reducing total building energy use. However, if the building lifetime between retrofitted homes and non-retrofitted homes will appear to be the same (now retrofitted have a longer lifetime), advanced new can be a better option.

The overall conclusion is that embodied energy use will play a large role in the future. Currently the share operational energy in total energy use is larger, which makes it easier to neglect embodied energy use. However, when the share of advanced buildings (passive and/or nZEB) increases, the share of embodied energy use in total building energy use becomes much more important. Particularly in light of the goal to reach a maximum temperature increase of 2˚C it is important to include embodied energy use in future policy.

7. References

abf Research (2016). Trendsettend in cijfers. Retrieved on December 10th, 2016 from https://www.abfresearch.nl/

Adalberth, K. (1997). *Energy use during the life cycle of single-unit dwellings: Examples*. Doi:10.1016/S0360-1323(96)00069-8

Agentschap NL (2011). *Voorbeeldwoningen 2011: Bestaande bouw.* No. 2KPWB1034. Sittard. Available at: https://www.rvo.nl/sites/default/files/bijlagen/4.%20Brochure%20 Voorbeeldwoningen%202011%20bestaande%20bouw.pdf

Agentschap NL (2013). *Referentiewoningen nieuwbouw 2013.* Brochure. Sittard. Available at: https://www.rvo.nl/sites/default/files/2013/09/Referentiewoningen.pdf

Arasteh, D., Selkowitz, S., & Wolfe, J. R. (1989). The design and testing of a highly insulating glazing system for use with conventional window systems. *Journal of Solar Energy Engineering, 111*(1), 44-53. doi:10.1115/1.3268286

Backer van Ommeren, E. (2011). *Globale schets gasolieverbruik binnenvaartschepen.* Available at: http://www.evo.nl/site/binnenvaart-tarieven-kosten/$FILE/Globale_ schets_gasolieverbruik_binnenvaartschepen_06.pdf

Balaras, C. A., Droutsa, K., Dascalaki, E., & Kontoyiannidis, S. (2005). Heating energy consumption and resulting environmental impact of European apartment buildings. *Energy and Buildings, 37*(5), 429-442. doi:10.1016/j.enbuild.2004.08.003

Barrows, A., Stockman, J. C., & Taylor, A. G. (2013). *Access 2013: All-in-one for dummies*. New Jersey: John Wiley & Sons, Inc.

Berghuis, M. (2016). *Isolatie-eisen bij verbouw.* Nieman Groep, Helpdesk Bouwbesluit. Available at: http://www.nieman.nl/wp-content/uploads/2016/07/Isolatie-eisen-bij-verbouw.pdf

Bijleveld, M. M., Bergsma, G. C., Krutwagen, B. T. J. M., & Afman, M. A. (2015). *Meten is weten in de nederlandse bouw: Milieu-impacts van bouw- en sloopactiviteiten in 2010.* No. 14.2746.25. Delft: CE Delft, in assignment of Bouwend Nederland. Available at: http://www.bouwendnederland.nl/download.php?itemID=904337

Bjørn Petter, J. (2011). Traditional, state-of-the-art and future thermal building insulation materials and solutions – properties, requirements and possibilities. *Energy and Buildings, 43*(10), 2549-2563. doi:10.1016/j.enbuild.2011.05.015

Blok, K. (2009). *Introduction to Energy Analysis*. Second edition, p.28, 47-50. Amsterdam: Techne Press.

Bosschaert, T. (2009). *Energy and cost analysis of double and triple glazing.* Rotterdam: Except. Available at: http://media.except.nl/media/uploaded_files/asset_files/Energy_ and_cost_benefit_analysis_of_double_and_triple_glazing.pdf

Bot, P. (2009). *Vademecum historische bouwmaterialen, installaties en infrastructuur*. First edition, p. 237. Veerhuis.

Buchanan, A. H., & Honey, B. G. (1993). Energy and carbon dioxide impacts of building construction. Paper presented at the *IPENZ Annual Conference 1993, Proceedings of: Sustainable Development: Papers Prepared for the Conference, the University of Waikato, Hamilton, 5th-9th February,* 354. Available at: https://search.informit.com.au/documentSummary;dn=928109279519301;res=IELENG

Butlin, J. (1989). Our common future. By world commission on environment and development. London, Oxford University press, 1987, p.383. *Journal of International Development, 1*(2), 284-287. doi:10.1002/jid.3380010208

Cabeza, L. F., Rincón, L., Vilariño, V., Pérez, G., & Castell, A. (2014). Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renewable and Sustainable Energy Reviews, 29*, 394-416. doi:10.1016/j.rser.2013.08.037

CBS (2016a). Voorraad woningen; woningtype, bouwjaar, oppervlakte, regio. Retrieved on May 10th 2016 from http://statline.cbs.nl/Statweb/publication/?DM=SLNL&PA=82550ned&D1=0&D2=a&D3=0,118&D4=a&VW=T

CBS (2016b). Vier op de tien huishoudens wonen in een rijtjeshuis. Retrieved on November 15th, 2016 from https://www.cbs.nl/nl-nl/nieuws/2016/14/vier-op-de-tien-huishoudens-wonen-in-een-rijtjeshuis

CBS (2017). Bevolking; kerncijfers. Retrieved on December 20nd, 2016 from http://statline.cbs.nl/StatWeb/publication/?PA=37296ned&D1=a&D2=0,10,20,30,40,50,60,(l-1),l&HDR=G1&STB=T

CE Delft (2016). Onafhankelijke denktank met durf. Retrieved on January 5th, 2017 from http://www.ce.nl/ce/over_ce_delft/100

Centrum Hout (2005). *Producten, toepassingen en aanbevelingen: Naaldhout in de bouw.* Almere: Centrum Hout. Available at: http://www.centrum-hout.nl/sites/default/files/u27/houtwijzer_naaldhout-in-de-bouw_jan2005.pdf

Chastas, P., Theodosiou, T., & Bikas, D. (2016). Embodied energy in residential buildings-towards the nearly zero energy building: A literature review. *Building and Environment, 105*, 267-282. doi:10.1016/j.buildenv.2016.05.040

Chen, T. Y., Burnett, J., & Chau, C. K. (2001). Analysis of embodied energy use in the residential building of Hong Hong. *Energy, 26*(4), 323-340. doi:10.1016/S0360-5442(01)00006-8

Circular Ecology (2011). *Embodied energy and carbon - the ICE database.* Available at http://www.circularecology.com/embodied-energy-and-carbon-footprint-database.html#.WOd1OdLyiHs

Circular Ecology (2016). Glossary of terms and definitions. Retrieved on January 2nd, 2017 from http://www.circularecology.com/glossary-of-terms-and-definitions.html#. WKc72fnhDDc

Crowther, P. (1999). Design for disassembly to recover embodied energy. *Proceedings of Passive and Low-Energy Architecture*. Melbourne

CvAE (2017). Retrieved on February 6th 2017 from https://www.cvae.nl/keramiek/keramiek

Debnath, A., Singh, S. V., & Singh, Y. P. (1995). *Comparative assessment of energy requirements for different types of residential buildings in india* doi:10.1016/0378-7788(95)00939-6

DGBC (2016). Materialentool. Available at https://www.dgbc.nl/materialentool

Dixit, M. K., Fernández-Solís, J. L., Lavy, S., & Culp, C. H. (2010). Identification of parameters for embodied energy measurement: A literature review. *Energy and Buildings*, *42*(8), 1238-1247. doi:10.1016/j.enbuild.2010.02.016

EICB (2017). Schepen. Retrieved on February 6th, 2017 from https://informatie.binnenvaart.nl/schepen

European Parliament and the Council of the European Union (2010). Richtlijn 2010/31/EU van het europees parlement en de raad van 19 mei 2010: Betreffende de energieprestatie van gebouwen (herschikking). Available at: http://eur-lex.europa.eu/legal-content/NL/TXT/PDF/?uri=CELEX:32010L0031&from=EN

Geertsma, p. (2014). Wat is bitumen en waarvoor wordt bitumen gebruikt? Retrieved on February 6th 2017 from http://www.technischwerken.nl/kennisbank/techniek-kennis/wat-is-bitumen-en-waarvoor-wordt-bitumen-gebruikt/

Gemeente Rotterdam (2017). Een huis uit de jaren 60 en 70. Retrieved on October 12th, 2016 from http://www.rotterdamenergiebesparing.nl/woningsoorten/een-huis-uit-de-jaren-1960-en-1970/

Goggins, J., Keane, T., & Kelly, A. (2010). The assessment of embodied energy in typical reinforced concrete building structures in Ireland. *Energy and Buildings, 42*(5), 735-744. doi:10.1016/j.enbuild.2009.11.013

Hopwood, B., Mellor, M., & O'Brien, G. (2005). Sustainable development: Mapping different approaches. *Sustainable Development*, *13*(1), 38-52. doi:10.1002/sd.244

Institut Wohnen und Umwelt GmBH (2016). Section "building typologies"- principles and functions in a nutshell. Retrieved on February 20th, 2017 from http://episcope.eu/building-typology/webtool/

IPCC (2014). *Climate change 2014: Synthesis report. contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change*. [core writing team, R.K. pachauri and L.A. meyers]. IPCC, Geneva, Switzerland. P. 151.

Available at: https://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full_wcover.pdf

IRU (2009). *"Wist u het?" cijfers en gegevens over het wegvervoer in europa.* Available at: http://febetra.be/wp-content/uploads/2014/07/Wist-u-het.pdf

Kajikawa, Y. (2008). Research core and framework of sustainability science. *Sustainability Science, 3*(2), 215. doi:10.1007/s11625-008-0053-1

KNB (2013). Gevelbaksteen. Retrieved on February 6th, 2017 from http://www.knb-keramiek.nl/themas/baksteen/

Langston, Y. L., & Langston, C. A. (2008). Reliability of building embodied energy modelling: An analysis of 30 Melbourne case studies. *Construction Management and Economics, 26*(2), 147. doi:10.1080/01446190701716564

Liebregts, M., & Persoon, J. (2011). Technische eigenschappen van het woningcasco in de tijd. Retrieved on September 22th 2016 from http://www.bestaandewoningbouw.nl/technische-eigenschappen-van-het-woningcasco-in-de-tijd/

Meijer, F., Itard, L., & Sunikka-Blank, M. (2009). Comparing European residential building stocks: Performance, renovation and policy opportunities. *Building Research & Information, 37*(5-6), 533-551. doi:10.1080/09613210903189376

Ministry of Internal Affairs and Kingdom Relations (2016). *Cijfers over wonen en bouwen 2016.* Den Haag. Available at: https://vois.datawonen.nl/jive/report?id=cow2016

Monier (2016). Daktechniek. Available at http://www.monier.nl/fileadmin/bu-files/nl/Algemene_daktechniek/Technisch_HandboekPDF/Technisch_Handboek_NIEUW/Monier_TH_8_Daktechniek.pdf

Moors, E. H. M. (2006). Technology strategies for sustainable metals production systems: A case study of primary aluminium production in the Netherlands and Norway. *Journal of Cleaner Production, 14*(12–13), 1121-1138. doi:10.1016/j.jclepro.2004.08.005

Pérez-Lombard, L., Ortiz, J., & Pout, C. (2008). A review on buildings energy consumption information. *Energy and Buildings, 40*(3), 394-398. doi:10.1016/j.enbuild.2007.03.007

PHI (2015). *Defining the nearly zero energy building, passive house + renewables: Municipalities lead the way.* Darmstadt, Germany: Passive House Institute. Available at: https://ec.europa.eu/easme/sites/easme-site/files/Defining%20the%20Nearly%20Zero%20Energy%20Building.pdf

Proietti, S., Sdringola, P., Desideri, U., Zepparelli, F., Masciarelli, F., & Castellani, F. (2013). Life cycle assessment of a passive house in a seismic temperate zone. *Energy and Buildings, 64,* 463-472. doi:10.1016/j.enbuild.2013.05.013

Ramesh, T., Prakash, R., & Shukla, K. (2010). Life cycle energy analysis of buildings: An overview. *Energy and Buildings, 42*(10), 1592-1600. doi:10.1016/j.enbuild.2010.05.007

RDW (2012). *Overzicht maten en gewichten in nederland.* Available at: https://www.rdw.nl/SiteCollectionDocuments/Ontheffingen%20(TET)/Themasite%20Ontheffingen/Handleidingen/2%20B%201097b%20Overzicht%20maten%20en%20gewichten.pdf

RVO (2015a). *Referentiewoning EPC 0,4 tussenwoning.* Utrecht: RVO. Available at: http://www.rvo.nl/sites/default/files/2015/10/Tussenwoning%20-%20referentiewoning.pdf

RVO (2015b). *Referentiewoning EPC 0,4 hoekwoning.* Utrecht: RVO. Available at: http://www.rvo.nl/sites/default/files/2015/10/Hoekwoning%20-%20referentiewoning.pdf

RVO (2015c). *Referentiewoning EPC 0,4 twee-onder-eenkapwoning.* Utrecht: RVO. Available at: http://www.rvo.nl/sites/default/files/2015/10/Twee-onder-een-kapwoning%20-%20referentiewoning.pdf;

RVO (2015d). *Referentiewoning EPC 0,4 vrijstaande woning.* Utrecht: RVO. Available at: http://www.rvo.nl/sites/default/files/2015/10/Vrijstaande%20woning%20-%20referentiewoning.pdf;

RVO (2015e). *Referentiewoning EPC 0,4 appartementencomplex.* Utrecht: RVO. Available at: http://www.rvo.nl/sites/default/files/2015/10/Appartementencomplex%20-%20referentiewoning.pdf

RVO (2016a). Energieprestatie (EPC). Retrieved on August 30th, 2016 from http://www.rvo.nl/onderwerpen/duurzaam-ondernemen/gebouwen/energieprestatie

RVO (2016b). Energieprestatie-eisen bij renovaties. Retrieved on December 2nd, 2016 from http://www.rvo.nl/onderwerpen/duurzaam-ondernemen/gebouwen/wetten-en-regels-gebouwen/energieprestatie-epc/energieprestatie-eisen-bij-renovaties

Saltelli, A., Tarantola, S., & Chan, K. P. (1999). A quantitative model-independent method for global sensitivity analysis of model output. *Technometrics, 41*(1), 39-56.

Sarangapani, G., Venkatarama Reddy, B. V., & Jagadish, K. S. (2005). Brick-mortar bond and masonry compressive strength. *Journal of Materials in Civil Engineering, 17*(2), 229-237.

