Energy & Buildings 165 (2018) 233–245

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enbuild

The relationship between operational energy demand and embodied energy in Dutch residential buildings

A. Koezjakov [a], D. Urge-Vorsatz [b], W. Crijns-Graus [a,*], M. van den Broek [a]

[a] Copernicus Institute of Sustainable Development, Utrecht University, Heidelberglaan 2, Utrecht 3584 CS, The Netherlands
[b] Centre for Climate Change and Sustainable Energy Policy, Central European University, Nádor utca 9, Budapest, Hungary

ARTICLE INFO

Article history:
Received 6 October 2017
Revised 7 January 2018
Accepted 10 January 2018
Available online 31 January 2018

ABSTRACT

Reducing heat demand of buildings, due to legal and technological advances in the EU, shifts the ratio of operational vs. embodied energy towards an increasing share of the latter. This leads to a shifting focus on building materials (embodied) energy use. In this study the relationship between heat demand and embodied energy use was investigated, using Dutch residential buildings as a case study. The analysis was performed using the 3SCEP HEB (Center for Climate Change and Sustainable Energy Policy High Efficiency Buildings) model and a constructed Embodied Energy Database Management System (EEDMS), containing embodied energy use of materials most common in Dutch residential construction. The resulting embodied energy use in Dutch dwelling archetypes varies from 52 to 106 MJ/(m^2·a), annualised over building lifetimes and 3.0 to 6.4 GJ/m^2 in total. These values are for the building construction and exclude recurrent embodied energy and technical installations. For operational energy use the range is 124 to 682 MJ/(m^2·a). A total energy use reduction of 36% can be reached in 2050 through 46% reduction in operational energy use and 35% increase in embodied energy use, compared to 2015. This research confirms that the relative importance of embodied energy use is increasing: the embodied energy use in standard homes is about 10–12% of the total energy use, while it is 36–46% in energy efficient homes. Particularly in light of the goal to reach a maximum global temperature increase of well below 2 °C by 2100, it is important to include embodied energy use in future policy objectives.

1. Introduction

The operational energy use of buildings, i.e. the energy required for heating and cooling of buildings [8], leads to about 33% of the total final energy demand globally and to 30% of the global CO_2 emissions related to energy use [60]. Therefore, to reach the target to limit the increase in global average surface temperature to well below 2 °C as compared to pre-industrial levels, greenhouse gas emissions from the built environment should be reduced, especially since these are identified to have the highest potential [24]. There have been significant advances in both technologies and policies to reduce the energy consumption for heating, accounting for the largest share of building energy use in most developed countries. However, this often leads to an increase in embodied energy use, i.e. the energy consumption required to produce the building capital [28,47].

According to Langston and Langston [26], assessing embodied energy is more complex and time consuming than measuring operational energy use. Trusty and Horst [58] used LCA (Life Cycle Assessment) tools like SimaPro and Athena for energy analysis of buildings. However, this LCA approach does not provide an easy way to compare and show the interaction of the different phases of energy use (construction, operation and demolition phase) in buildings, because it usually focuses on the aggregated energy picture.

The embodied energy analyses usually focussed on a specific country or location. For example, Reddy and Jagadish [62] investigated embodied energy in buildings in the Indian context. In this study it 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. Takano et al. [55] showed that particularly in low-energy buildings, embodied energy contributes highly to the building life cycle energy with contributions up to 46% of total energy use. Several other studies were done on embodied energy use in

* Corresponding author.
E-mail address: w.h.j.graus@uu.nl (W. Crijns-Graus).

https://doi.org/10.1016/j.enbuild.2018.01.036

buildings; Chen et al. [12] investigated the embodied energy use profile in buildings in Hong Kong and Buchanan & Honey [9] investigated this for New Zealand. When considering Europe, most countries seem advanced in increasing the energy efficiency of buildings compared to countries on 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 [30]. Especially the impact of different deployment pathways for retrofitting and renewing of building stock on total building lifetime energy use on a country level is missing. This study therefore aims to analyse the relationship between operational energy and embodied energy use in residential buildings in a scenario context. This gives information for policy makers on the total impact of building renovation and renewal instead of only the impact on operational energy use. As a case study in this research the analysis is performed for residential buildings in the Netherlands in the period up to 2050. Building regulations in the Netherlands date back to 1901, when the Housing Act was adopted [53]. This Act was extended in 1993 with the Building Decree with national minimum requirements for the energy performance of new buildings measured by the Energy Performance Coefficient (EPC) [37]. 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 developer is also obligated to include an environmental performance calculation of every newly supplied building (De Klijn-Chevalerias and Javed, 2017). This calculation is meant to stimulate the developer to use sustainable construction materials, but does not enforce any restriction on the amount of embodied energy used in the construction materials. The assessment of the trade-off between operational energy use and embodied energy use will allow decision makers to take a step towards optimisation of the performance of Dutch 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 [51]. This assessment can also be used as an example for other countries to map their embodied energy use.

Embodied energy in this research is defined as the initial energy required to produce the building materials plus transport energy required to transport the materials to the construction site. The *initial* embodied energy depends on the material choice in the building and the manufacturing processes that were needed to produce the material (cradle to gate energy). Also, energy that is directly associated with the construction process, like the transport of materials to the factory site, is included in the embodied energy [49,50]. The *transport* energy is defined as the average primary energy necessary to transport the building materials from factory gate to construction site. In this research, demolition energy (energy necessary to demolish a building at the end of its lifetime) is excluded because this energy is not directly influenced by material choice. Furthermore the demolition stage includes a lot of uncertainties with regard to the fate of a building in the future [48]. According to Crowther [15] and Stephan, Crawford, and de Myttenaere [51] the energy required for demolition, represents however only about 1% of the total life cycle energy of the building. Recurrent energy (energy that applies to the embodied energy of components of the building with a shorter lifetime than the lifetime of the building) is also excluded since it is susceptible to consumer preferences. This makes it difficult to include in an overview of average embodied energy use (see Section 4 “discussion of uncertainties”, for possible impacts on results).

2. Method

The research method is based on the joint application of two tools: the Embodied Energy Database Management System (EEDMS) and the $_3$SCEP HEB model.

The Embodied Energy Database Management System (EEDMS) was developed in this study to analyse the embodied energy use in the Dutch residential sector based on 23 materials most commonly used in Dutch residential construction. The tool includes material volumes and material energy intensities for 25 Dutch building archetypes.

The $_3$SCEP HEB model was developed by the Center for Climate Change and Sustainable Energy Policy ($_3$SCEP) to perform a policy-based scenario analysis concerning the global potential of reducing operational energy use and associated greenhouse gas emissions by high efficiency buildings (HEB). This analysis started under guidance of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) and was extended in cooperation with the Global Buildings Performance Network (GBPN) in 2011 and 2012 [61]. This model simulates the development of the world's building stock and related operational energy use. The building stock is broken down by regions, climate zones, building types and building vintages.

The $_3$SCEP HEB model is used to model the development of the Dutch building stock development in floor area from 2015 to 2050. These outcomes are used as input in the EEDMS to calculate total embodied and operational energy use from 2015 to 2050.

The method consists of three steps, which are further described in the subsections below:

1. Identifying buildings archetypes for the key Dutch building typologies and their operational energy use (Section 2.1)
2. Data collection of average material composition in building archetypes and corresponding embodied energy intensities to calculate embodied energy use (Section 2.2)
3. Modelling floor areas for different scenarios with the $_3$SCEP HEB model (Section 2.3)

2.1. Building archetypes and operational energy use

All residential buildings in the Dutch residential stock are categorised into 25 building archetypes on the basis of two factors: building types and building vintages. Five types of buildings are distinguished that occur most in the Netherlands in 2015 [10]: mid-terrace, end-of-terrace, detached, semi-detached and apartments.

The vintages are based on the construction period and their specific energy performance due to building regulations:

- The *standard* (conventional) vintage category includes dwellings built before 2015. These are based on a selection of building archetypes that are most common in the Netherlands. The dwelling archetypes are built in the period 1965–1974, which reflects the average age of the current building stock and the energy use that is representative for the building regulations in that period [2]. The selected archetypes together account for nearly 20% of the total dwellings in the Netherlands in 2015 (see Table 1).
- The *New* vintage represents an average home that is built according to building regulations set in 2015.
- *Advanced new* represents a building built from 2015 in line with the requirements of a nearly-Zero Energy Building (nZEB) standard. A nZEB is a building with a low energy demand which can largely be met by renewable energy sources at the same location or nearby (European Parliament & EU Council, 2010). In this research this is represented by a passive home (PH), which is a concept to define a nZEB according to the Passive

Table 1
Archetypes for dwellings and floor area per type and vintage in m^2.

	Share of building archetype in total dwellings in 2015[a]	Floor area (m^2)[b]	
		Standard, retrofit and advanced retrofit	New and advanced new
Mid-terrace	6.0%	106	124
End-of-terrace	3.0%	106	124
Detached	1.8%	144	170
Semi-detached	2.1%	123	148
Apartment	4.3%	76.7	91.9

References:
[a] Agentschap NL [2]
[b] RVO (2011) and RVO (2015)

Table 2
Thermal resistance of construction U-values ($W/(m^2{\cdot}K)$) of the five vintages [2,38–42,44,5].

