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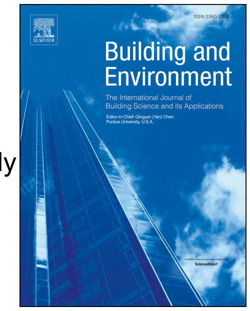

Environmental impact evaluation of energy saving and energy generation: Case study for two Dutch dwelling types

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Environmental impact evaluation of energy saving and energy generation: case study for two Dutch dwelling types.

Abstract

The existing building stock is a logical target to improve the level of sustainability of the built environment by energy saving measures. These measures typically entail a decrease of operational energy demand, mainly by adding building components such as insulation packages and energy generating devices. Consequently, material related environmental impact might create a collateral disproportionate burden, which is not well addressed in current assessment methods. In an attempt to evaluate this effect, two common dwelling types in the Netherlands, a terraced and a detached dwelling, have been redesigned to the level of Zero Energy Building in four scenarios, and the environmental impact of these scenarios has been assessed, expressed in embodied energy and related to the carrying capacity, expressed in embodied land ($m^2 \cdot a$). The lowest environmental impact is achieved in the scenario with an average U-value of 0.29 W/m^2K and 35 m² and 75 m^2 of PV modules for the terraced and the detached dwelling, respectively. In this scenario, added embodied energy is 3.4 GJ/m^2 and embodied land is 308,777 $m^2 \cdot a$ land for the terraced dwelling and 5.2 GJ/m^2 and 653,644 $m^2 \cdot a$ land for the detached dwelling. This evaluation indicates that a focus on only energy efficiency improvement shows a collateral material related environmental impact which should be embedded in the complete environmental assessment of buildings.

Highlights:

- Existing Dutch dwelling stock logical target for improving sustainability.
- Impact of sustainability measures studied in two Dutch dwelling types.
- Environmental impact assessment covers operational and embodied aspects.
- Lowest impact reached with an average U-value of 0.29 W/m^2K and 35 m² - 75 m^2 PV modules.

Keywords: Zero energy buildings; Energy efficient renovation; Building envelope; Building environmental assessment.

Nomenclature

COP	Coëfficiënt Of Performance	nZEB	nearly Zero Energy Building
EE	Embodied Energy	OE	Operational Energy
EPBD	Energy Performance Building Directive	PEC	Primary Energy Consumption
EU	European Union	PV	photovoltaic
FEC	Final Energy Consumption	RE	Renewable Energy
LCA	Life Cycle Assessment	STC	Standard Test Conditions
LC-ZEB	Life cycle Zero Energy Building	Wp	Wattpeak, nominal power at STC of PV modules
Mtoe	Million tons of oil equivalent	ZEB	Zero Energy Building

1. Introduction

Worldwide, the consumption of energy and material resources is increasing significantly to maintain, and even improve, our standards of living. Between 1973 and 2012 the global final energy consumption increased from 4,672 Million tons of oil equivalent (Mtoe) to 8,979 Mtoe and is expected to grow to 12,001 Mtoe in 2035 [1]. 20% to 40% of this global final energy consumption is attributed to the built environment, more than 86% of this consumption is based on fossil fuels [2].

In the Netherlands, the residential sector accounts for approximately 17% of the total primary energy consumption [3]. The residential energy consumption consists of 74% natural gas and 2.5% renewable energy sources, 18.9% of which is solar energy [4].

Global developments such as the depletion of fossil fuels, climate change and social-economic issues, emphasize the need to improve energy efficiency. In this respect, targets have been set in the European Union (EU) to achieve a lower overall energy consumption in the built environment and to decrease dependency on fossil fuels. Being a main agent, buildings are crucial towards achieving the EU objective of reducing greenhouse gas emissions by 80-95 % by 2050 compared to 1990 [5]. The EU Energy Performance Building Directive (EPBD) requires all new buildings to be nearly Zero Energy Buildings (*nZEB*) by the end of 2020 and existing buildings should be *nZEB* in 2050 to meet European targets [6, 7]. A *nZEB* has a very high energy performance and the very low remaining amount of energy required should be covered to a very significant extent by energy from renewable sources, produced on-site or nearby [6]. The implementation in legislation of *nZEB* in the EU leaves room for interpretation on a member state level. In a Zero Energy Building (*ZEB*) all necessary energy is generated on site based on renewable sources, possibly by means of connection to a storage medium or the grid for balancing over days, seasons or the year [8-10], however consensus on EU level is still to be developed on the exact definition. There are a number of long-term advantages of a *ZEB*, such as lower operating and maintenance costs, better resilience to natural disasters, better resilience to power outages and a higher level of energy security [10]. Considering the EU economy, renovation of existing buildings is a win-win option because it has implications for growth and jobs, energy and climate and cohesion policies [11].