Sartori, I., & Hestnes, A. G. (2007). Energy use in the life cycle of conventional and low-energy buildings: A review article. *Energy and Buildings, 39*(3), 249-257. doi:10.1016/j.enbuild.2006.07.001

SBRCURnet (2015). Passiefhuisconcept voor woningbouw. Retrieved on September 10th, 2016 from http://www.sbrcurnet.nl/producten/infobladen/passiefhuisconcept-voor-woningbouw

SBRCURnet (2017a). Over SBRCURnet: Kennispartner in de bouw en GWW. Retrieved on September 10th, 2016 from http://www.sbrcurnet.nl/over-sbrcurnet

SBRCURnet (2017b). SBR-referentiedetails. Retrieved on September 10th, 2016 from http://www.sbrcurnet.nl/producten/referentiedetails

SenterNovem (2005). *Woningen met EPC ≤ 0,8: Berekend met de herziening van NEN 5128.* Brochure No. 1KPWB 05.02. SenterNovem, Sittard. Available at: file:///C:/Windows/Temp/39br2005g004-2008514-101522.pdf

SEV (2004). *Bouwen met tijd: Een praktische verkenning naar de samenhang tussen levensduur, kenmerken en milieubelasting van woningen.* Den Haag: Ministerie van VROM. Available at: http://www.slimbouwen.nl/fileadmin/user_upload/documents/Bouwen%20met%20tijd.pdf

Skantrae (2017). Standaard deurmaten. Retrieved on January 20th, 2017 from https://www.skantrae.com/service-advies/veelgestelde-vragen/binnendeur/standaard-deurmaten/

Sorrell, S. (2007). The rebound effect: An assessment of the evidence for economy-wide energy savings from improved energy efficiency. Available at: http://ukerc.rl.ac.uk/UCAT/PUBLICATIONS/The_Rebound_Effect_An_Assessment_of_the_Evidence_for_Economy-wide_Energy_Savings_from_Improved_Energy_Efficiency.pdf

Stephan, A. (2013). *Towards a comprehensive energy assessment of residential buildings: A multi-scale life cycle energy analysis framework.* PhD thesis, Brussels School of Engineering, Université Libre de Bruxelles & Faculty of Architecture, Building and Planning, The University of Melbourne. Available at: https://minerva-access.unimelb.edu.au/bitstream/handle/11343/38263/300596_Andre%20Stephan_PhD_Towards_a_comprehensive_energy_assessment_of_res._bldgs.pdf?sequence=1

Stephan, A., Crawford, R. H., & de Myttenaere, K. (2012). Towards a comprehensive life cycle energy analysis framework for residential buildings. *Energy and Buildings, 55*, 592-600. doi:10.1016/j.enbuild.2012.09.008

Takano, A., Pal, S. K., Kuittinen, M., & Alanne, K. (2015). Life cycle energy balance of residential buildings: A case study on hypothetical building models in Finland. *Energy and Buildings, 105*, 154-164. doi:10.1016/j.enbuild.2015.07.060

Timmermans, M. (2014). Renovatie buitengevel zorgt voor win-winsituatie. Retrieved on March 2nd, 2017 from http://www.innozaam.com/renovatie-buitengevel-zorgt-voor-win-winsituatie/

Tremco Illbruck (2017). U waarde (glas) en R waarde (isolatie). Retrieved on January 10th, 2017 from http://www.luchtdichtbouwen.nl/nieuws/u-waarde-en-r-waarde

Trusty, W., & Horst, S. (2005). LCA tools around the world. *Building Design and Construction, 5*, 12-16.

TU Delft (2015). *Tabula WebTool.* Available at: http://webtool.building-typology.eu/#bm

Urge-Vorsatz, D., Petrichenko, K., Antal, M., Staniec, M., Labelle, M., Ozden, E., & Labzina, E. (2012). *Best practice policies for low energy and carbon buildings. A scenario analysis.* Budapest, Global Buildings Performance Network. Available at: http://www.gbpn.org/sites/default/files/08.CEU%20Technical%20Report%20copy_0.pdf

Urge-Vorsatz, D., Petrichenko, K., Staniec, M., & Eom, J. (2013). Energy use in buildings in a long-term perspective. *Current Opinion in Environmental Sustainability, 5*(2), 141. doi:10.1016/j.cosust.2013.05.004

Venkatarama Reddy, B. V., & Jagadish, K. S. (2003). Embodied energy of common and alternative building materials and technologies. *Energy and Buildings, 35*(2), 129-137. doi:10.1016/S0378-7788(01)00141-4

Veronove (2016). Keramische muurtegels. Retrieved on December 22nd, 2016 from http://www.veronove.be/nl/info/167/Muurtegels.html

VROM (2007). *Oppervlakte verdiepingsdocument voor gemeenten.* No. 2.0. Den Haag, VROM Advice and Expert service. Available at: https://www.kadaster.nl/documents/20838/87954/BAG+verdiepingsdocument+oppervlakte/08bb2abd-b22d-43cd-af82-8c9e89dc0076

Weiler, V., Harter, H., & Eicker, U. (2017). Life cycle assessment of buildings and city quarters comparing demolition and reconstruction with refurbishment. *Energy and Buildings, 134*, 319-328. doi:10.1016/j.enbuild.2016.11.004

Worrell, E., van Heijningen, R. J. J., de Castro, J. F. M., Hazewinkel, J. H. O., de Beer, J. G., Faaij, A. P. C., & Vringer, K. (1994). New gross energy-requirement figures for materials production. *Energy vol. 19, No. 6, pp.627-640. Elsevier Science.* doi:10.1016/0360-5442(94)90003-5

Xella Group (2017). Cellenbeton. Retrieved on February 6th, 2017 from http://www.xella.nl/cellenbeton_3962.php

Zinkbouwmarkt.nl (2017). Maatvoeringen. Retrieved on February 6th, 2017 from https://www.zinkbouwmarkt.nl/maatvoeringen-dakgoten

Appendix A: Calculations gross floor area building types

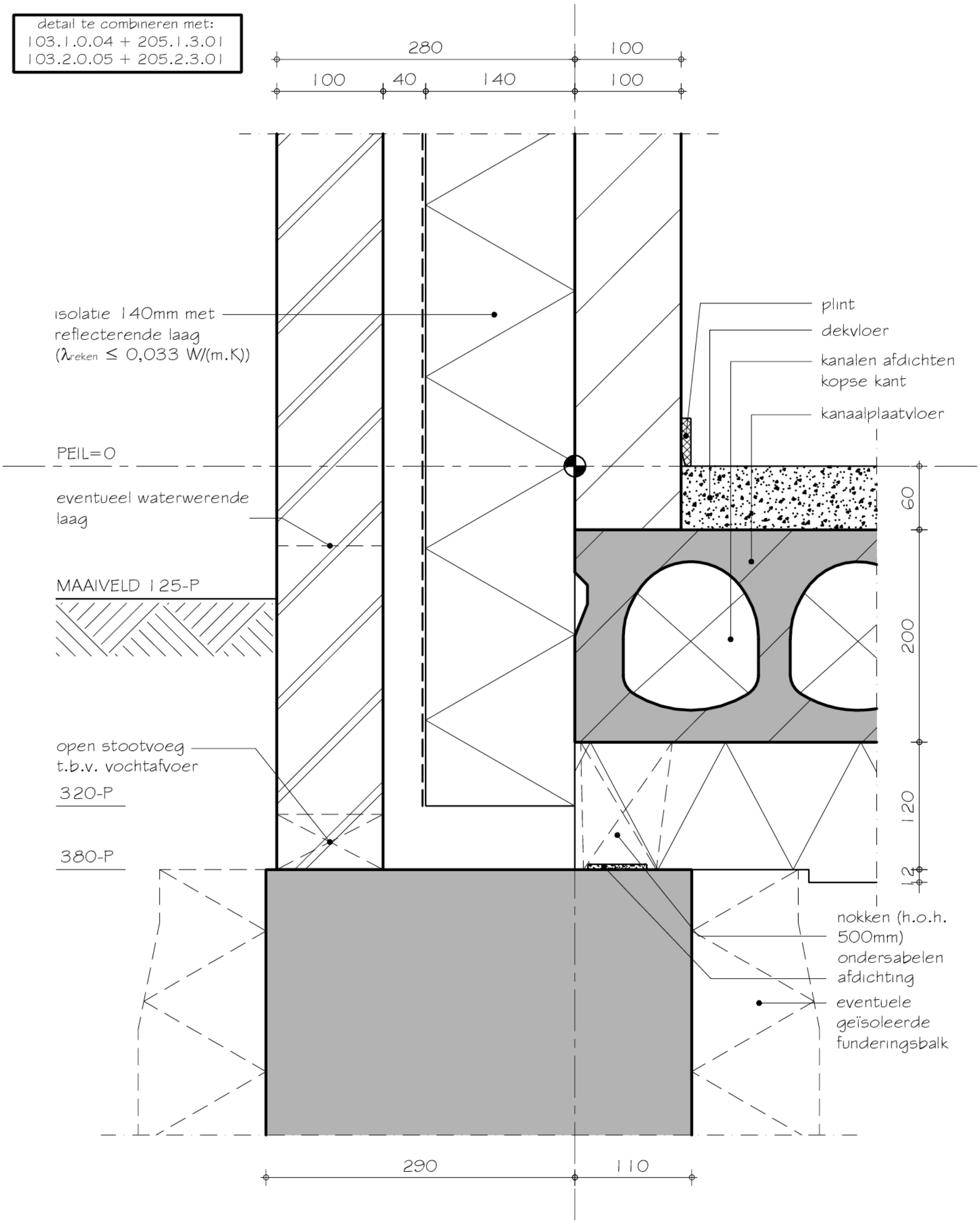
The table below shows the conversion of user surface areas obtained from Agentchap NL (2011) and RVO (2015a-e) into gross floor area (BVO) values, used in the DGBC tool (2016).

Terraced BVO *standard home* is 106 m^2/0.79= 134.18 m^2
Terraced BVO *new home* is 124.3 m^2/0.79= 157.34 m^2
Detached BVO *standard home* is 144 m^2/0.75= 192 m^2
Detached BVO *new home* is 169.5 m^2/0.75= 226 m^2
Semidetached BVO *standard home* is 123 m^2/0.76= 161.84 m^2
Semidetached BVO *new home* is 147.7 m^2/0.76= 194.34 m^2
Apartment BVO *standard home* is 76.67 m^2/0.9=85.19 m^2
Apartment BVO *new home* is 91.9 m^2/0.9=102.11 m^2