	Ground floor	Roof	Facade	Windows
Standard	5.9	1.2	2.3	5.3
New	0.29	0.17	0.22	1.3
Retrofit	0.40	0.50	0.77	2.2
Advanced New	0.15	0.10	0.10	0.80
Advanced Retrofit	0.15	0.10	0.10	0.80

House Institute (PHI, 2015). A passive home is built according to a certain level of minimum insulation necessary to reach passive home standards. Note that the optimal insulation level still leaves room for interpretation, depending on social and economic optima [34], see Section 4 “discussion of uncertainties”.

- The *Retrofit* vintage represents all standard buildings converted to a more energy efficient home according to standard renovation requirements of the Netherlands Enterprise Agency (RVO) in 2015.
- *Advanced Retrofit* represents a standard building that is renovated according to the passive home requirements.

Table 1 shows the average floor area of the houses per type and vintage.

Table 2 shows the thermal resistance of construction components, i.e. U-values that correspond with a particular energy performance level of the vintages included in this study.

The operational energy use (in MJ/a) is based on the required heating and cooling demand in Dutch residential buildings obtained from the TABULA web tool [23]. For the Netherlands this data is collected by TU Delft [59]. Since cooling is hardly necessary in the Netherlands, the collection only includes heating demand. Cooling is likely to increase in importance in the future due to climate change, but there is no insight in when cooling will make up a susceptible amount of the operational energy use.

2.2. Calculation of and data collection for embodied and operational energy demand

2.2.1. Material composition

The Dutch Green Building Council [18] (2016) Materialentool 3.01 is used to determine the basic material characteristics of the building types and vintages. The DGBC tool provides data of the building structure, façade, inner walls, floors, roof, technical installations and interior design for the detached and mid-terrace building types built since 2015. The output is a series of materials, their surface areas and sometimes other characteristics (thickness and R-values). Based on these building types, also assumptions were made for the end-of-terrace, semi-detached and apartment building types.

Additional data with regard to material usage was obtained from the website of the knowledge institute for construction, SBR-CURnet. This source provides details of standards for building components used in the Dutch construction industry. The SBR reference details include drawings of the structure, U-values, types and thickness of materials of the building components [45]. Depending on the U-values of the vintages (see Table 2) appropriate SBR reference details were selected for the estimation of the material usage.

Table 3 shows the most important assumptions derived from the SBR reference details and other literature, internet and interview sources. The specific SBR reference details that were used in this research can be found in the appendix. Note that material use of technical installations like heating equipment and ventilation system of the building are not considered in this material assessment.

To calculate the material volumes for every building representative, the material surfaces were multiplied with the corresponding thickness, and summed per type. This data is processed in the EEDMS, which contains the material characteristics (material type, surface, thickness, and volume) for every building archetype within the categories structure, façade, inside walls, floors and roof. The embodied energy inventory of the retrofit and advanced retrofit archetypes includes the materials used for the retrofit, and the materials that were already present before retrofitting.

2.2.2. Embodied energy

To get the *initial* embodied energy intensities, the inventory of carbon and energy (ICE) [14] was used. 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 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*’ [13]. The intensities are given in MJ/kg, thus multiplying it with the corresponding material density in kg/m^3 gives the initial embodied energy intensity (IEEI) in MJ/m^3. For all materials the standard IEEI is used, but the minimum and maximum values are also included in Table 4. For most materials the range is quite big, illustrating the uncertainty is this data (see Section 4 “discussion of uncertainties”).

Transport energy from the factory gate to the construction site in the Netherlands is estimated using Eqs. (1) and (2):

$$TEEI\left(\frac{MJ}{kg}\right) = \frac{\left(avg\,fuel\,use\left(\frac{l}{km}\right) * avg\,transport\,distance(km)\right) * energy\,content\,fuel\left(\frac{MJ}{l}\right)}{avg\,load\,(kg)} \quad (1)$$

$$\begin{aligned} WA\ TEEI\ building\ material\ \left(\frac{MJ}{kg}\right) &= \left(TEEI\ road\ transport\ \left(\frac{MJ}{kg}\right) * \ share\ transported\ by\ truck\right) \\ &+ \left(TEEI\ ship\ transport\ \left(\frac{MJ}{kg}\right) * share\ transported\ by\ ship\right) \end{aligned} \quad (2)$$

The transport embodied energy intensity (TEEI) is calculated for road and ship transport in the Netherlands separately by using Eq. (1). The average fuel used by trucks in the Netherlands is diesel, with an average usage of 0.32 l/km [25]. The average transport distance by truck estimated for an average building material in the Netherlands, including import from other countries, is 96 km [6]. The energy content of diesel is 36 MJ/l [8]. The maximum average truck load is 40 tonnes [33]. This 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. Specific diesel oil usage of an

Table 3
Assumptions on materials used for the different vintages based on SBR reference details [45] unless stated otherwise.

		Standard	New	Retrofit	Advanced new	Advanced retrofit
Foundation structure	Poles	Concrete[b]	Wood[a]	Concrete	Wood	Concrete
	Floor type	'Kwaaitaal[#]' cantilevered[c,d]	Hollow core slab cantilevered[a]	'Kwaaitaal' cantilevered	Hollow core slab cantilevered	'Kwaaitaal' cantilevered
	Cantilevered floor insulation	No insulation[e]	No insulation	No insulation	EPS box (thickness 100 mm surrounding the floor from 4 sides)	EPS of 240 mm thick
	Internal walls	Gypsum[b,c]	Aerated concrete[a]	Gypsum	Aerated concrete	Gypsum
Façade structure	Wall insulation	No insulation[e]	MW of 140 mm thick	MW of 50 mm thick	WF of 20 mm thick, and MW of 400 mm thick	MW of 300 mm thick
	Doors & window frames	Softwood[b]	Aluminium[a]	Softwood	Aluminium doors & frames[a], doors insulated with PUR of 30 mm thick	Softwood
Ground floor	Insulation	No insulation[e]	EPS of 120 mm thick	PUR foam of 100 mm thick	XPS of 180 mm thick	MW wool of 240 mm thick
Roof	Insulation	No insulation[b]	MW of 270 mm thick	MW of 100 mm thick	PUR of 275 mm thick	PUR of 275 mm thick

Abbreviations: EPS is expanded polystyrene, MW is mineral wool, WF is wood fibreboard, PUR is polyurethane foam and XPS is extruded polystyrene. References:
[a] DGBC material tool [18],
[b] Rotterdam Municipality [35],
[c] p.c. Broekhuizen, H. (29-09-2016),
[d] Liebregts & Persoon [27],
[e] Agentschap NL [2],
[#] Precast reinforced concrete.

Table 4
Most common Dutch residential building materials, their labels, initial embodied energy intensity (IEEI), embodied energy intensity (EEI) and density; sorted by IEEI from high to low.

Material name	Label	Minimum IEEI (MJ/kg)	Standard IEEI (MJ/kg)	Maximum IEEI (MJ/kg)	EEI (MJ/kg)	Density (kg/m^3)
Aluminium	Al	58.0	108.6	184.0	108.7	2700
Polyurethane foam	PUR	71.1	101.5	132.0	101.6	45
Expanded polystyrene	EPS	62.0	88.6	115.2	88.7	27.5
Extruded polystyrene	XPS	61.2	87.4	113.6	87.5	37.5
Polyvinylchloride	PVC	47.3	67.5	87.8	67.6	1380
Zinc	Zi	8.5	53.1	105.8	53.2	7000
Bitumen	Bi	2.4	51.0	51.0	51.1	2400
Mineral wool	MW	10.0	16.6	23.2	16.7	140
Wood fibre	WF	15.0	16.0	35.0	16.1	750
Plywood	Pl	10.0	15.0	20.0	15.1	540
Primary glass	PG	10.5	15.0	19.5	15.1	2500
Ceramics	Ce	2.5	12.0	19.5	12.1	2000
Hardwood	HW	0.72	10.4	16.0	10.5	750
Softwood	SW	0.72	7.4	13.0	7.5	560
Argon	Ar	6.80	6.8	6.80	6.9	1.66
Aerated concrete	AC	1.97	3.5	4.76	3.6	750
Gypsum plaster	Gy	0.90	3.48	8.64	3.6	1120
Brick, clay	Br	1.00	3.0	5.00	3.1	1700
Reinforced concrete	RC	1.76	2.07	2.20	2.15	2300
Precast concrete	PC	1.20	1.27	3.80	1.35	2200
Sand cement	SC	0.54	0.99	1.28	1.07	2200
Gravel	Gr	0.01	0.01	0.50	0.16	2240
Sand	Sa	0.01	0.01	0.15	0.014	2240

inland ship is 6500 l/km [3]. 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 [6]. The average maximum ship load in the Netherlands is 1200 tonnes [21]. This leads to a TEEI of ship transport in the Netherlands of 0.21 MJ/kg. Eq. (2) is used to calculate the weighted average transport embodied energy intensity (WATEEI) per unit of building material. In the Netherlands, the share of building materials transported by truck is 72% and by ship is 28% [6]. This leads to a WATEEI of 0.08 MJ/kg for every material.