A *ZEB* can be realized by lowering the energy demand of the building, for instance through better insulation, and by generating energy at the building scale, for instance by solar energy systems. Both strategies have implications for the building envelope as this is the building part that determines heat losses and gains and also provides the necessary area for the installation of solar energy systems [12, 13]. Solar energy is seen as one of the most promising alternative sources to meet our energy demands [14]. However, for the realization of higher insulation levels of for the realization of solar energy systems, materials are needed. Worldwide, 50% of all extracted materials are used in the built environment [15], and the extraction of building materials has increased with 30% between 1995 and 2005 [16]. In general, buildings have a linear pattern of resource consumption resulting in disposal ('from cradle to grave'), without qualitative or quantitative recycling or re-use of these resources [17]. In a linear pattern, raw materials are extracted and used in the realization and operational phase, after which they are mostly not re-used at all in the decommissioning phase, or are used at lower quality levels, called *down-cycling*. This may not cause a deficit of resources if all these materials are renewed or renew themselves in their effective lifespan. At this moment, many countries import more materials than they produce themselves [18]. This might lead to an intensified international competition for raw materials [16]. Design philosophies such as *Cradle to Cradle* and the *Circular Economy*, attempt to adapt the linear process into a circular one by re-using or recycling materials [19, 20].

One of the indicators in the field of environmental assessment is embodied energy; the amount of energy necessary to process raw materials, modify materials and transport materials [21-24]. In this way, the operational energy and the embodied energy in materials can be evaluated at the same scale.

For instance, extremely low energy buildings have a total of ca. 900 MJ/m^3 for heating over 30 years and have a total of 1400 MJ/m^3 embodied energy, indicating the share of materials in the environmental assessment with this indicator [23, 25]. Other recent studies show the significance of increased embodied energy due to the addition of insulation materials and installations [22].

In most buildings, embodied energy is seldom evaluated, or only evaluated after completion, and to date there appears to be no universal methodology to assess the total embodied energy of a building [21, 26, 27]. Current embodied energy databases show a large bandwidth of results for the same materials, among others due to the different calculation methodologies [21]. This is illustrated in Figure 1, in which the embodied energy per m^2 is shown for different buildings and different climatic zones, ranging between 3.6 and 8.8 GJ/m^2 [22].