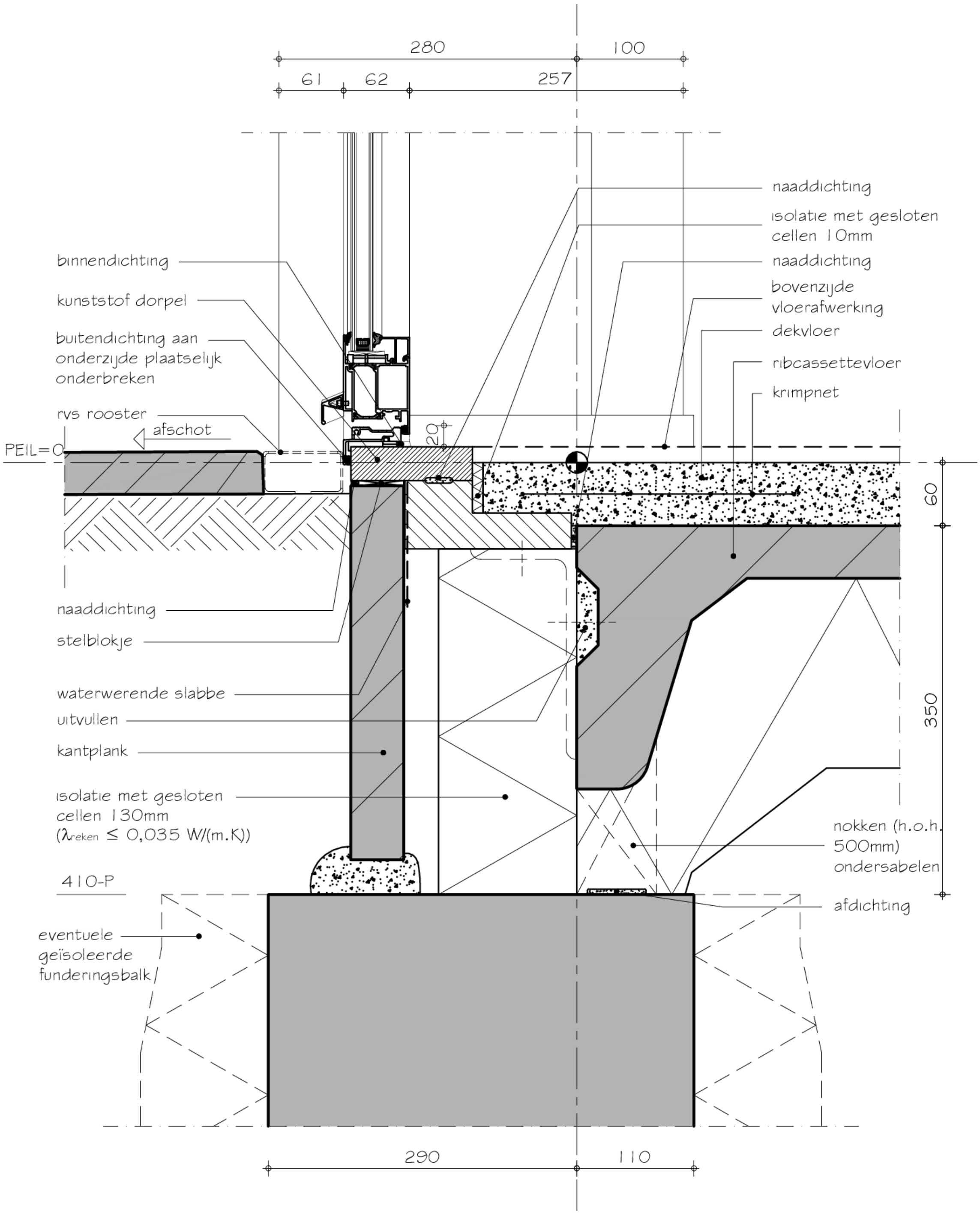
Appendix B: SBR Referencedetails

B.1 New vintage

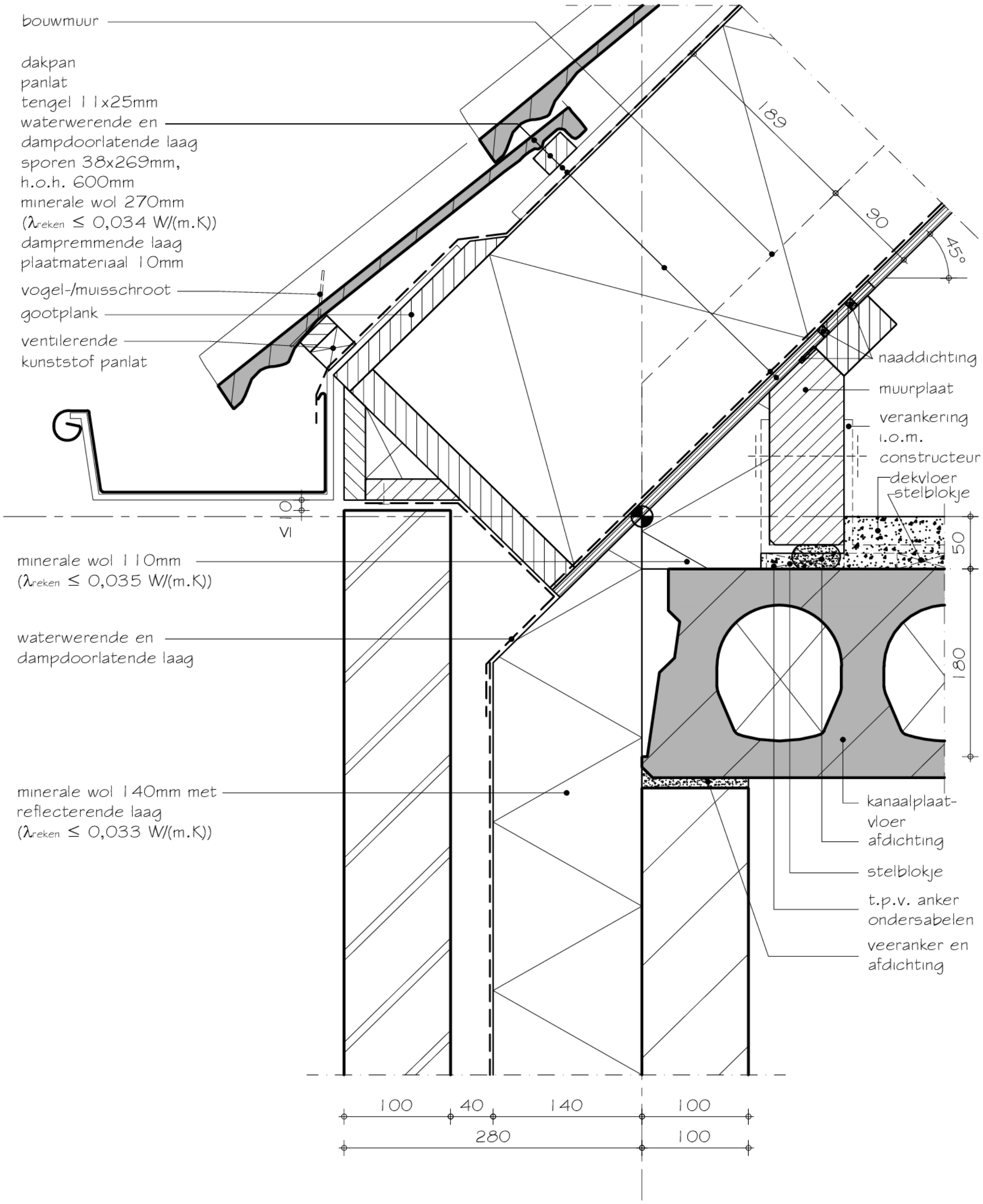
B.1a SBR referencedetail (2015) 101.0.3.02, Title: Kanaalplaatvloer



B.1b SBR referencedetail (2015) 102.0.3.16, Title: Aluminium kozijn, naar binnen draaiende deur

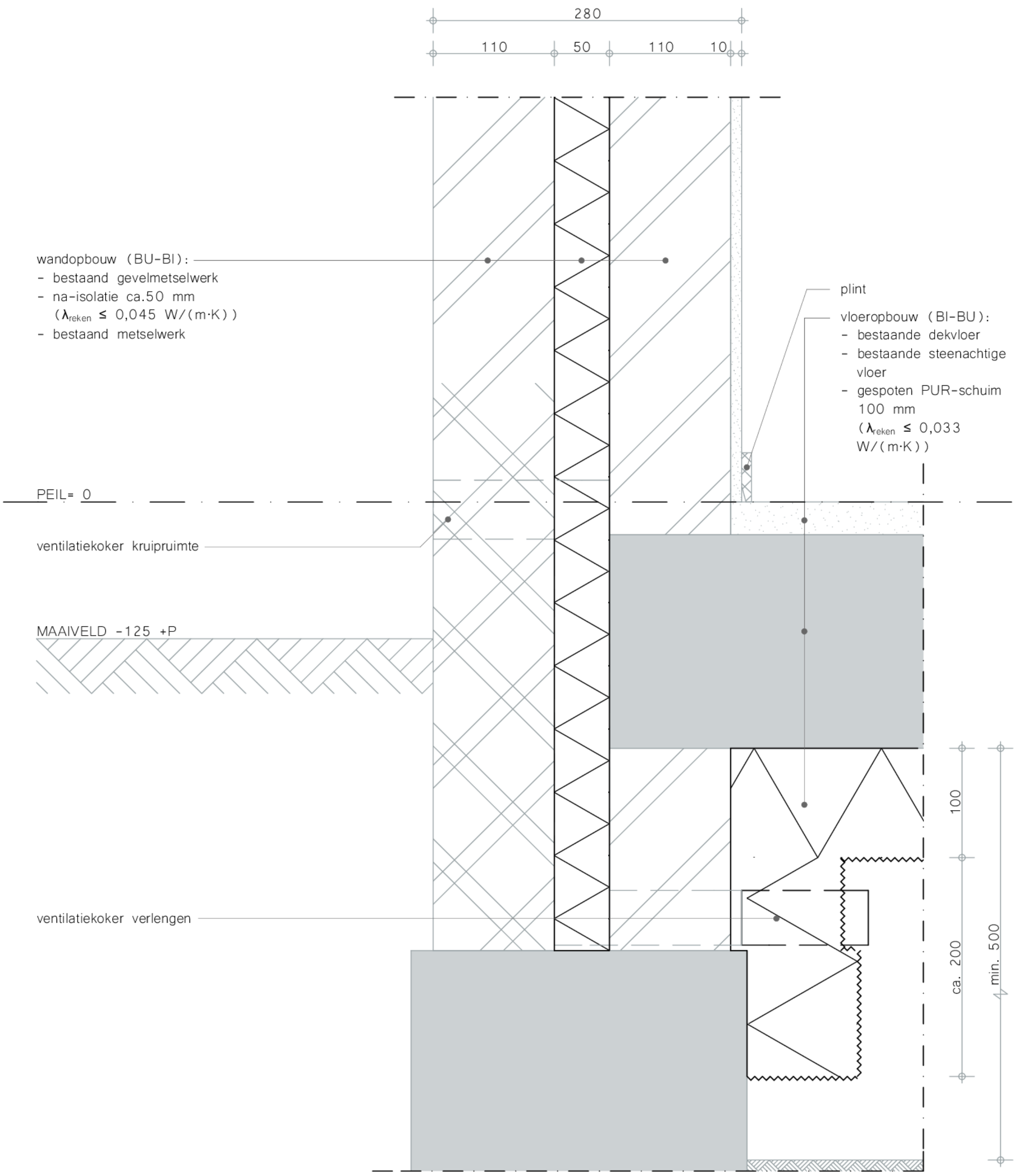


B.1c SBR referencedetail (2015) 401.0.1.03, Title: Kanaalplaatvloer

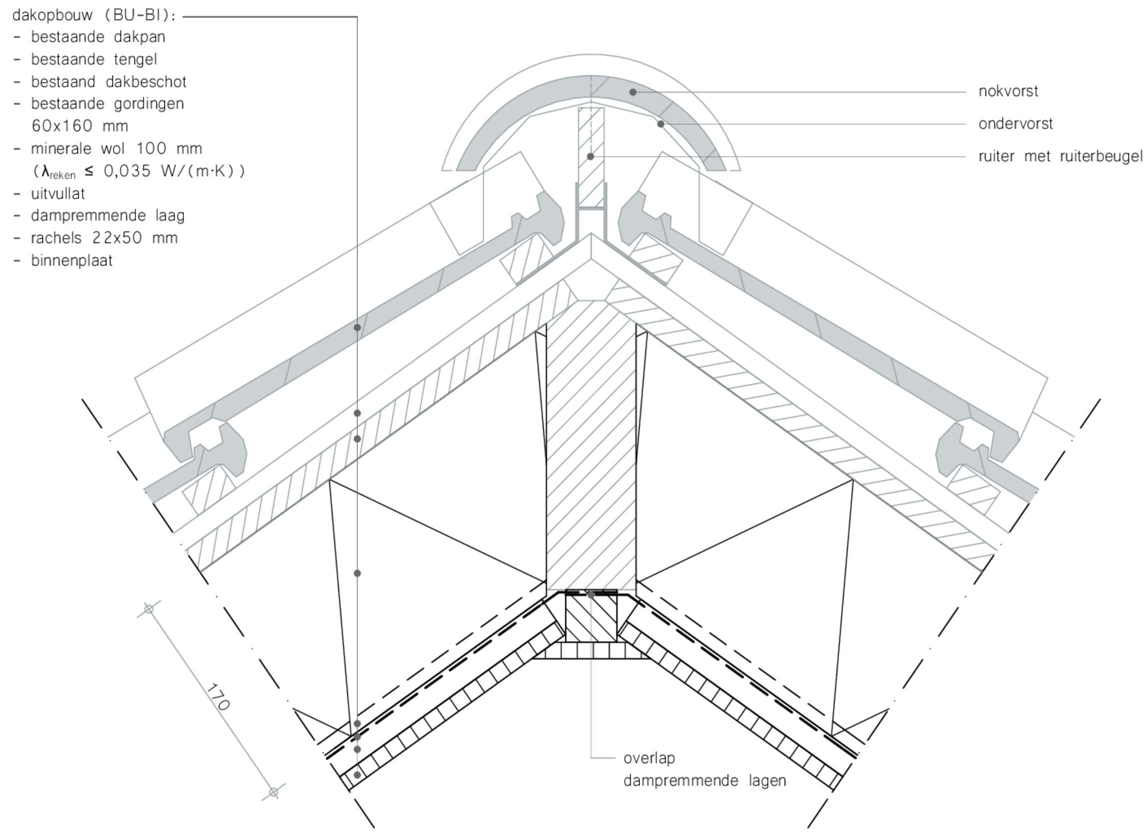


B.2 Retrofit vintage

B.2a SBR referencedetail (2016) B 101.7.3.01, Title: vloerisolatie d.m.v. gespoten polyurethaanschuim

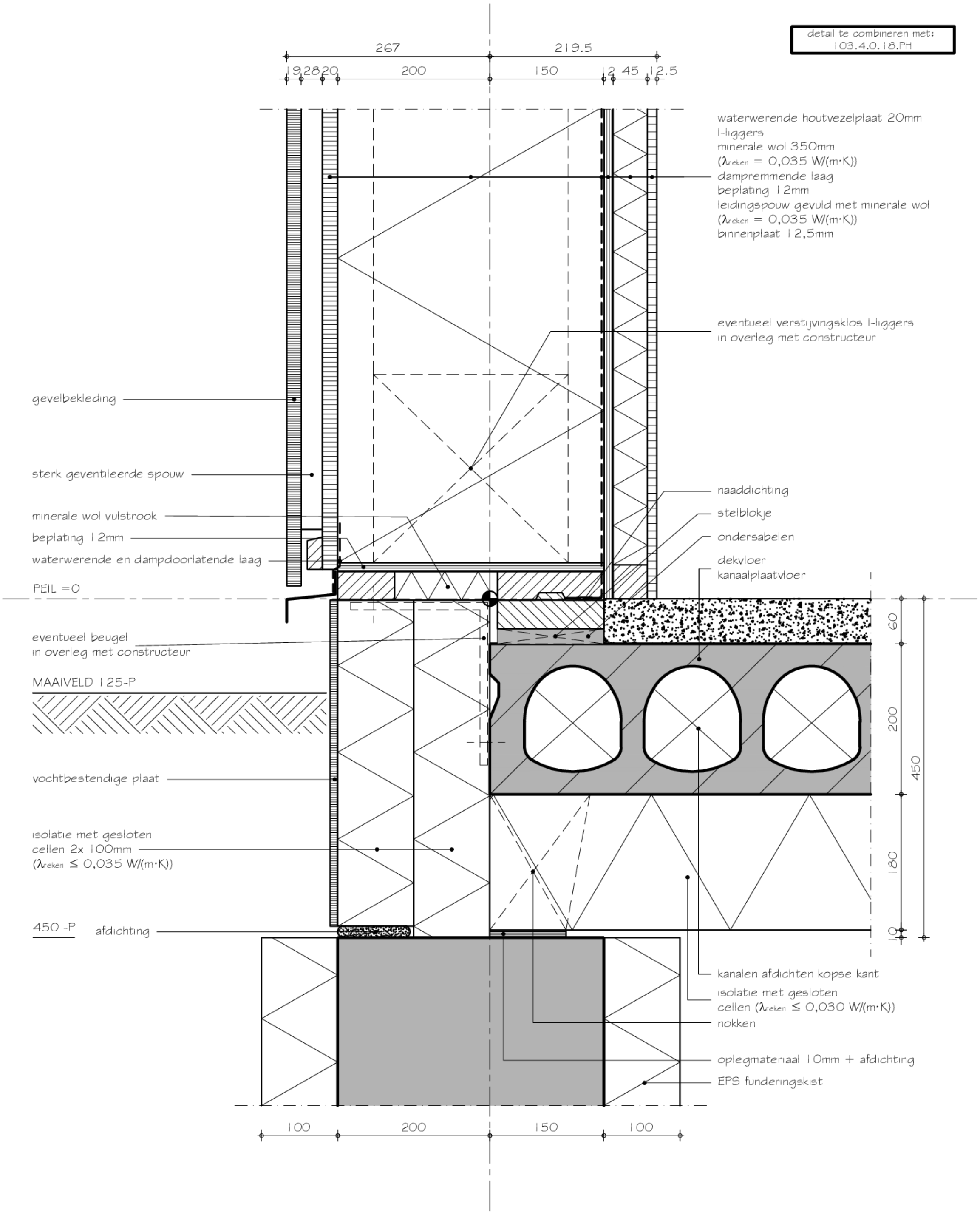


B.2b SBR referencedetail (2016) B 404.0.0.08, Title: Bestaand dakbeschot, na-isolatie binnenzijde