Table 4 shows the density, IEEI, and the total embodied energy intensity (EEI, i.e. IEEI plus WATEEI) for 23 materials most often used in the Netherlands. The table is sorted by EEI: from highest intensity to lowest. For most materials including the transport energy only increases the EEI with a very small amount.

Eq. (3) is used to sum the embodied energy use (EEU) outcomes for every material that occurs in a building representative. x stands for one of the 23 materials shown in Table 4.

$$\begin{aligned} &EEU\ building\ representative(MJ) \\ &= \sum \left(EEI_x\left(\frac{MJ}{kg}\right) * density\ material_x\left(\frac{kg}{m^3}\right) \right. \\ &\quad \left. * \ volume\ material_x\left(m^3\right) \right) \end{aligned} \tag{3}$$

In order to compare building archetypes, the EEUs are divided by the corresponding user surface areas (Table 1) which leads to the specific EEUs in MJ/m^2. Thereafter the EEU is divided by the building lifetime to be able to compare the values to operational energy in MJ/(m^2·a). The building stock in the Netherlands is continuously changing: some buildings are demolished, but others are renovated and adapted to foresee in new needs of the population. 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 [46]. However, when differentiating between single family (SF) and multi-family (MF, i.e. apartments) 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 lifetime statistics leads to an average lifetime of SF homes of 73.3 years, and for MF homes of 66.8 years. Furthermore, a distinction is made between retrofitted and non-retrofitted homes. A simple renovation often increases the lifetime with 15 years [56]. Therefore, the lifetimes included in the EEDMS are for retrofit and advanced retrofit SF and MF homes, 73.3 and 66.8 years, respectively, and for standard, new and advanced new SF and MF homes 58.3 (73.3–15) and 51.8 (66.8–15) years, respectively.

2.3. Scenarios

In the $_3$SCEP HEB model scenarios are defined to estimate the development of floor area per building type. The starting points of these scenarios are the floor areas in 2015, population projections, and policy initiatives. Two scenarios are defined: a *frozen efficiency* and an *improved efficiency* scenario. Both scenarios are based on:

- a population growth of 7% in 2050, compared to 2015 (based on CBS, 2017 and Ministry of Internal Affairs and Kingdom relations, 2016),
- a demolition rate (percentage of existing homes that are demolished every year) of 0.16% (Ministry of Internal Affairs and Kingdom relations, 2016),
- a new construction rate (percentage of existing homes that are newly constructed every year) of 0.64% (Ministry of Internal Affairs and Kingdom relations, 2016),
- a constant shares of dwelling types (34.9% MF, 17.4% ET, 10.5% D, 12.2% SD and 25.0% A, see Table 1).

The *frozen efficiency* scenario assumes retrofit rates (the percentage of existing homes that are renovated every year compared to total building stock) remain stable (at 1.4%/a) [60] and only the vintages "new" and "retrofit" are included in this scenario.

The *improved 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 directive aims to increase the energy efficiency of buildings in the EU with 20% in 2020. Furthermore, all new residential buildings should be nZEB's by December 31st in 2020. To reach the goals of the EBPD, an accelerated renovation rate from 1.4% to 1.9% per annum (of which 0.7%/a for retrofit and 1.2%/a for advanced retrofit) is assumed in the improved efficiency scenario [60]. Furthermore, all new buildings, starting in 2020 are of the type advanced new. The resulting floor area's per dwelling are presented in Table 5.

Table 5
Total floor area per dwelling archetype in 2015 and 2050 (in million m^2).

	2015	Frozen efficiency scenario 2050	Improved efficiency scenario 2050
	Million m^2		
MT.st	40.5	13.5	4.0
MT.new	–	13.3	1.8
MT.ret	7.5	32.9	20.5
MT.anew	–	–	11.2
MT.aret	–	–	22.2
ET.st	20.2	6.7	2.0
ET.new	–	6.6	0.9
ET.ret	3.8	16.4	10.2
ET.anew	–	–	5.6
ET.aret	–	–	11.1
D.st	12.1	4.0	1.2
D.new	–	4.0	0.5
D.ret	2.3	9.9	6.1
D.anew	–	–	3.4
D.aret	–	–	6.7
SD.st	14.2	4.7	1.4
SD.new	–	4.6	0.6
SD.ret	2.6	11.5	7.2
SD.anew	–	–	3.9
SD.aret	–	–	7.8
A.st	29.0	9.7	2.8
A.new	–	9.5	1.3
A.ret	5.4	23.6	14.7
A.anew	–	–	8.0
A.aret	–	–	15.9
Total	**137.6**	**170.9**	**170.9**

Note: MT = mid-terrace, SD = semi-detached, ET = end-of-terrace, D = detached, st = standard, ret = retrofit, anew = advance new, aret = advance retrofit.

3. Results

3.1. Embodied energy use

Fig. 1 shows the specific annual EEU per building archetype in MJ/(m^2·a), which varies from 52 to 106 MJ/(m^2·a). It is mostly the highest for the advanced new vintage and the lowest for retrofit. When comparing building *types*: apartments have the lowest specific EEU and mid-terraced homes the highest mainly caused by the reinforcements of their walls. The total EEU (not annualised over the building lifetime) varies from 232 to 1042 GJ and from 3 to 6.4 GJ/m^2.

The order of magnitude for embodied energy use in the building archetypes can be explained by the material choice, material volumes, the specific embodied energy intensities of these materials and building life time. Fig. 2 shows an overview of the contribution of the materials in percentages. It displays the twelve materials that have the highest share in the embodied energy use: precast concrete (PC), 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). Table 6 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 differ most significantly. The data is ordered by the material with the highest volume on average in the building archetypes to the lowest.

3.1.1. Results by building types

For most of the building types precast concrete is the most important contributor to embodied energy use (EEU), and reinforced concrete is of second importance, with 27% and 21% on average respectively (see Fig. 2). In all building types except apartments, softwood is third in ranking mainly caused by the relatively large volume used. In apartments instead of ply- and softwood more bitumen and sand cement is used because of the flat roofs. These consist of concrete, bitumen and gravel, while an (partially) inclined roof also consist of ply- and softwood.

When comparing the mid-terrace building type with highest specific EEU and the apartment type with lowest, the main differences are found in the EEU shares of softwood, PUR, plywood and bitumen. In mid-terrace homes these shares are on average, respectively, 9.3%, 10.4%, 5.1%, and 3%, while in apartments, these are, respectively 0.3%, 4.3%, 2.7% and 8%. Even though bitumen has a high EEI (123 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.

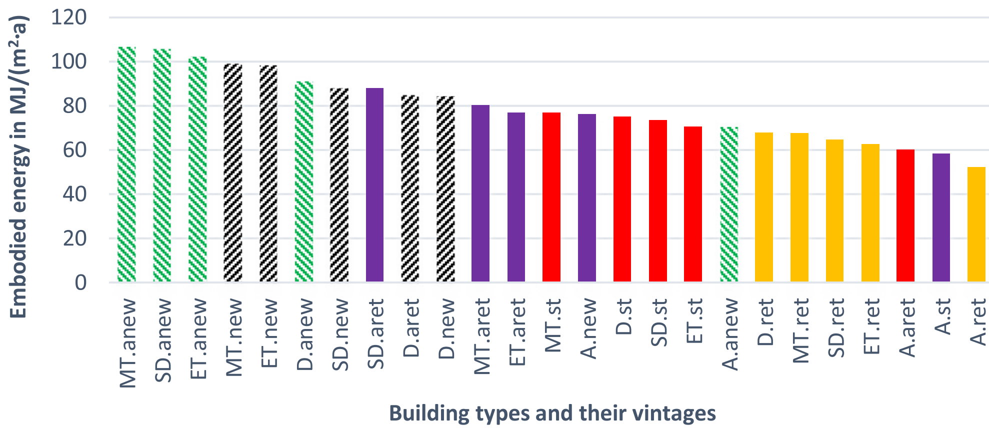

Fig. 1. Specific embodied energy use for building archetypes in the Netherlands in MJ/(m^2·a). Green is advanced new, black is new, purple is advanced retrofit, red is standard and yellow is retrofit. (MT = mid-terrace, SD = semi-detached, ET = end-of-terrace, D = detached, st = standard, ret = retrofit, anew = advance new, aret = advance retrofit). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