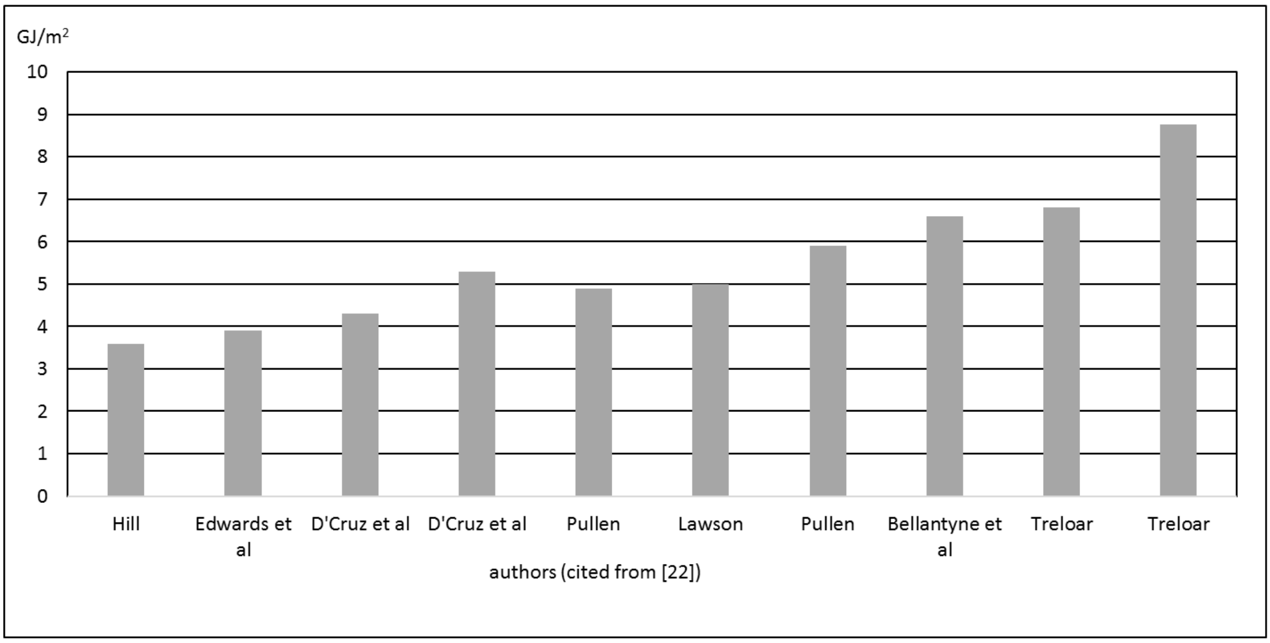

Fig. 1. Differing embodied energy values (GJ/m^2) in different investigations in residential buildings (cited from [22]).

Furthermore, embodied energy is not considered in both the EPBD and the Dutch energy agreement for sustainable growth [28]. Hence, being more energy efficient in the built environment might prove to be deceptive when following current policies and tools including embodied energy based on Life Cycle Assessment (LCA). However, it could be argued whether calculating all aspects into only energy generates the needed insight in the environmental impact of buildings.

On the track towards *ZEB*s, the performance of building materials will become more important because they create the only environmental impact once the operational energy will be completely generated on site, and therefore they should be part of the assessment [29, 30]. Because both materials and energy interact and influence the final environmental impact of a building, a joint evaluation is necessary. Thus, the environmental assessment should generate insight in the level of sustainable production of materials, and not only in energy, which can be related to the carrying capacity and expressed in land footprint [31]. In future, land necessary to produce renewable energy might compete with land necessary for food production and material production, which may lead to other choices in the design and realization of buildings [32].

In the Netherlands, the dwelling stock has a turnover smaller than 1% each year, complying with the energy performance regulations, making the existing building stock one of the key sectors where action is needed to meet energy efficiency goals [33-36]. As the focus on energy efficiency has mainly emerged after the first oil crisis in 1973, many dwellings, especially from before this time, are characterized by poor energy efficiency. 58% of Dutch dwellings are built before 1975 [37]. As many of these dwellings are still technically and socially adequate for housing, ways for sustainable renovation are being investigated [38]. The quest is to find the optimum between reduction of energy demand and generation of energy demand, in terms of lowest environmental impact of energy performance and material consumption [39]. Until 2012, in approximately 17% of the existing Dutch dwelling stock energy efficiency improvement measures have been realized to decrease energy consumption with 20% - 30% [40].

To investigate the combined environmental impact of energy performance and material consumption, expressed in two indicators, embodied energy and embodied land. The environmental impact is assessed of four successive renovation scenarios of insulation levels and associated surface of PV modules for two existing dwelling types in the Netherlands. The dwelling types are the terraced dwelling built between 1946-1964 and the detached dwelling built before 1964 [36, 37] due to the large energy consumption and large number of these dwelling types. The insulation packages are based on 100% renewable materials to minimize material related environmental impact. The environmental impact of the original state of the dwelling types itself is outside the scope of this study. The environmental impact is related to the carrying capacity - the amount of land-time necessary to create the materials used for both energy saving and energy generation, based on the MAXergy methodology [41, 42], the BINK tool [43] and the ICE database on embodied energy [44]. The impact indicator of carrying capacity based on the MAXergy methodology is expressed in Embodied Land (EL) in m^2a.