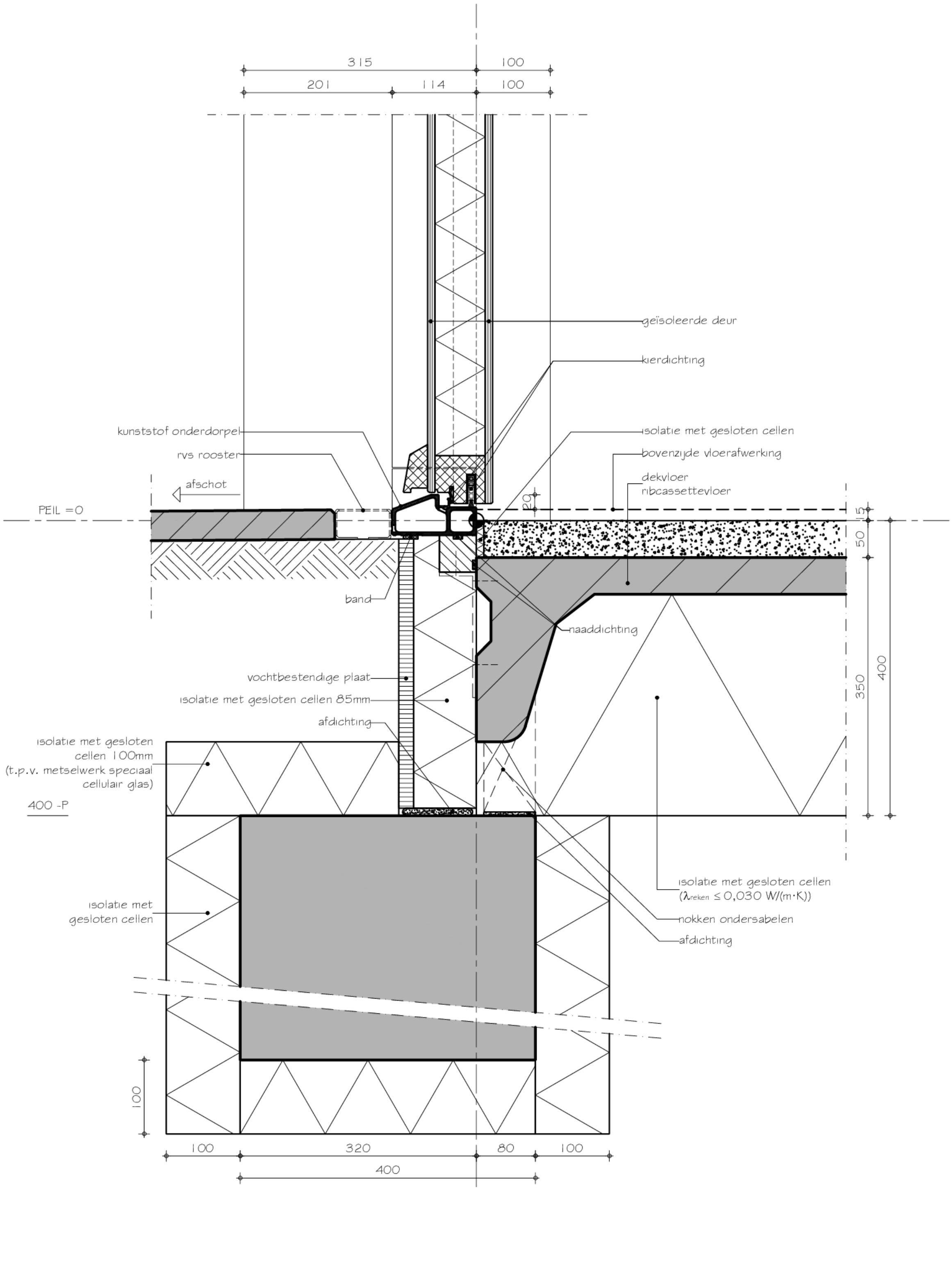


B.3 Advanced new vintage

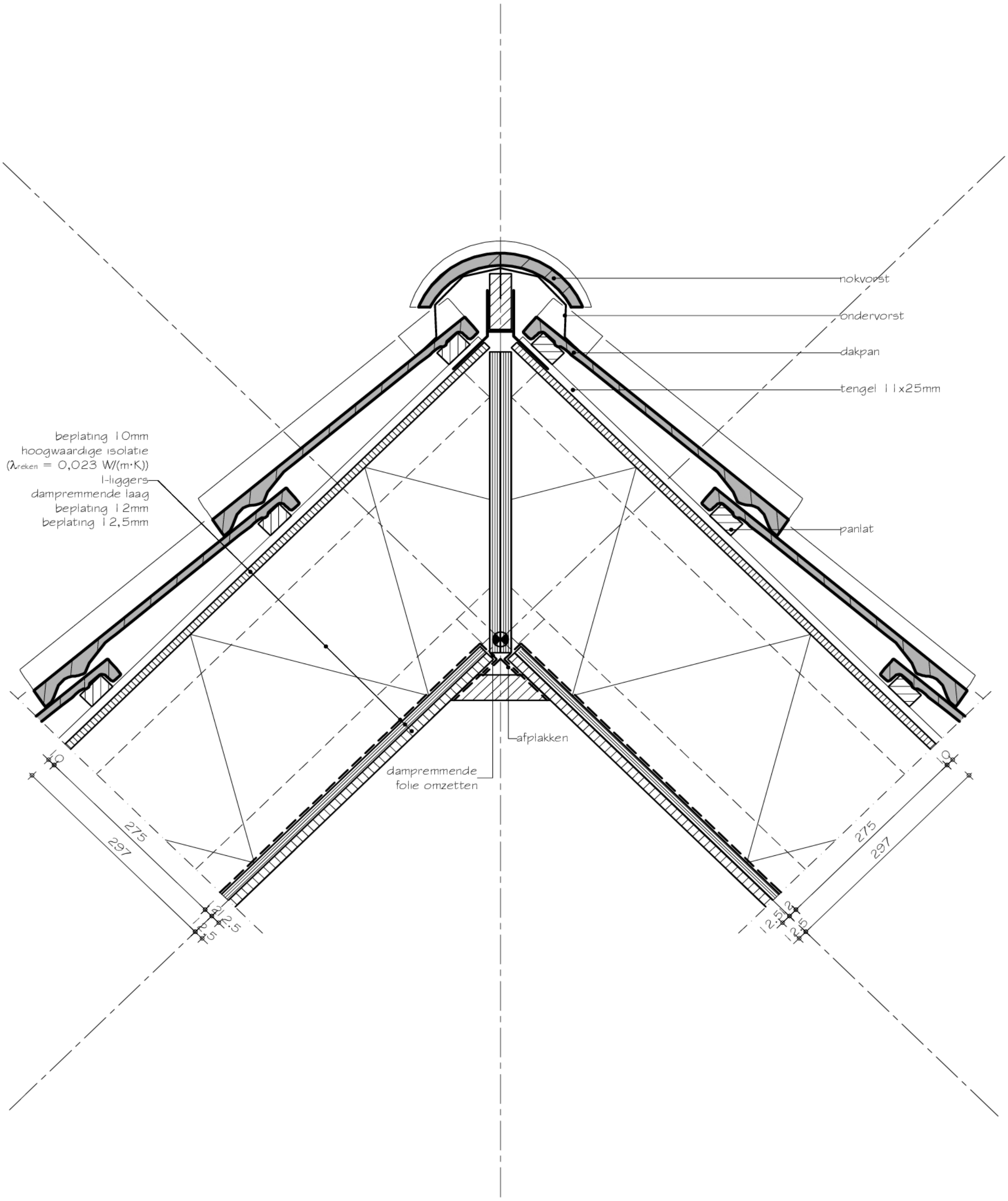
B.3a SBR referencedetail (2015) 101.4.2.04.PH , Title: Passiefhuis, HSB-element met L-ligger en leidingspouw, kanaalplaatvloer, geisoleerde fundering



B.3b SBR referencedetail (2009) 102.0.3.04.PH, Title: Passiefhuis, geïsoleerde dorpel, naar binnen draaiende geïsoleerde deur, ribcassette vloer, geïsoleerde fundering

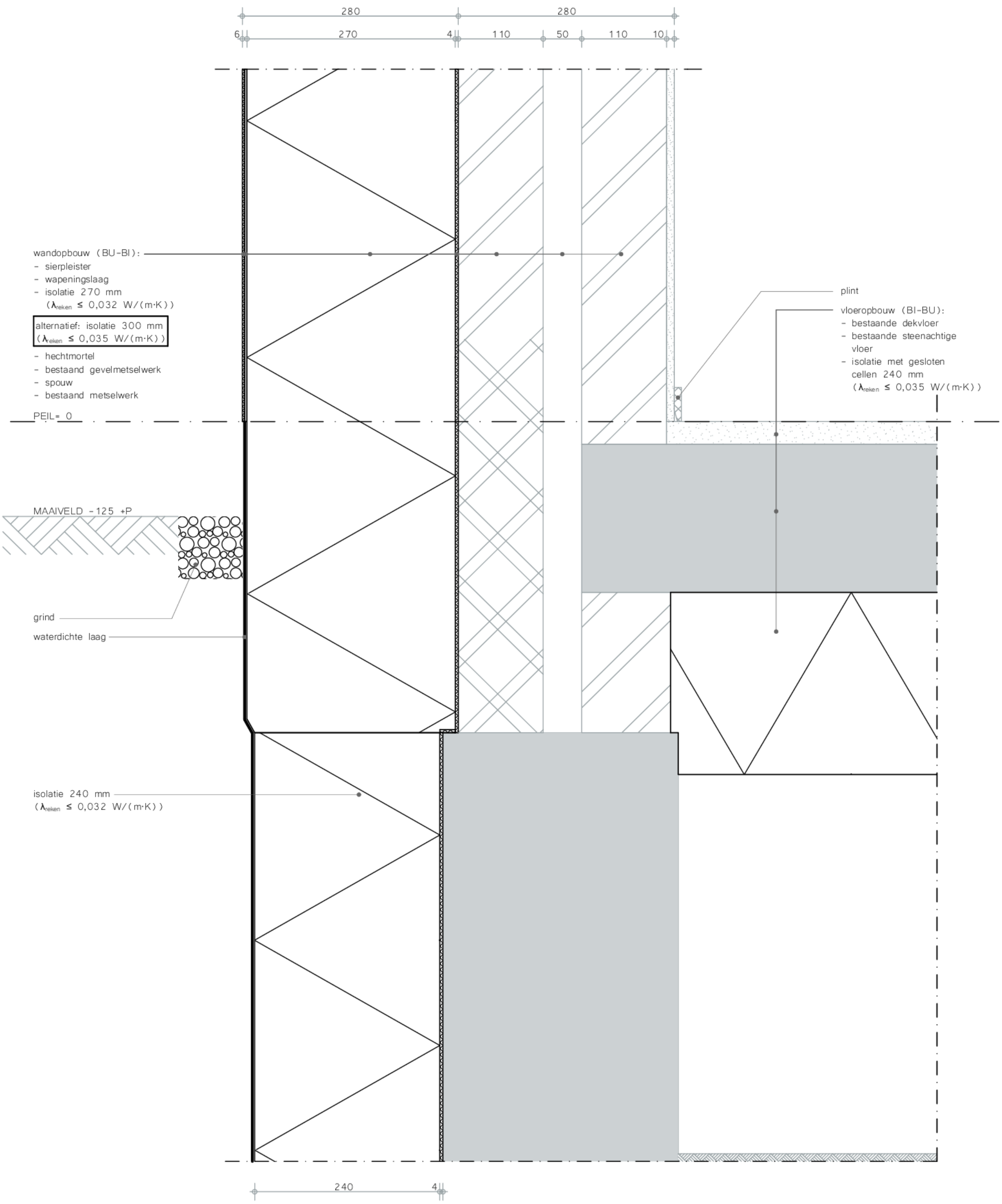


B.3c SBR referencedetail (2009) 404.0.0.01.PH, Title: Passiefhuis, sporenkap met I-ligger, gevuld met hoogwaardige isolatie, vaste nokaansluiting

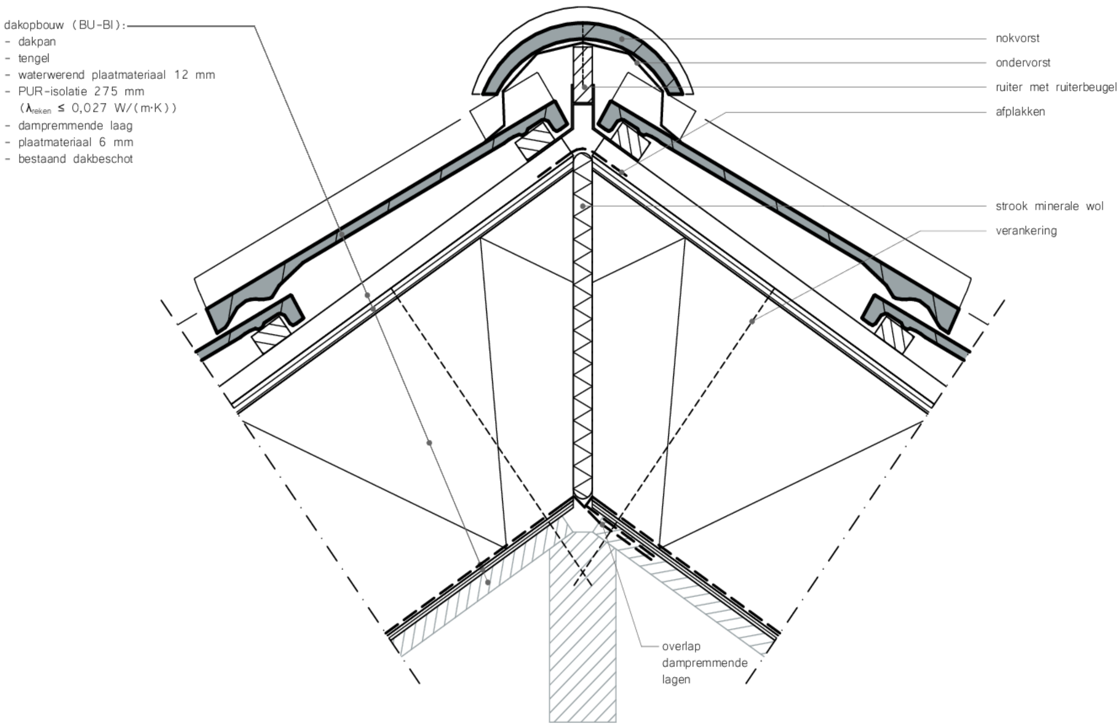


B.4 Advanced retrofit vintage

B.4a SBR referencedetail (2016) B103.7.0.02, Title: Passiefhuis, buitengevelisolatie



B.4b SBR referencedetail (2016) B404.0.0.05, Title: Passiefhuis, bestaand dakbeschot