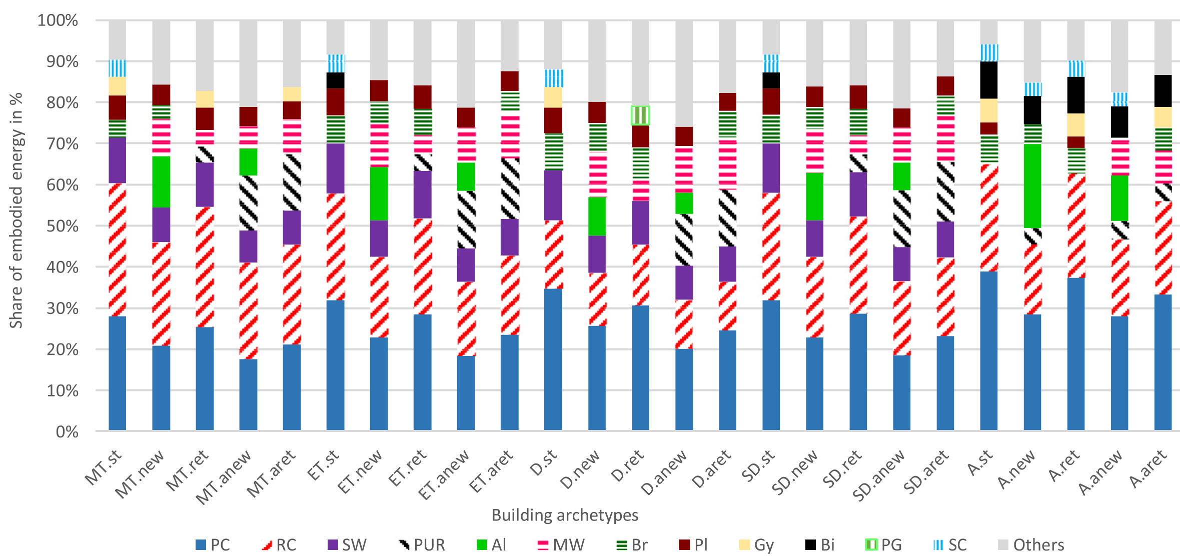

Fig. 2. The share of materials in the total embodied energy use for the Dutch residential building archetypes (MT = mid-terrace, SD = semi-detached, ET = end-of-terrace, D = detached, st = standard, ret = retrofit, anew = advance new, aret = advance retrofit, PC = precast concrete, RC = reinforced concrete, SW = softwood, PUR = polyurethane insulation, Al = aluminium, MW = mineral wool, Br = clay brick, Pl = plywood, Gy = gypsum, Bi = bitumen, PG = primary glass and SC = sand cement).

3.1.2. Results by vintages

In the standard vintage, the building materials gypsum, clay brick and sand cement play an important role. When gypsum is present in the vintage (standard, retrofit and advanced retrofit) this material is a large contributor to the embodied energy use. Interestingly aerated concrete–the replacement of gypsum in the new and advanced new vintage–did not appear in Fig. 2. The reason for this is the lower EEI of aerated concrete (2.68 GJ/m^3) compared to gypsum (3.99 GJ/m^3). The standard vintage has a lower embodied energy use compared to the new vintage due to three 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 GJ/m^3) compared to softwood (4.19 GJ/m^3) used for the same purposes in the standard vintage.
3. The foundation poles in the new vintage consist of hardwood with an EEI of 7.86 GJ/m^3, whilst these poles consist of precast concrete with a 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, e.g. single glass is replaced by HR glass, which leads to a higher primary glass volume. 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 archetypes. This is because detached homes have a relatively higher window surface. 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 Fig. 2. This is mainly caused by the large volume used of this material. Table 6 shows that particularly the amount of PUR is huge in the advanced retrofit and new vintages.

The advanced new vintage has the highest specific embodied energy use (MJ/(m^2·a)) relative to the others. 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 EEI of 3.28 GJ/m^3), which is more energy intensive than mineral wool or EPS. Furthermore, the façade structure is completely dif-

Table 6
The 23 materials most used in Dutch residential construction, their embodied energy intensities (EEI) in GJ/m^3 and the volumes present of these materials in the building archetypes in m^3, ordered by volume. (MT: mid-terrace, SD: semi-detached, ET: end-of-terrace, D: detached, st: standard, ret: retrofit, anew: advance new, aret: advance retrofit).

Material	Embodied energy intensity (GJ/m^3)	Volume in 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	44.2	50.2	44.8	45.7	44.8	73.7	83.3	73.7	70.5	73.7	21.3	34.8	30.0	31.5	30.0
Sa	0.20	34.3	40.2	34.3	41.2	34.3	49.0	57.7	49.0	57.7	49.0	21.8	26.1	21.8	26.1	21.8
RC	4.94	31.1	36.5	31.1	36.5	31.1	21.4	25.1	21.4	25.1	21.4	12.3	12.6	12.3	12.6	12.3
MW	2.34		28.2	8.85	17.9	22.6		46.0	15.4	50.7			4.66	2.35	13.2	9.14
PUR	4.57			4.57	22.4	19.0			6.54	28.7	27.2		3.07	0.31	3.25	2.62
SW	4.19	12.5	14.4	13.4	14.4	12.5	18.2	20.8	18.2	20.8	18.2	0.17		0.17		0.17
SC	2.35	8.27	9.69	8.27	9.69	8.27	11.8	13.9	11.8	13.9	11.8	4.12	4.91	4.12	4.91	4.12
XPS	3.28				9.64					13.9					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	10.9	12.8	10.9	2.44	10.9	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	12.1				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	24.2	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	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		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	123	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	37.7	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	93.3	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

ferent compared to the other vintages; it consists of mineral wool of 400 mm thick and wood fibreboard. Even though mineral wool is less energy intensive than the traditionally used clay brick (EEI of 5.24 GJ/m^3) and precast concrete (EEI of 2.97 GJ/m^3), the high volume amount of mineral wool, together with medium intensive wood fibreboard (EEI 12.06 GJ/m^3) lead to a higher embodied energy use of the building façade.

Considering the fact that the low specific embodied energy use in MJ/(m^2·a) in retrofitted homes is caused by the higher lifetime of these buildings compared to non-retrofitted homes, standard homes have in absolute sense the lowest embodied energy use. The reasons are mainly the absence of insulation materials and aluminium.

3.2. Operational energy use

The specific heat demand of the building archetypes is shown in Fig. 3. It is sorted from highest (682 MJ/(m^2·a)) for standard houses to lowest (124 MJ/(m^2·a)) for advanced new houses. In terms of building types, detached homes have the highest specific energy use while apartments have the lowest. The volume that needs to be heated and the sharing of walls play a role here.

3.3. Total energy use

Fig. 4 shows the specific embodied energy use plus operational energy use for the building types and vintages, varying from 193 to 758 MJ/(m^2·a). The embodied energy use in standard homes is about 10–12% of the total energy use. These shares are 15–18% for retrofit homes, 29–34% for new dwellings, 31–35% for advanced retrofit and 31–46% for advanced new. This clearly shows the impact of more insulating materials used and the increasing importance of embodied energy use. However in absolute sense the (advanced) new and retrofit dwellings show a strong reduction in total energy use compared to standard dwellings up to 63–66%, depending on type.

Fig. 5 shows the development of the total energy use of the selected residential buildings in the Netherlands, in the frozen efficiency scenario. These account for about 20% of total residential buildings. A reduction in annual energy use is visible of 13% in 2050 compared to 2015 level, due to an increase of retrofit and new dwellings. 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 of EEU in total energy use increases from 12% in 2015 to 17% in 2050; mainly caused by the increasing shares of new and retrofit homes.

Fig. 6 shows a total decrease in energy use between 2015 and 2050 of 36% in the improved efficiency scenario, which is much more significant than in the frozen efficiency scenario. The share of embodied energy in total energy use increases from 12% in 2015 to 24% in 2050, mainly caused by increasing advanced new and retrofit homes.

4. Discussion of uncertainties

Even though the assumptions and data used in this research are chosen as carefully as possible, there are a number of uncertainties. The most important ones are discussed below.

4.1. Recurrent embodied energy use and technical installations

When defining the embodied energy use, it is chosen to exclude recurrent energy, which applies to the embodied energy of components with a shorter lifetime than the building itself. In our definition this includes technical installations and energy supply technologies such as PV. These have typically shorter lifetimes and are susceptible to consumer preferences and changes in the course of the building lifetime. Studies have found that recurrent energy is typically 20–30% of the initial embodied energy over an assessed building lifetime of 30–50 years ([49,57] and [16]), but some studies find values up to 60% [32]. When we add 30% to embodied