2 Methodology

For two typical Dutch dwelling types, four *ZEB* renovation scenarios have been developed. The dwelling types are described in chapter 2.1 and the four renovation scenarios are further described in chapter 2.2. To assess the environmental impact of the different renovation scenarios for both dwelling types, the following calculations have been carried out in sequence:

- Firstly the operational energy demand for heating, cooling, ventilation, and lighting has been calculated using the BINK software tool and the PVGIS software tool has been used to calculate the amount of PV modules necessary to generate the operational energy demand for the different scenarios[43, 45]. The BINK software tool is used in the Dutch construction industry to indicate if a building project complies with energy efficiency regulations. In this study, the software is only used to indicate the energy consumption in the building, not taking national standards into account. PVGIS is a widely applied software tool developed by the Joint Research Centre of the European Commission.

- Secondly, the mass and the embodied energy have been calculated of based on information from the material supplier [46], the ICE database developed by the University of Bath [44], and previous research conducted by Zuyd University [41, 42].

- Thirdly, the carrying capacity related impact of all insulation packages and associated surface of PV modules has been calculated using the MAXergy methodology. MAXergy relates the environmental impact to global carrying capacity, based on the urban harvest method [47, 48]. In MAXergy, the energy and materials impact can be calculated and expressed in an unit called embodied land, defined as the land over time required to restore the consumed resources [49]. The land-time necessary to generate a source (either materials or energy) is a parameter to measure energy and materials on a same scale. In MAXergy, a selection of data from large international databases such as the ICE database of the University of Bath and data from international publications are used for the impact calculations [44].

2.1 Dwelling types

On a regular basis, the governmental Dutch Enterprise Agency (RVO.nl) of the Ministry of Economy, Innovation and Agriculture publishes a document of example dwellings in The Netherlands [37]. The document distinguishes between 7 types of Dutch dwellings, indicated in Table 1, with categories corresponding to the building period. For this research, two dwelling types with very low energy efficiency have been selected; the terraced dwelling type built between 1946 and 1964 and the detached dwelling type built before 1964. In the Netherlands, 42% of all dwellings are terraced dwellings and 41% of primary energy is consumed in this type. Within this number of dwellings, mostly row houses, large-scale repetition is common and resulted in communities with a large number of exactly the same dwellings. With about 14% of all dwellings, the detached dwelling type is smaller in number, but shows the second largest primary energy demand with 24%. The two types combined account for 56% of the Dutch dwelling stock and for 65% of the total primary energy demand in the Dutch dwelling stock.

Table 1. Number of dwellings and annual primary energy demand of the distinguished dwelling types in the Netherlands (based on [37].

Type	Number of dwellings	Percentage of total	Annual primary energy demand (TJ)	Percentage of total
Detached	959,000	14%	153,361	24%
Semi-detached	824,000	12%	94,012	15%
Terraced	2,839,000	42%	260,187	41%
Duplex apartment	382,000	6%	33,621	5%
Gallery apartment	465,000	7%	20,788	3%
Tenement apartment	847,000	12%	45,476	7%
Other apartment	485,000	7%	22,070	4%

The example dwelling publication gives specific characteristics for dwellings from each building period, based on medians from governmental research in which the energy performance of 5,000 existing dwellings was identified [50]. In order to use the example dwelling data as initial input for this research and to eventually be able to calculate the overall improvements for the existing Dutch dwelling stock, the research focuses on a subcategory for both a detached and a terraced dwelling. Fig. 2 distinguishes between the dwelling types according to the building period and shows the total annual primary energy demand per dwelling subcategory (TJ).