Appendix C: Material volumes per building representative

C.1 Mid-terraced

C.1.1 Standard

	Material	Surface	Thickness	Volume
		m2	m	m3
Structure	Precast concrete	34.26	0.40	13.70
	Concrete poles	71.72	0.02	1.41
	Precast concrete	15.68	0.40	6.27
	Cast-in concrete with reinforcement	7.61	0.28	2.13
	Sand	34.26	1.00	34.26
Facade	Single glass	10.35	0.01	0.10
	Softwood window frames	1.83	0.06	0.11
	Softwooden doors	2.54	0.04	0.10
	Brick masonry, outside wall	38.64	0.10	3.86
	Precast concrete	38.64	0.10	3.86
Inside walls	Cast-in concrete with reinforcement	64.71	0.25	16.18
	Gypsum	54.24	0.10	5.42
	Ceramic tiles	30.45	0.01	0.30
	Plywood inside doors	13.96	0.04	0.54
Floors	Cast-in concrete with reinforcement	45.68	0.28	12.79
	Sand cement	45.68	0.04	1.83
	Kwaaitaal & Breedplaat floor: precast concrete	88.50	0.20	17.70
	Sand cement	107.34	0.06	6.44
	Ceramic tiles	7.33	0.01	0.07
	Plywood	64.71	0.01	0.78
Roof	Concrete tiles	61.59	0.02	1.29
	Softwood, pitched roof	61.59	0.20	12.32
	Plywood, sheet flat roof	7.61	0.28	2.15
	Bitumen	7.61	0.02	0.14
	Gravel	7.61	0.05	0.38
	PVC rainwater drains	2.02	0.002	0.004
	Zinc gutters	1.34	0.20	0.27

C.1.2 New

	Material	Surface	Thickness	Volume
		m2	m	m3
Structure	Precast concrete	40.16	0.40	16.07
	Hardwooden poles	84.06	0.02	1.65
	Precast concrete	18.39	0.40	7.36
	Cast-in concrete with reinforcement	8.92	0.28	2.50
	Sand	40.16	1.00	40.16
Facade	HR glass	12.14	0.01	0.13
	Aluminium window frames	2.14	0.06	0.13
	Aluminium doors	4.31	0.04	0.17
	Brick masonry, outside wall	45.29	0.10	4.53
	Mineral wool	45.29	0.14	6.34
	Precast concrete	45.29	0.10	4.53
Inside walls	Cast-in concrete with reinforcement	75.86	0.25	18.97
	Aerated concrete	63.59	0.10	6.36
	Ceramic tiles	35.70	0.01	0.36
	Plywood inside doors	23.68	0.04	0.92
Floors	Cast-in concrete with reinforcement	53.55	0.28	14.99
	Sand cement	53.55	0.04	2.14
	EPS	53.55	0.12	6.43
	Hollow-core slab: precast concrete	103.75	0.20	20.75
	Sand cement	125.84	0.06	7.55
	Ceramic tiles	8.59	0.01	0.09
	Meranti wooden floor (plywood)	75.86	0.01	0.91
Roof	Concrete tiles	72.20	0.02	1.52
	Softwood, pitched roof	72.20	0.20	14.44
	Plywood, sheet flat roof	8.92	0.28	2.52
	Bitumen	8.92	0.02	0.16
	Gravel	8.92	0.05	0.45
	PVC rainwater drains	2.37	0.002	0.004
	Zinc gutters	1.57	0.20	0.32
	Mineral wool	81.12	0.27	21.90

C.1.3 Retrofit

	Material	Surface	Thickness	Volume
		m2	m	m3
Structure	Precast concrete	34.26	0.40	13.70
	Concrete poles	71.72	0.02	1.41
	Precast concrete	15.68	0.40	6.27
	Cast-in concrete with reinforcement	7.61	0.28	2.13
	Sand	34.26	1.00	34.26
Facade	Single glass	10.53	0.01	0.11
	HR glass	10.53	0.01	0.12
	Softwood window frames	1.88	0.06	0.12
	Softwooden doors	2.54	0.39	0.99
	Brick masonry, outside wall	38.64	0.10	3.86
	Mineral wool	38.64	0.05	1.93
	Precast concrete	38.64	0.10	3.86
Inside walls	Cast-in concrete with reinforcement	64.71	0.25	16.18
	Gypsum	54.24	0.10	5.42
	Ceramic tiles	30.45	0.01	0.30
	Plywood inside doors	13.96	0.04	0.54
Floors	Cast-in concrete with reinforcement	45.68	0.28	12.79
	Sand cement	45.68	0.04	1.83
	PUR foam	45.68	0.10	4.57
	Kwaaitaal & Breedplaat floor: precast concrete	88.50	0.20	17.70
	Sand cement	107.34	0.06	6.44
	Ceramic tiles	7.33	0.01	0.07
	Plywood	64.71	0.01	0.78
Roof	Concrete tiles	61.59	0.03	1.85
	Softwood, pitched roof	61.59	0.20	12.32
	Plywood, sheet flat roof	7.61	0.28	2.15
	Bitumen	7.61	0.02	0.14
	Gravel	7.61	0.05	0.38
	PVC rainwater drains	2.02	0.002	0.004
	Zinc gutters	1.34	0.20	0.27
	Mineral wool	69.20	0.10	6.92

When retrofitting a standard home:

is replaced
is added

C.1.4 Advanced new

	Material	Surface	Thickness	Volume
		m2	m	m3
Structure	Precast concrete	40.16	0.40	16.07
	Hardwooden poles	84.06	0.02	1.65
	Precast concrete	18.39	0.40	7.36
	Cast-in concrete with reinforcement	8.92	0.28	2.50
	EPS	35.68	0.10	3.57
	Sand	41.24	1.00	41.24
Facade	HR ++ glass	12.14	0.01	0.13
	Argon	12.14	0.02	0.18
	Aluminium window frames	2.14	0.06	0.13
	Aluminium doors	4.31	0.01	0.04
	PUR insulation, door	4.31	0.03	0.13
	Facadesiding, brick	45.29	0.02	0.86
	Wood fibreboard	45.29	0.02	0.91
	Mineral wool	45.29	0.35	15.85
	Mineral wool	45.29	0.05	2.04
Inside walls	Cast-in concrete with reinforcement	75.86	0.25	18.97
	Aerated concrete	63.59	0.10	6.36
	Ceramic tiles	35.70	0.01	0.36
	Plywood inside doors	23.68	0.04	0.92
Floors	Cast-in concrete with reinforcement	53.55	0.28	14.99
	Sand cement	53.55	0.04	2.14
	XPS	53.55	0.18	9.64
	Hollow-core slab: precast concrete	103.75	0.20	20.75
	Sand cement	125.84	0.06	7.55
	Ceramic tiles	8.59	0.01	0.09
	Meranti wooden floor (plywood)	75.86	0.01	0.91
Roof	Concrete tiles	72.20	0.02	1.52
	Softwood, pitched roof	72.20	0.20	14.44
	Plywood, sheet flat roof	8.92	0.28	2.52
	Bitumen	8.92	0.02	0.16
	Gravel	8.92	0.05	0.45
	PVC rainwater drains	2.37	0.002	0.004
	Zinc gutters	1.57	0.20	0.32
	PUR	81.12	0.28	22.31

C.1.5 Advanced retrofit

	Material	Surface	Thickness	Volume
		m2	m	m3
Structure	Precast concrete	34.26	0.40	13.70
	Concrete poles	71.72	0.02	1.41
	Precast concrete	15.68	0.40	6.27
	Cast-in concrete with reinforcement	7.61	0.28	2.13
	EPS	7.61	0.24	1.83
	Sand	34.26	1.00	34.26
Facade	Single glass	10.35	0.01	0.10
	HR++ glass	10.35	0.01	0.11
	Argon	10.35	0.02	0.16
	softwood window frames	1.83	0.06	0.11
	softwooden doors	2.54	0.04	0.10
	Mineral wool	38.64	0.30	11.59
	Brick masonry, outside wall	38.64	0.10	3.86
	Precast concrete	38.64	0.10	3.86
Inside walls	Cast-in concrete with reinforcement	64.71	0.25	16.18
	Gypsum	54.24	0.10	5.42
	Ceramic tiles	30.45	0.01	0.30
	Plywood inside doors	13.96	0.04	0.54
Floors	Cast-in concrete with reinforcement	45.68	0.28	12.79
	Sand cement	45.68	0.04	1.83
	Mineral wool	45.68	0.24	10.96
	Kwaaitaal & Breedplaat floor: precast concrete	88.50	0.20	17.70
	Sand cement	107.34	0.06	6.44
	Ceramic tiles	7.33	0.01	0.07
	Plywood	64.71	0.01	0.78
Roof	Concrete tiles	61.59	0.03	1.85
	Softwood, pitched roof	61.59	0.20	12.32
	Plywood, sheet flat roof	7.61	0.28	2.15
	Bitumen	7.61	0.02	0.14
	Gravel	7.61	0.05	0.38
	PVC rainwater drains	2.02	0.002	0.004
	Zinc gutters	1.34	0.20	0.27
	PUR	69.2	0.275	19.03

When advance retrofitting a standard home:

(red)	is replaced
(orange)	is added

C.2 End-of-terrace

C.2.1 Standard

	Material	Surface	Thickness	Volume
		m2	m	m3
Structure	Precast concrete	34.26	0.40	13.70
	Concrete poles	71.72	0.02	1.41
	Precast concrete	15.68	0.40	6.27
	Cast-in concrete with reinforcement	7.61	0.28	2.13
	Sand	34.26	1.00	34.26
Facade	Single glass	10.35	0.01	0.10
	softwood window frames	1.83	0.06	0.11
	softwooden doors	2.54	0.04	0.10
	Brick masonry, outside wall	57.96	0.10	5.80
	Precast concrete	57.96	0.10	5.80
Inside walls	Cast-in concrete with reinforcement	32.355	0.25	8.09
	Gypsum	27.12	0.10	2.71
	Ceramic tiles	15.225	0.01	0.15
	Plywood inside doors	13.96	0.04	0.54
Floors	Cast-in concrete with reinforcement	45.68	0.28	12.79
	Sand cement	45.68	0.04	1.83
	Kwaaitaal & Breedplaat floor: precast concrete	88.50	0.20	17.70
	Sand cement	107.34	0.06	6.44
	Ceramic tiles	7.33	0.01	0.07
	Plywood	64.71	0.01	0.78
Roof	Concrete tiles	61.59	0.02	1.29
	Softwood, pitched roof	61.59	0.20	12.32
	Plywood, sheet flat roof	7.61	0.28	2.15
	Bitumen	7.61	0.02	0.14
	Gravel	7.61	0.05	0.38
	PVC rainwater drains	2.02	0.002	0.004
	Zinc gutters	1.34	0.20	0.27

C.2.2 New

	Material	Surface	Thickness	Volume
		m2	m	m3
Structure	Precast concrete	40.16	0.40	16.07
	Hardwooden poles	84.06	0.02	1.65
	Precast concrete	18.39	0.40	7.36
	Cast-in concrete with reinforcement	8.92	0.28	2.50
	Sand	40.16	1.00	40.16
Facade	HR glass	12.14	0.01	0.13
	Aluminium window frames	2.14	0.06	0.13
	Aluminium doors	4.31	0.04	0.17
	Brick masonry, outside wall	67.935	0.10	6.79
	Mineral wool	67.935	0.14	9.51
	Precast concrete	67.935	0.10	6.79
Inside walls	Cast-in concrete with reinforcement	37.93	0.25	9.48
	Aerated concrete	31.795	0.10	3.18
	Ceramic tiles	17.85	0.01	0.18
	Plywood inside doors	23.68	0.04	0.92
Floors	Cast-in concrete with reinforcement	53.55	0.28	14.99
	Sand cement	53.55	0.04	2.14
	EPS	53.55	0.12	6.43
	Hollow-core slab: precast concrete	103.75	0.20	20.75
	Sand cement	125.84	0.06	7.55
	Ceramic tiles	8.59	0.01	0.09
	Meranti wooden floor (plywood)	75.86	0.01	0.91
Roof	Concrete tiles	72.20	0.02	1.52
	Softwood, pitched roof	72.20	0.20	14.44
	Plywood, sheet flat roof	8.92	0.28	2.52
	Bitumen	8.92	0.02	0.16
	Gravel	8.92	0.05	0.45
	PVC rainwater drains	2.37	0.002	0.004
	Zinc gutters	1.57	0.20	0.32
	Mineral wool	81.12	0.27	21.90

C.2.3 Retrofit

	Material	Surface	Thickness	Volume
		m2	m	m3
Structure	Precast concrete	34.26	0.40	13.70
	Concrete poles	71.72	0.02	1.41
	Precast concrete	15.68	0.40	6.27
	Cast-in concrete with reinforcement	7.61	0.28	2.13
	Sand	34.26	1.00	34.26
Facade	Single glass	10.53	0.01	0.11
	HR glass	10.53	0.01	0.12
	softwood window frames	1.88	0.06	0.12
	softwooden doors	2.54	0.39	0.99
	Brick masonry, outside wall	57.96	0.10	5.80
	Mineral wool	57.96	0.05	2.90
	Precast concrete	57.96	0.10	5.80
Inside walls	Cast-in concrete with reinforcement	32.355	0.25	8.09
	Gypsum	27.12	0.10	2.71
	Ceramic tiles	15.225	0.01	0.15
	Plywood inside doors	13.96	0.04	0.54
Floors	Cast-in concrete with reinforcement	45.68	0.28	12.79
	Sand cement	45.68	0.04	1.83
	PUR foam	45.68	0.10	4.57
	Kwaaitaal & Breedplaat floor: precast concrete	88.50	0.20	17.70
	Sand cement	107.34	0.06	6.44
	Ceramic tiles	7.33	0.01	0.07
	Plywood	64.71	0.01	0.78
Roof	Concrete tiles	61.59	0.03	1.85
	Softwood, pitched roof	61.59	0.20	12.32
	Plywood, sheet flat roof	7.61	0.28	2.15
	Bitumen	7.61	0.02	0.14
	Gravel	7.61	0.05	0.38
	PVC rainwater drains	2.02	0.002	0.004
	Zinc gutters	1.34	0.20	0.27
	Mineral wool	69.20	0.10	6.92

When retrofitting a standard home:

(red) is replaced
(orange) is added

C.2.4 Advanced new

	Material	Surface	Thickness	Volume
		m2	m	m3
Structure	Precast concrete	40.16	0.40	16.07
	Hardwooden poles	84.06	0.02	1.65
	Precast concrete	18.39	0.40	7.36
	Cast-in concrete with reinforcement	8.92	0.28	2.50
	EPS	35.68	0.10	3.57
	Sand	41.24	1.00	41.24
Facade	HR ++ glass	12.14	0.01	0.13
	Argon	12.14	0.02	0.18
	Aluminium window frames	2.14	0.06	0.13
	Aluminium doors	4.31	0.01	0.04
	PUR insulation, door	4.31	0.03	0.13
	Facadesiding, brick	67.935	0.02	1.29
	Wood fibreboard	67.935	0.02	1.36
	Mineral wool	67.935	0.35	23.78
	Mineral wool	67.935	0.05	3.06
Inside walls	Cast-in concrete with reinforcement	37.93	0.25	9.48
	Aerated concrete	31.795	0.10	3.18
	Ceramic tiles	17.85	0.01	0.18
	Plywood inside doors	23.68	0.04	0.92
Floors	Cast-in concrete with reinforcement	53.55	0.28	14.99
	Sand cement	53.55	0.04	2.14
	XPS	53.55	0.18	9.64
	Hollow-core slab: precast concrete	103.75	0.20	20.75
	Sand cement	125.84	0.06	7.55
	Ceramic tiles	8.59	0.01	0.09
	Meranti wooden floor (plywood)	75.86	0.01	0.91
Roof	Concrete tiles	72.20	0.02	1.52
	Softwood, pitched roof	72.20	0.20	14.44
	Plywood, sheet flat roof	8.92	0.28	2.52
	Bitumen	8.92	0.02	0.16
	Gravel	8.92	0.05	0.45
	PVC rainwater drains	2.37	0.002	0.004
	Zinc gutters	1.57	0.20	0.32
	PUR	81.12	0.28	22.31

C.2.5 Advanced retrofit

	Material	Surface	Thickness	Volume
		m2	m	m3
Structure	Precast concrete	34.26	0.40	13.70
	Concrete poles	71.72	0.02	1.41
	Precast concrete	15.68	0.40	6.27
	Cast-in concrete with reinforcement	7.61	0.28	2.13
	EPS	7.61	0.24	1.83
	Sand	34.26	1.00	34.26
Facade	Single glass	10.35	0.01	0.10
	HR++ glass	10.35	0.01	0.11
	Argon	10.35	0.02	0.16
	softwood window frames	1.83	0.06	0.11
	softwooden doors	2.54	0.04	0.10
	Mineral wool	57.96	0.30	17.39
	Brick masonry, outside wall	57.96	0.10	5.80
	Precast concrete	57.96	0.10	5.80
Inside walls	Cast-in concrete with reinforcement	32.355	0.25	8.09
	Gypsum	27.12	0.10	2.71
	Ceramic tiles	15.225	0.01	0.15
	Plywood inside doors	13.96	0.04	0.54
Floors	Cast-in concrete with reinforcement	45.68	0.28	12.79
	Sand cement	45.68	0.04	1.83
	Mineral wool	45.68	0.24	10.96
	Kwaaitaal & Breedplaat floor: precast concrete	88.50	0.20	17.70
	Sand cement	107.34	0.06	6.44
	Ceramic tiles	7.33	0.01	0.07
	Plywood	64.71	0.01	0.78
Roof	Concrete tiles	61.59	0.03	1.85
	Softwood, pitched roof	61.59	0.20	12.32
	Plywood, sheet flat roof	7.61	0.28	2.15
	Bitumen	7.61	0.02	0.14
	Gravel	7.61	0.05	0.38
	PVC rainwater drains	2.02	0.002	0.004
	Zinc gutters	1.34	0.20	0.27
	PUR	69.2	0.275	19.03

When advance retrofitting a standard home:

(red) is replaced
(orange) is added

C.3 Detached

C.3.1 Standard

	Material	Surface	Thickness	Volume
		m2	m	m3
Structure	Precast concrete	57.19	0.40	22.88
	Concrete poles	111.16	0.02	2.18
	Precast concrete	24.52	0.40	9.81
	Cast-in concrete with reinforcement	10.89	0.28	3.05
	Sand	49.02	1.00	49.02
Facade	Single glass	40.85	0.01	0.41
	Softwood window frames	7.22	0.06	0.45
	Softwooden doors	2.54	0.04	0.10
	Brick masonry, outside wall	108.94	0.10	10.89
	Precast concrete	108.94	0.10	10.89
Inside walls	Gypsum	77.62	0.10	7.76
	Ceramic tiles	43.57	0.01	0.44
	Plywood inside doors	17.77	0.04	0.69
Floors	Cast-in concrete with reinforcement	65.36	0.28	18.30
	Sand cement	65.36	0.04	2.61
	Kwaaitaal & Breedplaat floor: precast concrete	126.64	0.20	25.33
	Sand cement	153.60	0.06	9.22
	Ceramic tiles	10.49	0.01	0.10
	Plywood	92.60	0.01	1.11
Roof	Concrete tiles	88.13	0.03	2.64
	Softwood, pitched roof	88.13	0.20	17.63
	Plywood, sheet flat roof	10.89	0.28	3.08
	Bitumen	10.89	0.02	0.20
	Gravel	10.89	0.05	0.54
	PVC rainwater drains	2.80	0.002	0.005
	Zinc gutters	1.92	0.02	0.03

C.3.2 New

	Material	Surface	Thickness	Volume
		m2	m	m3
Structure	Precast concrete	67.32	0.40	26.93
	Hardwooden poles	130.84	0.02	2.56
	Precast concrete	28.85	0.40	11.54
	Cast-in concrete with reinforcement	12.82	0.28	3.59
	Sand	57.70	1.00	57.70
Facade	HR glass	48.09	0.01	0.53
	Aluminium window frames	2.20	0.06	0.14
	Aluminium doors	4.31	0.04	0.17
	Brick masonry, outside wall	128.23	0.10	12.82
	Mineral wool	128.23	0.14	17.95
	Precast concrete	128.23	0.10	12.82
Inside walls	Aerated concrete	91.36	0.10	9.14
	Ceramic tiles	51.29	0.01	0.51
	Plywood inside doors	30.14	0.04	1.18
Floors	Cast-in concrete with reinforcement	76.94	0.28	21.54
	Sand cement	76.94	0.04	3.08
	EPS	76.94	0.12	9.23
	Hollow-core slab: precast concrete	149.06	0.20	29.81
	Sand cement	180.80	0.06	10.85
	Ceramic tiles	12.34	0.01	0.12
	Meranti wooden floor (plywood)	108.99	0.01	1.31
Roof	Concrete tiles	103.74	0.02	2.18
	Softwood, pitched roof	103.74	0.20	20.75
	Plywood, sheet flat roof	12.82	0.28	3.63
	Bitumen	12.82	0.02	0.23
	Gravel	12.82	0.05	0.64
	PVC rainwater drains	3.40	0.002	0.006
	Zinc gutters	2.26	0.02	0.04
	Mineral wool	103.74	0.27	28.01

C.3.3 Retrofit

	Material	Surface	Thickness	Volume
		m2	m	m3
Structure	Precast concrete	57.19	0.40	22.88
	Concrete poles	111.16	0.02	2.18
	Precast concrete	24.52	0.40	9.81
	Cast-in concrete with reinforcement	10.89	0.28	3.05
	Sand	49.02	1.00	49.02
Facade	Single glass	40.85	0.01	0.41
	HR glass	40.85	0.01	0.45
	Softwood window frames	7.22	0.06	0.45
	Softwooden doors	2.54	0.04	0.10
	Brick masonry, outside wall	108.94	0.10	10.89
	Mineral wool	108.94	0.05	5.45
	Precast concrete	108.94	0.10	10.89
Inside walls	Gypsum	77.62	0.10	7.76
	Ceramic tiles	43.57	0.01	0.44
	Plywood inside doors	17.77	0.04	0.69
Floors	Cast-in concrete with reinforcement	65.36	0.28	18.30
	Sand cement	65.36	0.04	2.61
	PUR foam	65.36	0.10	6.54
	Kwaaitaal & Breedplaat floor: precast concrete	126.64	0.20	25.33
	Sand cement	153.60	0.06	9.22
	Ceramic tiles	10.49	0.01	0.10
	Plywood	92.60	0.01	1.11
Roof	Concrete tiles	88.13	0.03	2.64
	Softwood, pitched roof	88.13	0.20	17.63
	Plywood, sheet flat roof	10.89	0.28	3.08
	Bitumen	10.89	0.02	0.20
	Gravel	10.89	0.05	0.54
	PVC rainwater drains	2.80	0.002	0.005
	Zinc gutters	1.92	0.02	0.03
	Mineral wool	99.02	0.10	9.90

When retrofitting a standard home:

is replaced
is added

C.3.4 Advanced new

	Material	Surface	Thickness	Volume
		m2	m	m3
Structure	Precast concrete	67.32	0.40	26.93
	Hardwooden poles	130.84	0.02	2.56
	Precast concrete	28.85	0.40	11.54
	Cast-in concrete with reinforcement	12.82	0.28	3.59
	EPS	51.28	0.10	5.13
	Sand	57.70	1.00	57.70
Facade	HR++ glass	48.09	0.01	0.53
	Argon	48.09	0.02	0.72
	Aluminium window frames	2.20	0.06	0.14
	Aluminium doors	4.31	0.01	0.04
	PUR insulation, door	4.31	0.03	0.13
	Facadesiding, brick	128.23	0.02	2.44
	Wood fibreboard	128.23	0.02	2.56
	Mineral wool	128.23	0.35	44.88
	Mineral wool	128.23	0.05	5.77
Inside walls	Aerated concrete	91.36	0.10	9.14
	Ceramic tiles	51.29	0.01	0.51
	Plywood inside doors	30.14	0.04	1.18
Floors	Cast-in concrete with reinforcement	76.94	0.28	21.54
	Sand cement	76.94	0.04	3.08
	XPS	76.94	0.18	13.85
	Hollow-core slab: precast concrete	149.06	0.20	29.81
	Sand cement	180.80	0.06	10.85
	Ceramic tiles	12.34	0.01	0.12
	Meranti wooden floor (plywood)	108.99	0.01	1.31
Roof	Concrete tiles	103.74	0.02	2.18
	Softwood, pitched roof	103.74	0.20	20.75
	Plywood, sheet flat roof	12.82	0.28	3.63
	Bitumen	12.82	0.02	0.23
	Gravel	12.82	0.05	0.64
	PVC rainwater drains	3.40	0.002	0.006
	Zinc gutters	2.26	0.02	0.04
	PUR	103.74	0.28	28.53

C.3.5 Advanced retrofit

	Material	Surface	Thickness	Volume
		m2	m	m3
Structure	Precast concrete	57.19	0.40	22.88
	Concrete poles	111.16	0.02	2.18
	Precast concrete	24.52	0.40	9.81
	Cast-in concrete with reinforcement	10.89	0.28	3.05
	EPS	10.89	0.24	2.61
	Sand	49.02	1.00	49.02
Facade	Single glass	40.85	0.01	0.41
	HR glass	40.85	0.01	0.45
	Argon	40.85	0.02	0.61
	Softwood window frames	7.22	0.06	0.45
	Softwooden doors	2.54	0.04	0.10
	Mineral wool	108.94	0.30	32.68
	Brick masonry, outside wall	108.94	0.10	10.89
	Precast concrete	108.94	0.10	10.89
Inside walls	Gypsum	77.62	0.10	7.76
	Ceramic tiles	43.57	0.01	0.44
	Plywood inside doors	17.77	0.04	0.69
Floors	Cast-in concrete with reinforcement	65.36	0.28	18.30
	Sand cement	65.36	0.04	2.61
	Mineral wool	65.36	0.24	15.69
	Kwaaitaal & Breedplaat floor: precast concrete	126.64	0.20	25.33
	Sand cement	153.60	0.06	9.22
	Ceramic tiles	10.49	0.01	0.10
	Plywood	92.60	0.01	1.11
Roof	Concrete tiles	88.13	0.03	2.64
	Softwood, pitched roof	88.13	0.20	17.63
	Plywood, sheet flat roof	10.89	0.28	3.08
	Bitumen	10.89	0.02	0.20
	Gravel	10.89	0.05	0.54
	PVC rainwater drains	2.80	0.002	0.005
	Zinc gutters	1.92	0.02	0.03
	PUR	99.02	0.28	27.23

When advance retrofitting a standard home:

is replaced (red)
is added (orange)

C.4 Semi-detached

C.4.1 Standard

	Material	Surface	Thickness	Volume
		m2	m	m3
Structure	Precast concrete	41.31	0.40	16.52
	Concrete poles	86.48	0.02	1.69
	Precast concrete	18.91	0.40	7.56
	Cast-in concrete with reinforcement	9.18	0.28	2.57
	Sand	41.31	1.00	41.31
Facade	Single glass	12.48	0.01	0.12
	Softwood window frames	2.20	0.06	0.14
	Softwooden doors	2.54	0.04	0.10
	Brick masonry, outside wall	69.89	0.10	6.99
	Precast concrete	69.89	0.10	6.99
Inside walls	Cast-in concrete with reinforcement	39.02	0.25	9.75
	Gypsum	32.71	0.10	3.27
	Ceramic tiles	18.36	0.01	0.18
	Plywood inside doors	15.23	0.04	0.59
Floors	Cast-in concrete with reinforcement	55.08	0.28	15.42
	Sand cement	55.08	0.04	2.20
	Kwaaitaal & Breedplaat floor: precast concrete	106.72	0.20	21.34
	Sand cement	129.44	0.06	7.77
	Ceramic tiles	8.84	0.01	0.09
	Plywood	78.03	0.01	0.94
Roof	Concrete tiles	74.27	0.03	2.23
	Softwood, pitched roof	74.27	0.20	14.85
	Plywood, sheet flat roof	9.18	0.28	2.60
	Bitumen	9.18	0.02	0.17
	Gravel	9.18	0.05	0.46
	PVC rainwater drains	2.44	0.002	0.004
	Zinc gutters	1.61	0.02	0.03

C.4.2 New

	Material	Surface	Thickness	Volume
		m2	m	m3
Structure	Precast concrete	49.62	0.40	19.85
	Hardwooden poles	103.87	0.02	2.04
	Precast concrete	22.72	0.40	9.09
	Cast-in concrete with reinforcement	11.03	0.28	3.09
	Sand	49.62	1.00	49.62
Facade	HR glass	15.00	0.01	0.17
	Aluminium window frames	2.65	0.06	0.16
	Aluminium doors	4.31	0.04	0.17
	Brick masonry, outside wall	83.94	0.10	8.39
	Mineral wool	83.94	0.14	11.75
	Precast concrete	83.94	0.10	8.39
Inside walls	Cast-in concrete with reinforcement	46.86	0.25	11.72
	Aerated concrete	39.28	0.10	3.93
	Ceramic tiles	22.06	0.01	0.22
	Plywood inside doors	25.84	0.04	1.01
Floors	Cast-in concrete with reinforcement	66.16	0.28	18.52
	Sand cement	66.16	0.04	2.65
	EPS	66.16	0.12	7.94
	Hollow-core slab: precast concrete	128.18	0.20	25.64
	Sand cement	155.47	0.06	9.33
	Ceramic tiles	10.61	0.01	0.11
	Meranti wooden floor (plywood)	93.72	0.01	1.12
Roof	Concrete tiles	89.20	0.02	1.87
	Softwood, pitched roof	89.20	0.20	17.84
	Plywood, sheet flat roof	11.03	0.28	3.12
	Bitumen	11.03	0.02	0.20
	Gravel	11.03	0.05	0.55
	PVC rainwater drains	2.93	0.002	0.005
	Zinc gutters	1.94	0.02	0.03
	Mineral wool	100.23	0.27	27.06