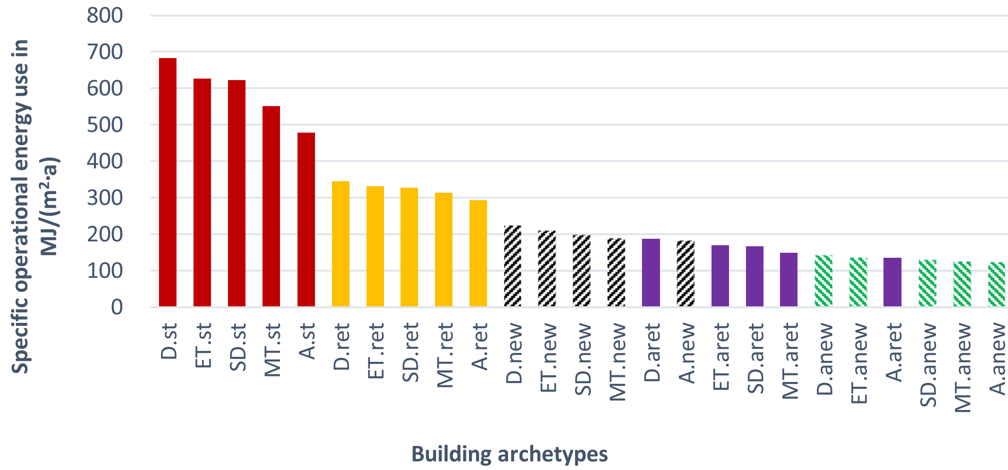

Fig. 3. Specific operational energy in MJ/(m^2·a) for residential building archetypes in the Netherlands. Green is advanced new, black is new, purple is advanced retrofit, red is standard and yellow is retrofit. (MT: mid-terrace, SD: semi-detached, ET: end-of-terrace, D: detached, st: standard, ret: retrofit, anew: advance new, aret: advance retrofit). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

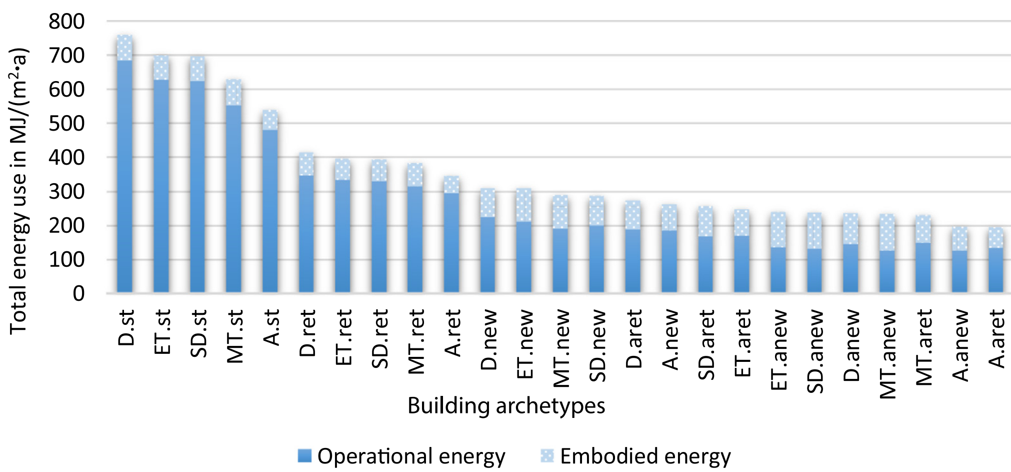

Fig. 4. Specific annual total energy use in MJ/(m^2·a) in the residential building archetypes in the Netherlands divided in operational and embodied energy use. (MT: mid-terrace, SD: semi-detached, ET: end-of-terrace, D: detached, st: standard, ret: retrofit, anew: advance new, aret: advance retrofit).

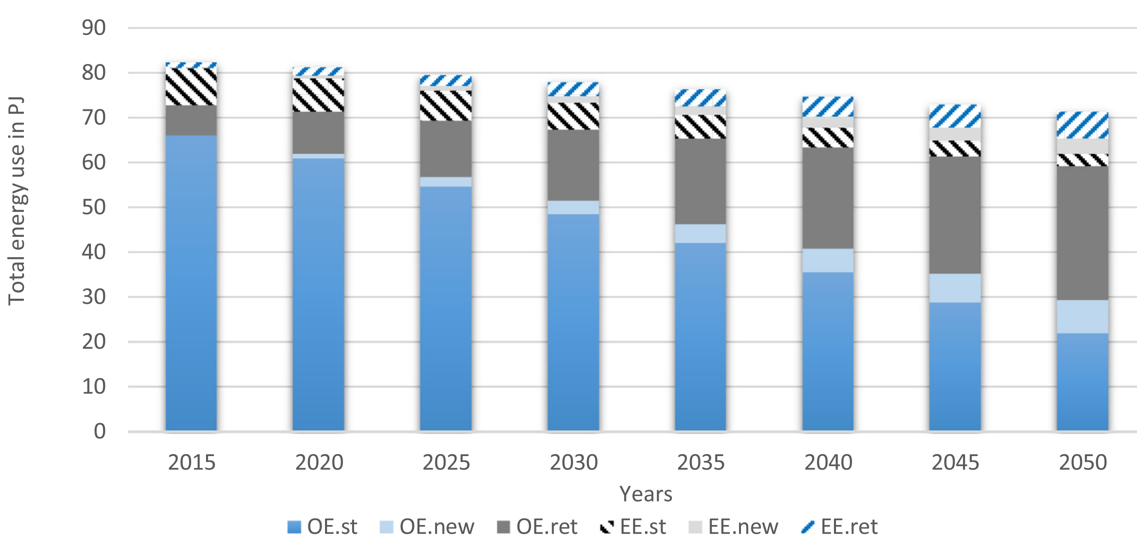

Fig. 5. The total energy use for selected dwellings in the Dutch residential sector per year, in frozen efficiency scenario, for the period 2015–2050. OE = operational energy and EE = embodied energy.

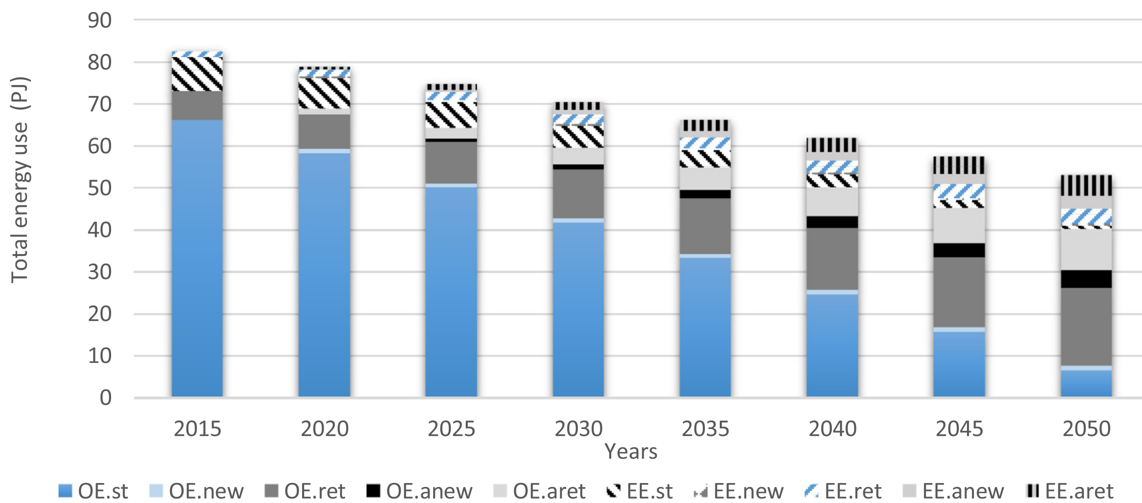

Fig. 6. The total energy use for selected dwellings in Dutch residential sector per year, in the improved efficiency scenario, over the years 2015–2050. OE = operational energy and EE = embodied energy.

energy use to account for recurrent energy, the embodied energy increases from 3.0–6.4 GJ/m^2 to 3.9–8.4 GJ/m^2 and annual embodied energy from 52–106 MJ/(m²•a) to 68–137 MJ/(m²•a). The ratio of embodied energy in total energy use increases from 17% to 21% in 2050 in the frozen efficiency scenario and from 24% to 30% in the improved efficiency scenario. The energy savings in 2050 compared to 2015 reduce from 36% to 34% when recurrent energy is taken into account. Although embodied energy increases in importance in the ratio and absolute figures, the relative results in terms of changes over time and differences between building archetypes remain still valid.

Besides the impact of energy supply technologies on the recurrent embodied energy use, these can also impact the embodied energy use of materials by influencing the energy needed to produce them. Rovers [36] indicates that the embodied energy use of average contemporary housing is around 5 GJ/m^2 floor area while with renewable and biobased materials this can go down to 3 GJ/m^2 or lower.

4.2. Embodied energy intensities

Another uncertainty concerns the embodied energy intensities of the materials. We used cradle to gate energy use for material production from the ICE (Inventory of Carbon and Energy) database [14]. A sensitivity analysis showed a deviation range of −32.5% to +78.4% for the embodied energy use, which is quite high. This was based on the lowest and highest values in the database for initial embodied energy intensity of the 23 materials (see Table 4). The deviation is partly a result of the difference between virgin and recycled materials. To get more precise numbers, the actual degree of recycling and reuse of every material should be known, because producing virgin materials leads often to higher embodied energy intensity than when producing recycled and/or reused materials. However, recycling is also responsible for other (energy) impacts related to transportation and re-processing which may lead to more energy spent than avoided [7]. In this paper, benefits and burdens of recycling parts of the dwellings at the end of their life time (module D impacts) are not included.

Furthermore, future embodied energy intensity can be lower due to technological progress, which is not taken into account in this research. 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 rough numbers were used. Although transport energy was estimated to be low compared to energy used during material manufacturing, future studies can more accurately assess the transport energy use part.