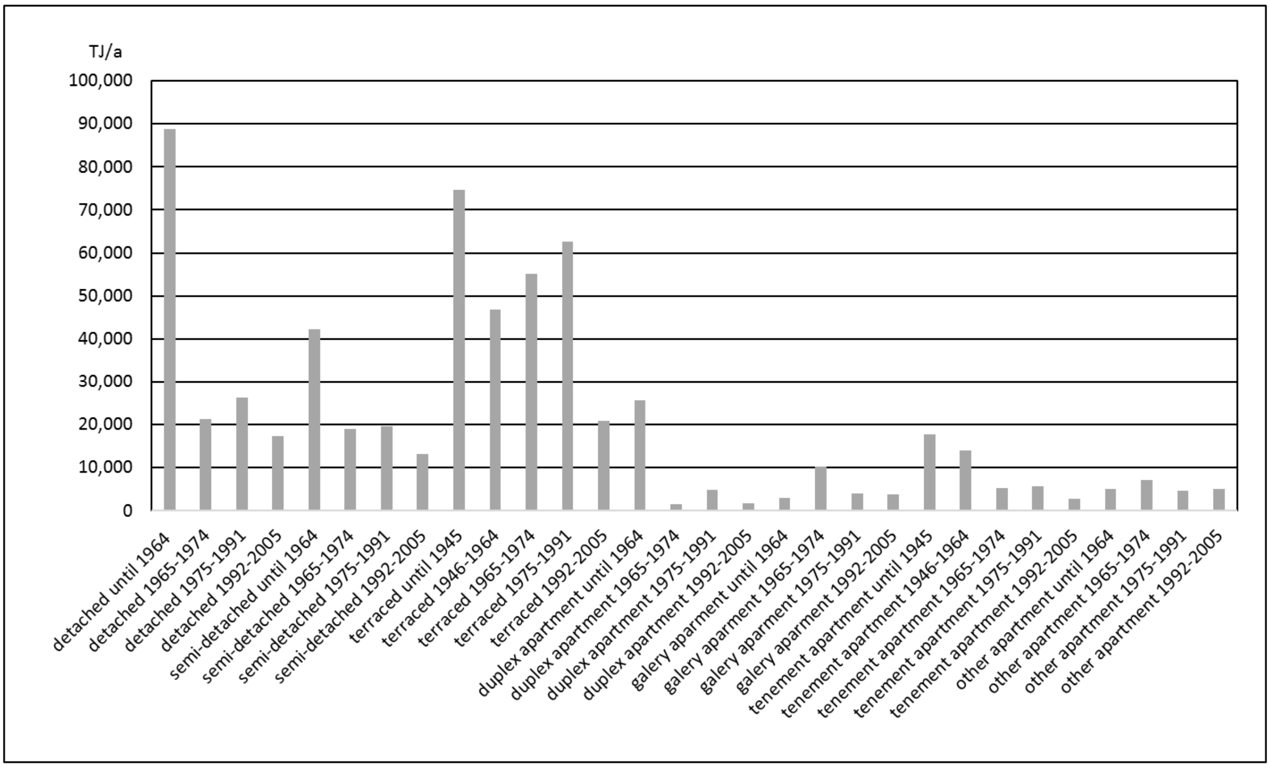

Fig. *2. Annual total primary energy demand per dwelling subcategory based on construction period (TJ) [37].*

In this study, the following 2 example dwellings are taken as the representation of the dwelling type. In practice, there is a large variety in the dwelling types, covering orientation, roof inclination, window and door sizing, etc.

2.1.1. Detached dwellings

The subcategory detached dwellings built before 1964 exceeds the other detached dwellings with 58% of the total energy demand within the category detached dwellings, due to the poor energy efficiency. Furthermore, the detached example dwelling built before 1964 has the highest energy demand of all dwellings in the Dutch dwelling stock. This dwelling typically consists of non-insulated cavity walls, a non-insulated wooden roof and a non-insulated floor. The general characteristics of the detached dwelling are listed in Table 2 and the dwelling is visualized in Fig. 3. Examples of the dwelling are shown in Fig. 4.

Table 2. General characteristics of the detached dwelling.

General characteristics		
Usable floor area[1]	130	m^2
Number of inhabitants	3.0	
Energy consumption	18,371	kWh/a
Building components	Surface (m^2)	U value (W/m^2K)
Ground floor	93.0	1.72
Inclined roof	128.1	1.54
Opaque facades	136.7	1.61
Single glazing[2]	8.0	5.20
Double glazing	20.3	2.90
Technical specifications		
Orientation front façade	Azimuth 90° (east)	
Roof angle	56°	

Fig. 3 Detached dwelling: floor plan, cross section and facades (back, side, front).