C.4.3 Retrofit

	Material	Surface	Thickness	Volume
		m2	m	m3
Structure	Precast concrete	41.31	0.40	16.52
	Concrete poles	86.48	0.02	1.69
	Precast concrete	18.91	0.40	7.56
	Cast-in concrete with reinforcement	9.18	0.28	2.57
	Sand	41.31	1.00	41.31
Facade	Single glass	12.48	0.01	0.12
	HR glass	12.48	0.01	0.14
	Softwood window frames	2.20	0.06	0.14
	Softwooden doors	2.54	0.04	0.10
	Brick masonry, outside wall	69.89	0.10	6.99
	Mineral wool	69.89	0.05	3.49
	Precast concrete	69.89	0.10	6.99
Inside walls	Cast-in concrete with reinforcement	39.02	0.25	9.75
	Gypsum	32.71	0.10	3.27
	Ceramic tiles	18.36	0.01	0.18
	Plywood inside doors	15.23	0.04	0.59
Floors	Cast-in concrete with reinforcement	55.08	0.28	15.42
	Sand cement	55.08	0.04	2.20
	PUR foam	55.08	0.10	5.51
	Kwaaitaal & Breedplaat floor: precast concrete	106.72	0.20	21.34
	Sand cement	129.44	0.06	7.77
	Ceramic tiles	8.84	0.01	0.09
	Plywood	78.03	0.01	0.94
Roof	Concrete tiles	74.27	0.03	2.23
	Softwood, pitched roof	74.27	0.20	14.85
	Plywood, sheet flat roof	9.18	0.28	2.60
	Bitumen	9.18	0.02	0.17
	Gravel	9.18	0.05	0.46
	PVC rainwater drains	2.44	0.002	0.004
	Zinc gutters	1.61	0.02	0.03
	Mineral wool	83.45	0.10	8.35

When retrofitting a standard home:

is replaced (red)
is added (orange)

C.4.4 Advanced new

	Material	Surface	Thickness	Volume
		m2	m	m3
Structure	Precast concrete	49.62	0.40	19.85
	Hardwooden poles	103.87	0.02	2.04
	Precast concrete	22.72	0.40	9.09
	Cast-in concrete with reinforcement	11.03	0.28	3.09
	EPS	44.12	0.10	4.41
	Sand	49.62	1.00	49.62
Facade	HR ++ glass	15.00	0.01	0.17
	Argon	15.00	0.02	0.23
	Aluminium window frames	2.65	0.06	0.16
	Aluminium doors	4.31	0.01	0.04
	PUR insulation, door	4.31	0.03	0.13
	Facadesiding, brick	83.94	0.02	1.59
	Wood fibreboard	83.94	0.02	1.68
	Mineral wool	83.94	0.35	29.38
	Mineral wool	83.94	0.05	3.78
Inside walls	Cast-in concrete with reinforcement	46.86	0.25	11.72
	Aerated concrete	39.28	0.10	3.93
	Ceramic tiles	22.06	0.01	0.22
	Plywood inside doors	25.84	0.04	1.01
Floors	Cast-in concrete with reinforcement	66.16	0.28	18.52
	Sand cement	66.16	0.04	2.65
	XPS	66.16	0.18	11.91
	Hollow-core slab: precast concrete	128.18	0.20	25.64
	Sand cement	155.47	0.06	9.33
	Ceramic tiles	10.61	0.01	0.11
	Meranti wooden floor (plywood)	93.72	0.01	1.12
Roof	Concrete tiles	89.20	0.02	1.87
	Softwood, pitched roof	89.20	0.20	17.84
	Plywood, sheet flat roof	11.03	0.28	3.12
	Bitumen	11.03	0.02	0.20
	Gravel	11.03	0.05	0.55
	PVC rainwater drains	2.93	0.002	0.005
	Zinc gutters	1.94	0.02	0.03
	PUR	100.23	0.28	27.56

C.4.5 Advanced retrofit

	Material	Surface	Thickness	Volume
		m2	m	m3
Structure	Precast concrete	41.31	0.40	16.52
	Concrete poles	86.48	0.02	1.69
	Precast concrete	18.91	0.40	7.56
	Cast-in concrete with reinforcement	9.18	0.28	2.57
	EPS	9.18	0.24	2.20
	Sand	41.31	1.00	41.31
Facade	Single glass	12.48	0.01	0.12
	HR++ glass	12.48	0.01	0.14
	Argon	12.48	0.02	0.19
	softwood window frames	2.20	0.06	0.14
	softwooden doors	2.54	0.04	0.10
	Brick masonry, outside wall	69.89	0.10	6.99
	Mineral wool	69.89	0.30	20.97
	Precast concrete	69.89	0.10	6.99
Inside walls	Cast-in concrete with reinforcement	39.02	0.25	9.75
	Gypsum	32.71	0.10	3.27
	Ceramic tiles	18.36	0.01	0.18
	Plywood inside doors	15.23	0.04	0.59
Floors	Cast-in concrete with reinforcement	55.08	0.28	15.42
	Sand cement	55.08	0.04	2.20
	Mineral wool	55.08	0.24	13.22
	Kwaaitaal & Breedplaat floor: precast concrete	106.72	0.20	21.34
	Sand cement	129.44	0.06	7.77
	Ceramic tiles	8.84	0.01	0.09
	Plywood	78.03	0.01	0.94
Roof	Concrete tiles	74.27	0.03	2.23
	Softwood, pitched roof	74.27	0.20	14.85
	Plywood, sheet flat roof	9.18	0.28	2.60
	Bitumen	9.18	0.02	0.17
	Gravel	9.18	0.05	0.46
	PVC rainwater drains	2.44	0.002	0.004
	Zinc gutters	1.61	0.02	0.03
	PUR	83.45	0.28	22.95

When advance retrofitting a standard home:

is replaced
is added

C.5 Apartment

C.5.1 Standard

	Material	Surface building	Surface average apartment	Thickness	Volume building	Volume average apartment
		m2	m2	m	m3	m3
Structure	Precast concrete	587.23	21.75	0.40	234.89	8.70
	Concrete poles	1229.28	45.53	0.02	24.09	0.89
	Precast concrete	268.85	9.96	0.40	107.54	3.98
	Cast-in concrete with reinforcement	130.50	4.83	0.28	36.54	1.35
	Sand	587.23	21.75	1.00	587.23	21.75
Facade	Single glass	173.26	6.42	0.01	1.73	0.06
	Softwood window frames	30.63	1.13	0.06	1.90	0.07
	Softwood doors	68.55	2.54	0.04	2.67	0.10
	Brick masonry, corner wall	107.81	3.99	0.10	10.78	0.40
	Precast concrete, corner wall	107.81	3.99	0.10	10.78	0.40
	Brick masonry, front/behind wall	646.83	23.96	0.10	64.68	2.40
	Precast concrete, front/behind wall	646.83	23.96	0.10	64.68	2.40
Inside walls	Cast-in concrete with reinforcement	1083.25	40.12	0.25	270.81	10.03
	Gypsum	902.70	33.43	0.10	90.27	3.34
	Ceramic tiles	424.78	15.73	0.01	4.25	0.16
	Plywood inside doors	239.93	8.89	0.04	6.68	0.25
Floors	Cast-in concrete with reinforcement	84.96	3.15	0.28	23.79	0.88
	Sand cement	84.96	3.15	0.04	9.36	0.35
	Breedplaatvloer: precast concrete	1481.49	54.87	0.20	296.30	10.97
	Sand cement	1796.87	66.55	0.06	107.81	3.99
	Ceramic tiles	122.70	4.54	0.01	1.23	0.05
	plywood	1083.25	40.12	0.01	13.00	0.48
Roof	Precast concrete	257.42	9.53	0.28	72.85	2.70
	Bitumen	257.42	9.53	0.02	4.63	0.17
	Gravel	257.42	9.53	0.05	12.87	0.48
	PVC rainwater drains	7.51	0.28	0.002	0.014	0.001
	Zinc gutters	4.98	0.18	0.02	0.09	0.003

C.5.2 New

	Material	Surface building	Surface average apartment	Thickness	Volume building	Volume average apartment
		m2	**m2**	**m**	**m3**	**m3**
Structure	Precast concrete	703.91	26.07	0.40	281.57	10.43
	Hardwooden poles	1473.54	54.58	0.02	28.88	1.07
	Precast concrete	322.28	11.94	0.40	128.91	4.77
	Cast-in concrete with reinforcement	156.43	5.79	0.28	43.80	1.62
	Sand	703.91	26.07	1.00	703.91	26.07
Facade	HR glass	206.50	7.65	0.01	2.27	0.08
	Aluminium window frames	36.40	1.35	0.06	2.26	0.08
	Aluminium doors	116.26	4.31	0.04	4.53	0.17
	Brick masonry, corner wall	128.40	4.76	0.10	12.84	0.48
	Mineral wool, corner wall	128.40	4.76	0.14	17.98	0.67
	Precast concrete, corner wall	128.40	4.76	0.10	12.84	0.48
	Brick masonry, front/behind wall	770.38	28.53	0.10	77.04	2.85
	Mineral wool, front/behind wall	770.38	28.53	0.14	107.85	3.99
	Precast concrete, front/behind wall	770.38	28.53	0.10	77.04	2.85
Inside walls	Cast-in concrete with reinforcement	1075.17	39.82	0.25	268.79	9.96
	Aerated concrete	901.39	33.38	0.10	90.14	3.34
	Ceramic tiles	506.05	18.74	0.01	5.06	0.19
	Plywood inside doors	406.91	15.07	0.04	15.87	0.59
Floors	Cast-in concrete with reinforcement	101.21	3.75	0.28	28.34	1.05
	Sand cement	101.21	3.75	0.04	4.05	0.15
	EPS	101.21	3.75	0.12	12.15	0.45
	Breedplaatvloer: precast concrete	1764.79	65.36	0.20	352.96	13.07
	Sand cement	2140.54	79.28	0.06	128.43	4.76
	Ceramic tiles	146.12	5.41	0.01	1.46	0.05
	Meranti wooden floor (plywood)	1290.38	47.79	0.01	15.48	0.57
Roof	Precast concrete	306.63	11.36	0.28	86.78	3.21
	Bitumen	306.63	11.36	0.02	5.52	0.20
	Gravel	306.63	11.36	0.05	15.33	0.57
	PVC rainwater drains	14.21	0.53	0.002	0.03	0.001
	Zinc gutters	9.42	0.35	0.02	0.17	0.01
	PUR	306.63	11.36	0.27	82.79	3.07

C.5.3 Retrofit

	Material	Surface building	Surface average apartment	Thickness	Volume building	Volume average apartment
		m2	m2	m	m3	m3
Structure	Precast concrete	587.23	21.75	0.40	234.89	8.70
	Concrete poles	1229.28	45.53	0.02	24.09	0.89
	Precast concrete	268.85	9.96	0.40	107.54	3.98
	Cast-in concrete with reinforcement	130.50	4.83	0.28	36.54	1.35
	Sand	587.23	21.75	1.00	587.23	21.75
Facade	Single glass	173.26	6.42	0.01	1.73	0.06
	HR glass	173.26	6.42	0.01	1.91	0.07
	Softwood window frames	30.63	1.13	0.06	1.90	0.07
	Softwood doors	68.55	2.54	0.04	2.67	0.10
	Brick masonry, corner wall	107.81	3.99	0.10	10.78	0.40
	Mineral wool	107.81	3.99	0.05	5.39	0.20
	Precast concrete, corner wall	107.81	3.99	0.10	10.78	0.40
	Brick masonry, front/behind wall	646.83	23.96	0.10	64.68	2.40
	Mineral wool	646.83	23.96	0.05	32.34	1.20
	Precast concrete, front/behind wall	646.83	23.96	0.10	64.68	2.40
Inside walls	Cast-in concrete with reinforcement	1083.25	40.12	0.25	270.81	10.03
	Gypsum	902.70	33.43	0.10	90.27	3.34
	Ceramic tiles	424.78	15.73	0.01	4.25	0.16
	Plywood inside doors	239.93	8.89	0.04	9.36	0.35
Floors	Cast-in concrete with reinforcement	84.96	3.15	0.28	23.79	0.88
	Sand cement	84.96	3.15	0.04	3.40	0.13
	PUR foam	84.96	3.15	0.10	8.50	0.31
	Breedplaatvloer: precast concrete	1481.49	54.87	0.20	296.30	10.97
	Sand cement	1796.87	66.55	0.06	107.81	3.99
	Ceramic tiles	122.70	4.54	0.01	1.23	0.05
	plywood	1083.25	40.12	0.01	13.00	0.48
Roof	Precast concrete	257.42	9.53	0.28	72.85	2.70
	Bitumen	257.42	9.53	0.02	4.63	0.17
	Gravel	257.42	9.53	0.05	12.87	0.48
	PVC rainwater drains	7.51	0.28	0.002	0.014	0.001
	Zinc gutters	4.98	0.18	0.02	0.09	0.003
	Mineral wool	257.42	9.53	0.10	25.74	0.95

When retrofitting a standard home:

is replaced
is added

C.5.4 Advanced new

	Material	Surface building	Surface average apartment	Thickness	Volume building	Volume average apartment
		m2	m2	m	m3	m3
Structure	Precast concrete	703.91	26.07	0.40	281.57	10.43
	Hardwooden poles	1473.54	54.58	0.02	28.88	1.07
	Precast concrete	322.28	11.94	0.40	128.91	4.77
	Cast-in concrete with reinforcement	156.43	5.79	0.28	43.80	1.62
	EPS	156.43	5.79	0.10	15.64	0.58
	Sand	703.91	26.07	1.00	703.91	26.07
Facade	HR++ glass	206.50	7.65	0.01	2.27	0.08
	Argon	206.50	7.65	0.02	3.10	0.11
	Aluminium window frames	36.40	1.35	0.06	2.26	0.08
	Aluminium doors	116.26	4.31	0.01	1.13	0.04
	PUR insulation, door	116.26	4.31	0.03	3.40	0.13
	Facadesiding, corner wall	128.40	4.76	0.02	2.44	0.09
	wood fibreboard, corner wall	128.40	4.76	0.02	2.57	0.10
	Mineral wool, corner wall	128.40	4.76	0.35	44.94	1.66
	Mineral wool, corner wall	128.40	4.76	0.05	5.78	0.21
	Facadesiding, front/behind wall	770.38	28.53	0.02	14.64	0.54
	Wood fibreboard, front/behind wall	770.38	28.53	0.02	15.41	0.57
	Mineral wool, front/behind wall	770.38	28.53	0.35	269.63	9.99
	Mineral wool, front/behind wall	770.38	28.53	0.05	34.67	1.28
Inside walls	Cast-in concrete with reinforcement	1075.17	39.82	0.25	268.79	9.96
	Aerated concrete	901.39	33.38	0.10	90.14	3.34
	Ceramic tiles	506.05	18.74	0.01	5.06	0.19
	Plywood inside doors	406.91	15.07	0.04	15.87	0.59
Floors	Cast-in concrete with reinforcement	101.21	3.75	0.28	28.34	1.05
	Sand cement	101.21	3.75	0.04	4.05	0.15
	XPS	101.21	3.75	0.18	18.22	0.67
	Breedplaatvloer: precast concrete	1764.79	65.36	0.20	352.96	13.07
	Sand Cement	2140.54	79.28	0.06	128.43	4.76
	Ceramic tiles	146.12	5.41	0.01	1.46	0.05
	Meranti wooden floor (plywood)	1290.38	47.79	0.01	15.48	0.57
Roof	Precast concrete	306.63	11.36	0.28	86.78	3.21
	Bitumen	306.63	11.36	0.02	5.52	0.20
	Gravel	306.63	11.36	0.05	15.33	0.57
	PVC rainwater drains	14.21	0.53	0.002	0.03	0.001
	Zinc gutters	9.42	0.35	0.02	0.17	0.01
	PUR	306.63	11.36	0.28	84.32	3.12