Another uncertainty relates to the lifecycle approach used. The ICE database contains data from different sources that do not always use consistent system boundaries. In general one can distinguish between three types of general techniques: process-based (bottom-up), input-output (topdown) and hybrid. The values in the ICE database are mostly process-based. An advantage this approach is more detail and deeper understanding of the nature of activities on product level [29]. However process analyses do not consider environmental impacts associated with inputs and outputs located outside of the system boundaries. The selection of system boundaries and the exclusion from the inventory of certain processes can be difficult because these have never been assessed and therefore their negligibility cannot be guaranteed [52]. This is typically referred to as the ‘truncation error’ which can underestimate requirements (see e.g. [29,54] and [16]). In this regard input-output based inventories have the advantage to be more comprehensive with a more complete system boundary, since they are based on data for the whole economy. But the major drawback of this approach is that they are generally used as a ‘black box’, with little understanding of the values being assumed in the model for each process [16]. Hybrid approaches that combine process-based and input-output data are therefore in theory superior to both methods but have yet to enter mainstream practice [29]. Since this study uses process-based data the embodied energy use may be lower than in reality. For instance, Crawford and Stephan [17] have shown that input-output-based hybrid analysis can produce embodied energy up to four times higher than process analysis, for the same building. Higher embodied energy values would not impact the comparative outcomes of this study in terms of the trends over time or differences between archetypes, but would increase the ratio of embodied energy to operational energy. It should be noted though that also the operational energy use is not all inclusive in terms of related lifecycle energy use. Only direct energy consumption is taken into account for heating and not the energy use related to e.g. the production and transport of the fuel.

4.3. Building lifetime

The assumptions regarding the lifetime of buildings for the embodied energy use calculation are also uncertain. Furthermore they do not reflect the actual energy use in time, since the embodied

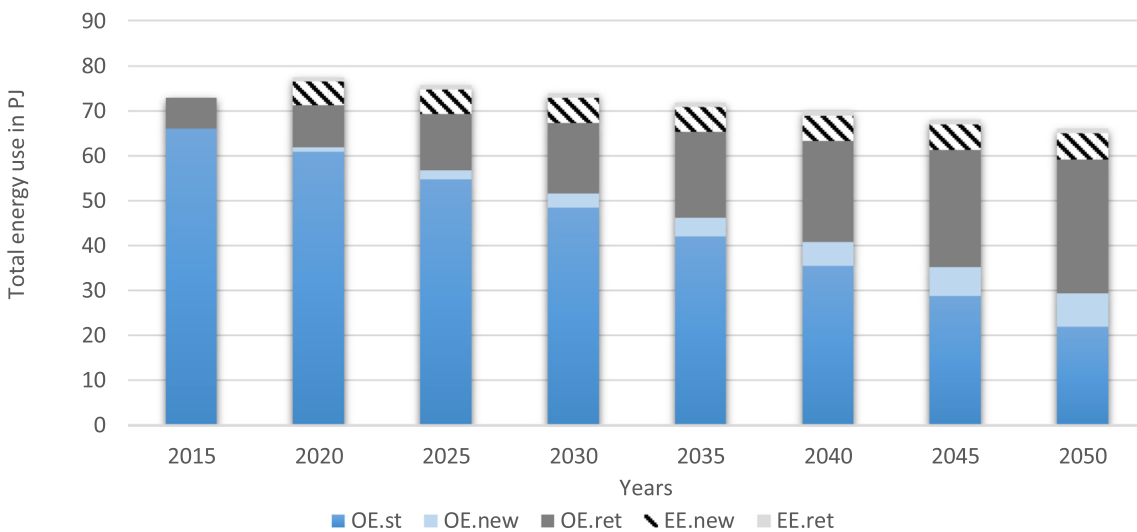

Fig. 7. The total energy use for selected dwellings in the Dutch residential sector per year, in frozen efficiency scenario, for the period 2015–2050. OE = operational energy and EE = embodied energy (not annualised over lifetime).

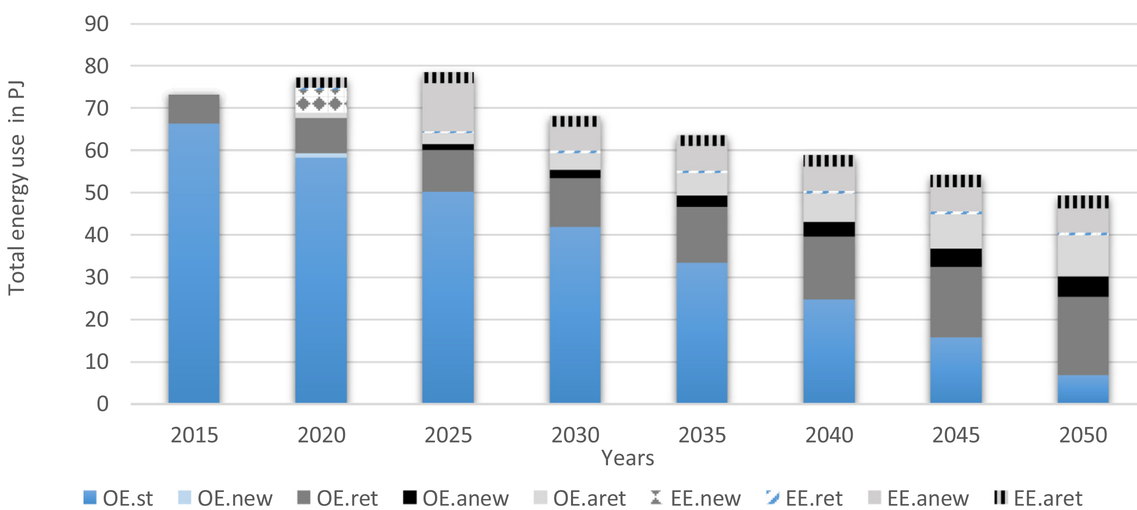

Fig. 8. The total energy use for selected dwellings in Dutch residential sector per year, in the improved efficiency scenario, over the years 2015–2050. OE = operational energy and EE = embodied energy (not annualised over lifetime).

Table 7
Results with and without annualising embodied energy use over the lifetime of the building.

Results		2050 frozen efficiency	2050 improved efficiency
EEU annualised over lifetime	Total energy savings compared to 2015	13%	36%
EEU not annualised over lifetime		9%	33%
EEU annualised over lifetime	Embodied energy use in total energy use	17% (57% standard, 34% retrofit, 8% new dwellings)	24% (38% advanced retrofit, 29% retrofit, 24% advanced new, 6% standard, 4% new)
EEU not annualised over lifetime		10% (16% retrofit and 84% new dwellings)	19% (63% advanced new, 31% advanced retrofit and 6% retrofit)

energy of the standard dwellings has already occurred in the past. Therefore we include Figs. 7 and 8 to show the developments of the frozen and improved efficiency scenario if the embodied energy use is not annualised over the lifetime of the dwellings but is based on the newly constructed or retrofitted houses in that year. For retrofit houses only the incremental embodied energy use is included for the newly added materials such as window glass and insulation materials. The results change as follows (see Table 7): energy savings in the frozen efficiency scenario reduce from 13% to 9% in 2050 and from 36% to 33% in the improved efficiency, in comparison to 2015. The share of embodied energy in total energy use reduces from 17% to 10% in 2050 in the frozen efficiency scenario and from 24% to 19% in the proved efficiency scenario.

The exact numbers and contribution of types of houses is different, but the overall conclusion holds regarding the increasing importance of embodied energy use. Note that in absolute sense the total energy use for the years 2020 and 2025 is somewhat higher in the improved efficiency scenario due to the higher embodied energy use of efficient houses.

4.4. Insulation levels

Another uncertainty rises from the insulation levels applied. We used the insulation levels for a passive home for nZEB (PHI, 2015). The configuration of a passive home and related amount and type of insulation materials used are however not necessarily optimal in terms of environmental impacts (see [34]). Taking into account multiple environmental impacts factors therefore may change the optimal insulation level and related embodied energy results.

4.5. Applicability of results to other countries

The results of the EEDMS are expected to differ for other countries. Operational energy 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.

4.6. Comparison to other studies

Often case studies executed for this topic differ in type of residential building, climate zone and data sources [43]. Comparison in absolute numbers between the case studies is therefore difficult. Where applicable, outcomes of other studies were compared in relative terms to the outcomes of this research. Furthermore, case studies for the Netherlands were unfortunately not available. First, literature reviews that show averages based on multiple case studies are discussed, and secondly, case studies focussing on one country are presented.

Sartori and Hestnes [43] 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. Chastas et al. [11] conducted a literature review on Life Cycle Energy Analysis (LCEA) studies in residential buildings. In this review it is confirmed that when a conventional home is transformed into a passive/low energy home (from standard to advanced), the share of embodied energy in total building energy use increases, while 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%.

For the embodied energy use a range is found of 0.9–13 GJ/m^2 floor area (for cradle-to-gate) in IEA [22], of 3.6–8.8 GJ/m^2 in Dixit et al. [19] and of 1.8–7.7 GJ/m^2 in Dixit [20]. The latter figures are for brick residential houses in Europe and are based mostly on studies with process-based life cycle inventory approaches. The embodied energy use found in this study falls largely within these ranges with 3.0–6.4 GJ/m^2.

Monteiro et al. [31] estimate embodied energy use for a new house in Portugal to be 4.5 GJ/m^2, with process-based lifecycle inventory. Adalberth [1] studied the embodied and operational energy use in three low energy use dwellings in Sweden. The average embodied energy was 3.0 GJ/m^2, equivalent to 15% of total building energy use. Bensal et al. [4] found embodied energy of 2.0–4.3 GJ/m^2 for dwellings in India with a floor surface between 20–60 m^2. Reddy and Jagadish [62] also executed an embodied energy analysis in residential buildings in India. In this study it 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 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. The results for Portugal, Sweden and India are comparable to the 3.0–6.4 GJ/m^2 range found in this study.

5. Conclusion

The purpose of this research was to show the effect of reducing heat demand on the embodied energy use in Dutch residential buildings. The found embodied energy use for 25 building archetypes in the Netherlands varies from 52 to 106 MJ/(m^2·a). Of the building types, apartments have the lowest embodied energy use and mid-terraced homes the highest. Of the building vintages, advanced new homes are most energy intensive, mostly due to large insulation volumes and standard homes are least energy intensive. Precast and reinforced concrete contribute most to the embodied energy in all building archetypes, with on average 27% and 21%, respectively.

The operational energy use in the Dutch building archetypes varies from 124 to 682 MJ/(m^2·a). Of the building types, apartments have the lowest operational energy use and detached homes the highest. Of the building vintages, standard homes have the highest specific heat demand and advanced new homes the lowest.

The embodied energy use as share in total energy of dwellings is lowest for standard homes with a range of 10–12% and highest for advanced new homes ranging from 31–46%. This clearly shows the impact of more insulating materials used and the increasing importance of embodied energy use. However in absolute sense advanced new dwellings show a strong reduction in total energy use compared to standard dwellings of 63–66%, depending on type.

The scenario analysis showed a total energy use decrease in the frozen efficiency scenario of 13% and 36% in the improved efficiency scenario in 2050, compared to 2015. This is accompanied by an embodied energy increase of 26% and 35%, respectively, while operational energy use decreases by 19% and 46%, respectively. In the improved efficiency scenario, the increase in embodied energy use is mainly caused by an increase in advanced retrofit and advanced new homes. The share of embodied energy use in total energy use increases from 12% in 2015 to 17% in the frozen efficiency and to 24% in the improved efficiency scenario, in 2050. This means that embodied energy use will play an increasing role in the future. Especially when the share of advanced new and advanced retrofit 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 deep greenhouse gas emission reduction scenarios in line with the goal to reach a maximum temperature increase of 2 °C or lower it is important to include embodied energy use in future policies. The study showed a high sensitivity of embodied energy use for virgin versus recycled materials, illustrating the importance of increased recycling of building materials to limit energy use.

Appendix

New vintage:

SBR reference detail (2015) 101.0.3.02, Title: Hollow core slab floor

SBR reference detail (2015) 102.0.3.16, Title: Aluminium frame, inward rotating door

SBR reference detail (2015) 401.0.1.03, Title: Hollow core slab floor

Retrofit vintage:

SBR reference detail (2016) B 101.7.3.01, Title: Floor insulation by means of sprayed PUR

SBR reference detail (2016) B 404.0.0.08, Title: Existing roof, insulation inside

Advanced new vintage:

SBR reference detail (2015) 101.4.2.04.PH, Title: Passive home, HSB-element with L-girder and cavity, hollow core slab floor, insulated foundation structure

SBR reference detail (2009) 102.0.3.04.PH, Title: Passive home, isolated sill, inward rotating insulated door, rib cassette floor, insulated foundation structure

SBR reference detail (2009) 404.0.0.01.PH, Title: Passive home, track cap with L-girder, filled with high quality insulation, fixed cam connection

Advanced retrofit vintage:

SBR reference detail (2016) B103.7.0.02, Title: Passive home, outside facade insulation

SBR reference detail (2016) B404.0.0.05, Title: Passive home, existing roof

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.enbuild.2018.01.036.