C.5.5 Advanced retrofit

	Material	Surface building	Surface average apartment	Thickness	Volume building	Volume average apartment
		m2	m2	m	m3	m3
Structure	Precast concrete	587.23	21.75	0.40	234.89	8.70
	Concrete poles	1229.28	45.53	0.02	24.09	0.89
	Precast concrete	268.85	9.96	0.40	107.54	3.98
	Cast-in concrete with reinforcement	130.50	4.83	0.28	36.54	1.35
	EPS	130.50	4.83	0.24	31.32	1.16
	Sand	587.23	21.75	1.00	587.23	21.75
Facade	Single glass	173.26	6.42	0.01	1.73	0.06
	HR++ glass	173.26	6.42	0.01	1.91	0.07
	Argon	173.26	6.42	0.02	2.60	0.10
	Softwood window frames	30.63	1.13	0.06	1.90	0.07
	Softwood doors	68.55	2.54	0.04	2.67	0.10
	Brick masonry, corner wall	107.81	3.99	0.10	10.78	0.40
	Mineral wool	107.81	3.99	0.30	32.34	1.20
	Precast concrete, corner wall	107.81	3.99	0.10	10.78	0.40
	Brick masonry, front/behind wall	646.83	23.96	0.10	64.68	2.40
	Mineral wool	646.83	23.96	0.30	194.05	7.19
	Precast concrete, front/behind wall	646.83	23.96	0.10	64.68	2.40
Inside walls	Cast-in concrete with reinforcement	1083.25	40.12	0.25	270.81	10.03
	Gypsum	902.70	33.43	0.10	90.27	3.34
	Ceramic tiles	424.78	15.73	0.01	4.25	0.16
	Plywood inside doors	239.93	8.89	0.04	9.36	0.35
Floors	Cast-in concrete with reinforcement	84.96	3.15	0.28	23.79	0.88
	Sand cement	84.96	3.15	0.04	3.40	0.13
	Mineral wool	84.96	3.15	0.24	20.39	0.76
	Breedplaatvloer: precast concrete	1481.49	54.87	0.20	296.30	10.97
	Sand cement	1796.87	66.55	0.06	107.81	3.99
	Ceramic tiles	122.70	4.54	0.01	1.23	0.05
	plywood	1083.25	40.12	0.01	13.00	0.48
Roof	Precast concrete	257.42	9.53	0.28	72.85	2.70
	Bitumen	257.42	9.53	0.02	4.63	0.17
	Gravel	257.42	9.53	0.05	12.87	0.48
	PVC rainwater drains	7.51	0.28	0.002	0.014	0.001
	Zinc gutters	4.98	0.18	0.02	0.09	0.003
	PUR	257.42	9.53	0.28	70.79	2.62

When advance retrofitting a standard home:

[red] is replaced
[orange] is added

Appendix D: Embodied Energy Database Management System

For quick and easy use of the EEDMS without having to cope with the large amount of data, five forms are created[4]:
1. Embodied energy: this forms shows the embodied energy use per building representative in three columns: total embodied energy use in GJ, embodied energy use in MJ/m^2/y and the EE/OE ratio.
2. Operational energy: this forms shows the operational energy use per building representative in two columns: total operational energy use in GJ and operational energy use in MJ/m^2/y.
3. Frozen efficiency-, moderate efficiency and deep efficiency scenario: in all three forms the energy use in TJ per building representative is shown for the particular scenario in three columns: embodied energy use, operational energy use and total energy use.

D.1 Embodied energy use

The model starts with defining the building representatives in ***Table BuildingTypes***: there are 5 types and 5 vintages, so 25 building representatives. The name and abbreviation for the representatives is given. ***Table BuildingParts*** defines the five parts of every representative that are analysed; the structure of the building, façade, inner walls, floors and roof. Then, the ***Table Buildingcomponents*** shows a component (insulation, door, wall etc.) for every building part that will be analysed. The last two tables are only created to make navigation in the model easier; this way the materials chosen are linked to the building component and building part it belongs to.

Table MaterialsNL shows the 23 materials that are most common in the Dutch residential building construction industry. The embodied energy intensity in MJ/kg, the transport embodied energy intensity in MJ/kg and the density in kg/m^3 is linked to the specific material. ***Query EE_m3*** then multiplies the embodied energy intensity- and transport embodied energy intensity in MJ/kg with the density in kg/m^3 to get the two energy intensities in MJ/m^3. The last column sums up the two intensities to get the total embodied energy intensity in MJ/m^3.

Table MaterialVolumes shows for every building representative and the corresponding building component; what material is used for that building component, the surface area of this material in m^2, and the thickness in m. The last column multiplies these two to get the volumes in m^3. The ***Query MaterialVolumes_SUM*** sums up the volume amount per material for every building representative. ***Query TotalVolumes*** is only created for further calculation; it presents the same information as ***MaterialVolumes_SUM***. Then ***Query TotalEE_mj*** shows for every building representative and corresponding material a column with their volume in m^3 and corresponding total embodied energy intensity in MJ/m^3. These last two columns are then multiplied to get the embodied energy in MJ. This query is used to create ***Query TotalEE_Btype*** that sums up the total embodied energy in MJ per building type.

Table BuildingLFFA shows for every building type the corresponding lifetime and floor area. ***Query EE_m2_LF*** shows two columns; in the first column the total embodied energy in MJ is divided by corresponding floor area to show the embodied energy use per building type in MJ/m^2, and in the second column the total embodied energy is divided by lifetime of every building type, which leads to a total embodied energy in MJ/y. ***Query TotalEE_M2/Y*** divides the total embodied energy by both lifetime and floor area to get the embodied energy in

[4] The ***Formquery*** queries in the EEDMS are used to create these forms.

MJ/m^2/year. This leads to the answer on the second sub-question in this research.

D.2 Scenario analysis embodied energy use

The ***Table FloorArea3SCEP*** is based on the outcomes of the 3SCEP HEB model, with adjusted input variables (explained in the method, chapter 3). The total floor area development output (for residential housing) from this model was given for the three scenarios divided amongst the five vintage types. This total was multiplied with the share of occurrence of every building type compared to total building stock in the Netherlands, to get the division per type and vintage. The ***Table Population*** is used as input in the 3SCEP HEB model and represents the observed and predicted Dutch population between 2015 and 2050 based on ABF Research data (2016). The outcome is shown in million m^2 for the three scenarios, over the years 2015-2050, in 5 year steps. The ***Queries SummaryDeepEE, SummaryModerateEE*** and ***SummaryFrozenEE*** show summarized information for every building representative: the total embodied energy in MJ/m^2/year and the floor area development in million m^2 between 2015-2050 for the specific scenario. The ***Queries EE_Deep***, ***EE_Moderate*** and ***EE_Frozen*** show the total embodied energy development in MJ over the years 2015-2050 for the particular scenario. This is calculated by simply multiplying the total embodied energy in MJ/m^2/year with the floor area development in million m^2.

D.3 Operational energy use

Table OEI shows the primary operational energy intensities in MJ/m^2/year, obtained from TABULA data, collected by TU Delft. ***Query TotalOE_Btype*** shows three colums; in the first column the operational energy intensities per building representative are multiplied with corresponding floor area and lifetime to show operational energy use in MJ/m^2/y, in the second column the intensities are only multiplied with lifetime to show the operational energy use in MJ/y, and in the last column the intensities are only multiplied with floor area to show operational energy use in MJ/m^2.

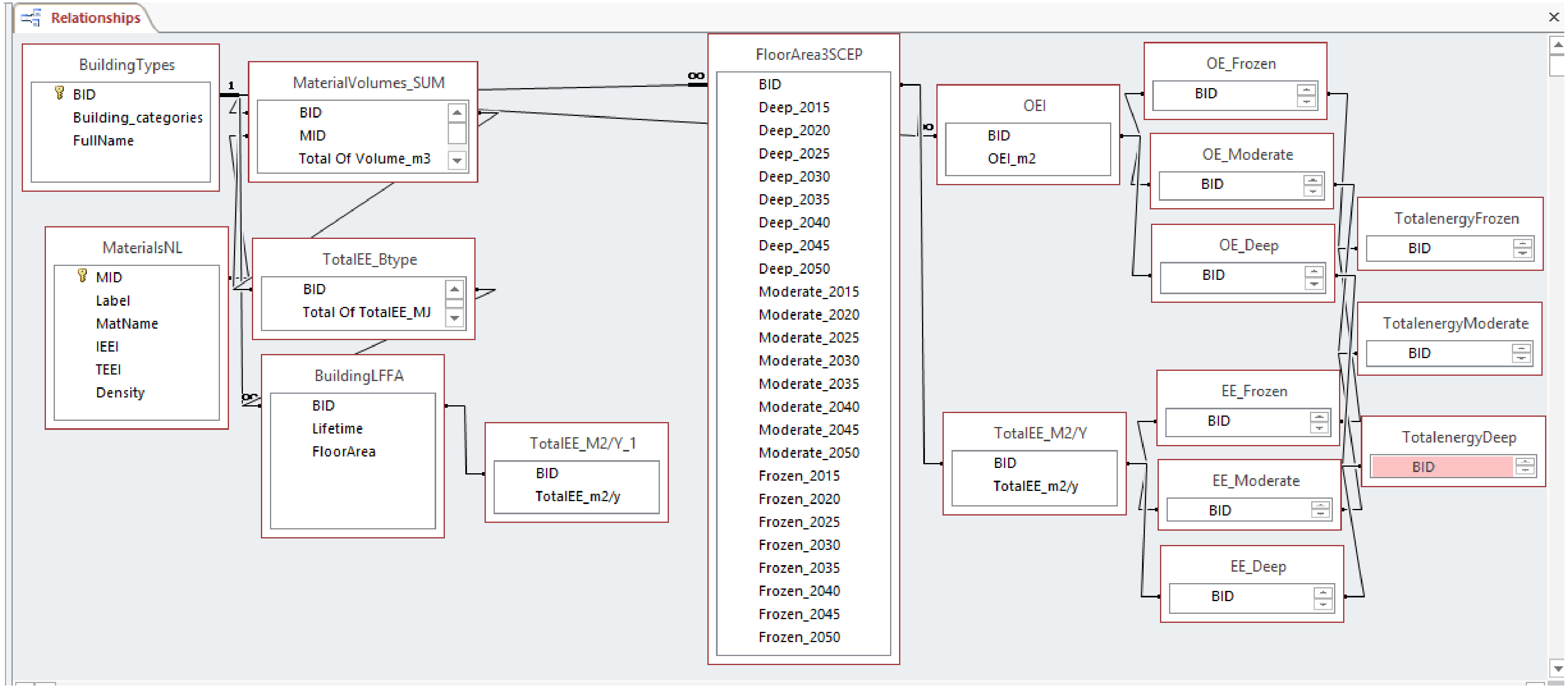
The next steps are exactly the same as was done for the scenario analysis of embodied energy use, using ***Table FloorArea3SCEP***. The ***Queries SummaryDeepOE, SummaryModerateOE*** and ***SummaryFrozenOE*** show summarized information for every building type: the total operational energy in MJ/m^2/year and the floor area development in million m^2 between 2015-2050 for the specific scenario. The ***Queries OE_Deep, OE_Moderate*** and ***OE_Frozen*** show the total operational energy development in MJ over the years 2015-2050 for the particular scenario. This is calculated by simply multiplying the operational energy use in MJ/m^2/year with the floor area development in million m^2.

D.4 Scenario analysis total energy use

The three ***Queries TotalenergyDeep, Totalenergymoderate*** and ***Totalenergyfrozen*** add up the embodied energy use scenario development (using ***query EE_Deep, EE_moderate*** and ***EE_frozen***) and the operational energy use scenario development (using ***query OE_Deep, OE_moderate*** and ***OE_frozen***) to show the total energy use development in the scenario analysis for the years 2015-2050 for all building representatives.

D.5 Relationship summary

The relationships between the tables and queries, that lead to the answer to the main research question in this thesis are shown in the figure below. This figure can be used for easier understanding of the model, particularly when the model will be updated/adjusted in the future.



Appendix E: Embodied energy intensity values

This table shows the standard embodied energy intensities of the materials in MJ/kg, and the minimum and maximum values used in the sensitivity analysis (Circular ecology, 2011). These values are converted in MJ/m^3 in the EEDMS.

Material name	**Standard**	**Minimum**	**Maximum**
Aerated concrete	3.50	1.97	4.76
Aluminium	108.60	58.00	184.00
Argon	6.80	6.80	6.80
Bitumen	51.00	2.40	51.00
Brick, clay	3.00	1.00	5.00
Reinforced concrete	2.07	1.76	2.20
Ceramics	12.00	2.50	19.50
Expanded polystyrene	88.60	62.02	115.18
Gravel	0.08	0.01	0.50
Gypsum plaster	3.48	0.90	8.64
Hardwood	10.40	0.72	16.00
Mineral wool	16.60	9.96	23.24
Plywood	15.00	10.00	20.00
Precast concrete	1.27	1.20	3.80
Primary glass	15.00	10.50	19.50
Polyurethane foam	101.50	71.05	131.95
Polyvinylchloride	67.50	47.25	87.75
Sand	0.01	0.05	0.15
Sand cement	0.99	0.54	1.28
Softwood	7.40	0.72	13.00
Wood fibre high density	16.00	15.00	35.00
Extruded polystyrene	87.40	61.18	113.62
Zinc	53.1	8.46	105.76