References

[1] K. Adalberth, Energy use during the life cycle of single-unit dwellings: examples, 1997. http://dx.doi.org.proxy.library.uu.nl/10.1016/S0360-1323(96)00069-8.
[2] Agentschap NL, Voorbeeldwoningen 2011: Bestaande Bouw, Sittard, 2011. No. 2KPWB1034 Available at: https://www.rvo.nl/sites/default/files/bijlagen/4.%20Brochure%20Voorbeeldwoningen%202011%20bestaande%20bouw.pdf.
[3] E. Backer van Ommeren, Globale schets gasolieverbruik binnenvaartschepen, 2011. Available at: http://www.evo.nl/site/binnenvaart-tarieven-kosten/$FILE/Globale_schets_gasolieverbruik_binnenvaartschepen_06.pdf.
[4] D. Bensal, R. Singh, R.L. Sawhney, Effect of construction materials on embodied energy and cost of buildings—a case study of residential houses in India up to 60 m2 of plinth area, Energy Build. 69 (2014) 260–266. https://doi.org/10.1016/j.enbuild.2013.11.006.
[5] M. Berghuis, Isolatie-Eisen bij Verbouw, Nieman Groep, Helpdesk Bouwbesluit, 2016 Available at: http://www.nieman.nl/wp-content/uploads/2016/07/Isolatie-eisen-bij-verbouw.pdf.
[6] M.M. Bijleveld, G.C. Bergsma, B.T.J.M. Krutwagen, M.A. Afman, Meten is weten in de Nederlandse bouw: Milieu-impacts van bouw- en sloopactiviteiten in 2010, Delft: CE Delft, 2015 No 14.2746.25 in assignment of Bouwend Nederland. Available at: http://www.bouwendnederland.nl/download.php?itemID=904337.
[7] G.A. Blengini, T. Di Carlo, The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings, Energy Build. 42 (6) (2010) 869–880, doi:10.1016/j.enbuild.2009.12.009.
[8] K. Blok, in: Energy Analysis, second ed., Techne Press, Amsterdam, 2009, p. 28.
[9] A.H. Buchanan, B.G. Honey, Energy and carbon dioxide impacts of building construction, in: 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, 1993, p. 354. Available at: https://search.informit.com.au/documentSummary;dn=928109279519301;res=IELENG.
[10] CBS, Vier op de tien huishoudens wonen in een rijtjeshuis, 2016. Retrieved from https://www.cbs.nl/nl-nl/nieuws/2016/14/vier-op-de-tien-huishoudens-wonen-in-een-rijtjeshuis.
[11] P. Chastas, T. Theodosiou, D. Bikas, Embodied energy in residential buildings-towards the nearly zero energy building: a literature review, Building Environ. 105 (2016) 267–282 10.1016/j.buildenv.2016.05.040.
[12] T.Y. Chen, J. Burnett, C.K. Chau, Analysis of embodied energy use in the residential building of Hong Kong, Energy 26 (4) (2001) 323–340 10.1016/S0360-5442(01)00006-8.
[13] Circular Ecology, Glossary of terms and definitions, 2016. Retrieved from http://www.circularecology.com/glossary-of-terms-and-definitions.html#.WKc72fnhDDc.
[14] Circular Ecology, Embodied Energy and Carbon, The ICE Database, 2011.
[15] P. Crowther, Design for disassembly to recover embodied energy, in: Proceedings of Passive and Low-Energy Architecture, Melbourne, 1999.
[16] R.H. Crawford, Validation of a hybrid life-cycle inventory analysis method, J. Environ. Manage. 88 (3) (2008) 496–506. http://dx.doi.org.proxy.library.uu.nl/10.1016/j.jenvman.2007.03.024.
[17] R.H. Crawford, A. Stephan, The significance of embodied energy in certified passive houses, in: ICCBM 2013: International Conference on Construction and Building Materials, Copenhagen, 2013, pp. 473–479. 13–14 June.
[18] DGBC, Materialtool, 2016. Retrieved from https://www.dgbc.nl/materialentool.
[19] M.K. Dixit, J.L. Fernàndez-Solıŝ, S. Lavy, C.H. Culp, Identification of parameters for embodied energy measurement: a literature review, Energy Build. 42 (8) (2010) 1238–1247 (2010).
[20] M.K. Dixit, Life cycle embodied energy analysis of residential buildings: a review of literature to investigate embodied energy parameters, Renewable Sustainable Energy Rev. 79 (2017) 390–413. https://doi.org/10.1016/j.rser.2017.05.051.
[21] EICB, Schepen, 2017 Retrieved fromhttps://informatie.binnenvaart.nl/schepen.
[22] International Energy Agency, Evaluation of Embodied Energy and CO_2eq. for Building Construction (Annex 57), International Energy Agency (IEA), 2016 http://www.iea-ebc.org/fileadmin/user_upload/docs/Annex/EBC_Annex_57_ST4_Case_Studies_Recommendations.pdf.
[23] Institut Wohnen und Umwelt GmbH, Section "building typologies"- principles and functions in a nutshell, 2016. Retrieved from http://episcope.eu/building-typology/webtool/.
[24] IPCC, Climate change 2014: mitigation of climate change, Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, 2014.
[25] IRU, "Wist u het?" cijfers en gegevens over het wegvervoer in Europa, 2009. Available at: http://febetra.be/wp-content/uploads/2014/07/Wist-u-het.pdf.
[26] Y.L. Langston, C.A. Langston, Reliability of building embodied energy modelling: an analysis of 30 Melbourne case studies, Construct. Manage. Econ. 26 (2) (2008) 147, doi:10.1080/01446190701716564.
[27] M. Liebregts, J. Persoon, Technische eigenschappen van het woningcasco in de tijd, 2011. Retrieved from http://www.bestaandewoningbouw.nl/technische-eigenschappen-van-het-woningcasco-in-de-tijd/.
[28] T. Lützkendorf, G. Foliente, M. Balouktsi, A.H. Wiberg, Net-zero buildings: incorporating embodied impacts, Build. Res. Inf. 43 (1) (2015) 62–81.
[29] G. Majeau-Bettez, A.H. Strømman, E.G. Hertwich, Evaluation of process- and input-output-based life cycle inventory data with regard to truncation and aggregation issues, Environ. Sci. Technol. 45 (23) (2011) 10170–10177.
[30] F. Meijer, L. Itard, M. Sunikka-Blank, Comparing European residential building stocks: Performance, renovation and policy opportunities, Build. Res. Inf. 37 (5-6) (2009) 533–551, doi:10.1080/09613210903189376.
[31] H. Monteiro, J.E. Fernández, F. Freire, Comparative life-cycle energy analysis of a new and an existing house: the significance of occupant's habits, building systems and embodied energy, Sustainable Cities Soc. 26 (2016) 507–518. http://dx.doi.org/10.1016/j.scs.2016.06.002.
[32] Rauf, A. and R.H. Crawford (2013). The relationship between material service life and the life cycle energy of contemporary residential buildings in Australia. Arch. Sci. Rev., 56. doi:10.1080/00038628.2013.810548.
[33] RDW, Overzicht maten en gewichten in Nederland, 2012. Available at: https://www.rdw.nl/SiteCollectionDocuments/Ontheffingen%20(TET)/Themasite%20Ontheffingen/Handleidingen/2%20B%201097b%20Overzicht%20maten%20en%20gewichten.pdf.
[34] M.J. Ritzen, T. Haagen, R. Rovers, Z.A.E.P. Vroon, C.P.W. Geurts, Environmental impact evaluation of energy saving and energy generation: case study for two Dutch dwelling types, Building Environ. 108 (2016) 73–84. https://doi.org/10.1016/j.buildenv.2016.07.020.
[35] Rotterdam Municipality, Een huis uit de jaren 60 en 70, 2017. Retrieved from http://www.rotterdamenergiebesparing.nl/woningsoorten/een-huis-uit-de-jaren-1960-en-1970/.
[36] R. Rovers, Zero-energy and beyond: a paradigm shift in assessment, Buildings 5 (1) (2015) 1–13, doi:10.3390/buildings5010001.
[37] RVO, Energieprestatie (EPC), 2016. Retrieved from http://www.rvo.nl/onderwerpen/duurzaam-ondernemen/gebouwen/energieprestatie.
[38] RVO, Referentiewoning EPC 0,4 tussenwoning, RVO, Utrecht, 2015 Available at: http://www.rvo.nl/sites/default/files/2015/10/Tussenwoning%20-%20referentiewoning.pdf.
[39] RVO, Referentiewoning EPC 0,4 hoekwoning, RVO, Utrecht, 2015 Available at: http://www.rvo.nl/sites/default/files/2015/10/Hoekwoning%20-%20referentiewoning.pdf.
[40] RVO, Referentiewoning EPC 0,4 twee-onder-eenkapwoning, RVO, Utrecht, 2015 Available at: http://www.rvo.nl/sites/default/files/2015/10/Twee-onder-een-kapwoning%20-%20referentiewoning.pdf.
[41] RVO, Referentiewoning EPC 0,4 vrijstaande woning, RVO, Utrecht, 2015 Available at: http://www.rvo.nl/sites/default/files/2015/10/Vrijstaande%20woning%20-%20referentiewoning.pdf.
[42] RVO, Referentiewoning EPC 0,4 appartementencomplex, RVO, Utrecht, 2015 Available at: http://www.rvo.nl/sites/default/files/2015/10/Appartementencomplex%20-%20referentiewoning.pdf.
[43] I. Sartori, A.G. Hestnes, Energy use in the life cycle of conventional and low-energy buildings: a review article, Energy Build. 39 (3) (2007) 249–257. http://dx.doi.org/10.1016/j.enbuild.2006.07.001.
[44] SBRCURnet, Passiefhuisconcept voor woningbouw, 2015. Retrieved from http://www.sbrcurnet.nl/producten/infobladen/passiefhuisconcept-voor-woningbouw.

[45] SBRCURnet, SBR-reference details online, 2017. Retrieved from http://www.sbrcurnet.nl/producten/referentiedetails.
[46] SEV, Bouwen met tijd: een praktische verkenning naar de samenhang tussen levensduur, Kenmerken en Milieubelasting van Woningen, Ministerie van VROM, Den Haag, 2004 Available at:http://www.slimbouwen.nl/fileadmin/user_upload/documents/Bouwen%20met%20tijd.pdf.
[47] S. Sorrell, The rebound effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency, 2007. 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.
[48] A. Stephan, A. Athanassiadis, Quantifying and mapping embodied environmental requirements of urban building stocks, Building Environ. 114 (2017) 187–202. http://dx.doi.org/10.1016/j.buildenv.2016.11.043.
[49] A. Stephan, 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, 2013. 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.
[50] A. Stephan, R.H. Crawford, K. de Myttenaere, Multi-scale life cycle energy analysis of a low-density suburban neighbourhood in Melbourne, Australia, Build. Environ. 68 (0) (2013) 35–49. http://dx.doi.org/10.1016/j.buildenv.2013.06.003.
[51] A. Stephan, R.H. Crawford, K. de Myttenaere, Towards a comprehensive life cycle energy analysis framework for residential buildings, Energy Build. 55 (2012) 592–600. http://dx.doi.org/10.1016/j.enbuild.2012.09.008.
[52] S. Suh, M. Lenzen, G.J. Treloar, H. Hondo, A. Horvath, G. Huppes, O. Jolliet, U. Klann, W. Krewitt, Y. Moriguchi, et al., System boundary selection in life–cycle inventories using hybrid approaches, Environ. Sci. Technol. 38 (2004) 657–664.
[53] M. Sunikka, Policies and regulations for sustainable building: a comparative study of five European countries, Hous. Urban Policy Stud. 19 (2017).
[54] G.J. Treloar, Extracting embodied energy paths from input-output tables: towards an input-output-based hybrid energy analysis method, Econ. Syst. Res. 9 (4) (1997) 375–391.
[55] A. Takano, S.K. Pal, M. Kuittinen, K. Alanne, Life cycle energy balance of residential buildings: a case study on hypothetical building models in Finland, Energy Build. 105 (2015) 154–164. http://dx.doi.org/10.1016/j.enbuild.2015.07.060.
[56] M. Timmermans, Renovatie buitengevel zorgt voor win-winsituatie, 2014. Retrieved from http://www.innozaam.com/renovatie-buitengevel-zorgt-voor-win-winsituatie/.
[57] G.J. Treloar, P.E.D. Love, O.O. Faniran, U. Iyer-Raniga, A hybrid life cycle assessment method for construction, Construct. Manage. Econ. 18 (1) (2000) 5–9, doi:10.1080/014461900370898.
[58] W. Trusty, S. Horst, LCA tools around the world, Build. Des. Construct. 5 (2005) 12–16.
[59] TU Delft, Tabula WebTool, 2015. Available at: http://webtool.building-typology.eu/#bm.
[60] D. Urge-Vorsatz, K. Petrichenko, M. Antal, M. Staniec, M. Labelle, E. Ozden, E. Labzina, Best practice policies for low energy and carbon buildings, A Scenario Analysis, Global Buildings Performance Network, Budapest, 2012 Available at: http://www.gbpn.org/sites/default/files/08.CEU%20Technical%20Report%20copy_0.pdf.
[61] D. Urge-Vorsatz, K. Petrichenko, M. Staniec, J. Eom, Energy use in buildings in a long-term perspective, Curr. Opin. Environ. Sustainability 5 (2) (2013) 141, doi:10.1016/j.cosust.2013.05.004.
[62] B.V. Venkatarama Reddy, K.S. Jagadish, Embodied energy of common and alternative building materials and technologies, Energy Build. 35 (2) (2003) 129–137. http://dx.doi.org/10.1016/S0378-7788(01)00141-4.