Fig. 4. Images of typical Dutch detached dwellings from the period before 1964 [37].

[1] Fully enclosed space that is available for the use of a building user.
[2] In this dwelling type both single and double glazing is present.

2.1.2 Terraced dwellings

Terraced dwellings from the building period 1946-1964 were rapidly built during the reconstruction after World War II in a period where there were no rules or regulations concerning energy performance. Due to a high level of repetition and the technical characteristics of this category, sustainable renovation is widely investigated in the Netherlands [51]. Many of these dwellings were equipped with gas heating devices in each room, electrical boilers for warm tap water, natural ventilation and steel / wooden window frames. The general characteristics of the terraced dwelling are listed in Table 3 and the dwelling is visualized in Fig. 5. Examples of the dwelling are shown in Fig. 6.

Table 3. General characteristics of the terraced dwelling.

General characteristics		
Usable floor area[3]	87	m^2
Number of inhabitants	2.8	
Energy consumption	9,201	kWh/a
Building components	**Surface (m^2)**	**U value (W/m^2K)**
Ground floor	47.0	1.72
Inclined roof	57.3	1.54
Opaque facades	42.3	1.61
Single glazing[4]	6.5	5.20
Double glazing	14.9	2.90
Wall between dwellings	53.0	1.61
Technical specifications		
Orientation front façade	Azimuth 180° (south)	
Roof angle	25°	

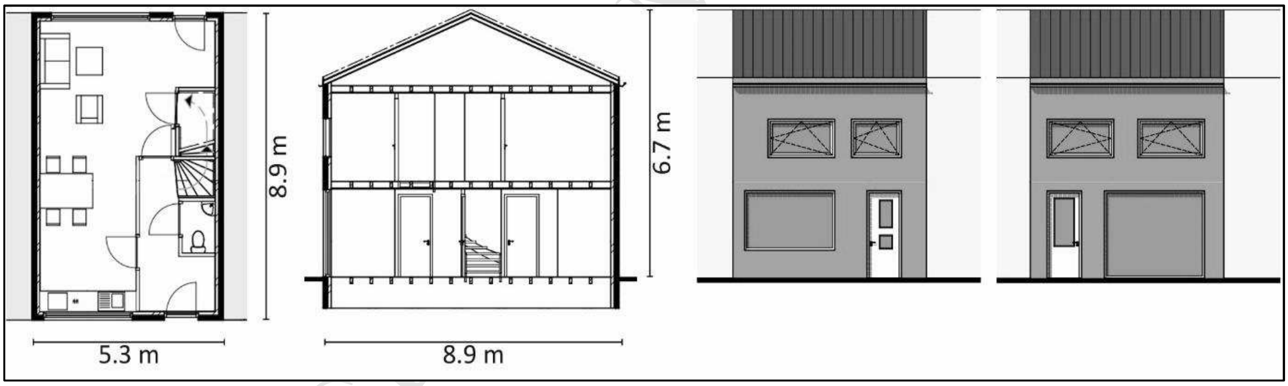

Fig. 5. Terraced dwelling: floor plan, cross section and facades (front, back).

Fig. 6. Images of typical Dutch terraced dwellings from the period 1964-1964 [37].

[3] Fully enclosed space that is available for the use of a building user.
[4] In this dwelling type both single and double glazing is present.

2.2 Renovation scenarios

The dwellings have both been redesigned with 4 successive *ZEB* scenarios, indicated in Fig. 7. The renovation scenarios are based on a theoretical framework of applicable add-on packages and do not represent the actual Dutch energy efficient renovation strategies. Materials selected for the insulation packages are fully based on renewable sources, to minimize material related environmental impact.

The impact of the following 4 scenarios is calculated, which are further described in the following paragraph and the applied materials are indicated in Table 4:

A. current situation with no added insulation and supplied with 100% Renewable Energy (RE) by PV;
B. current situation with insulation by filling air cavities in the floor, roof and wall and 100% RE for remaining demand by PV;
C. add-on insulation package and 100% RE for remaining demand by PV;
D. add-on insulation package with a load-bearing additional wall structure and 100% RE for remaining demand by PV.

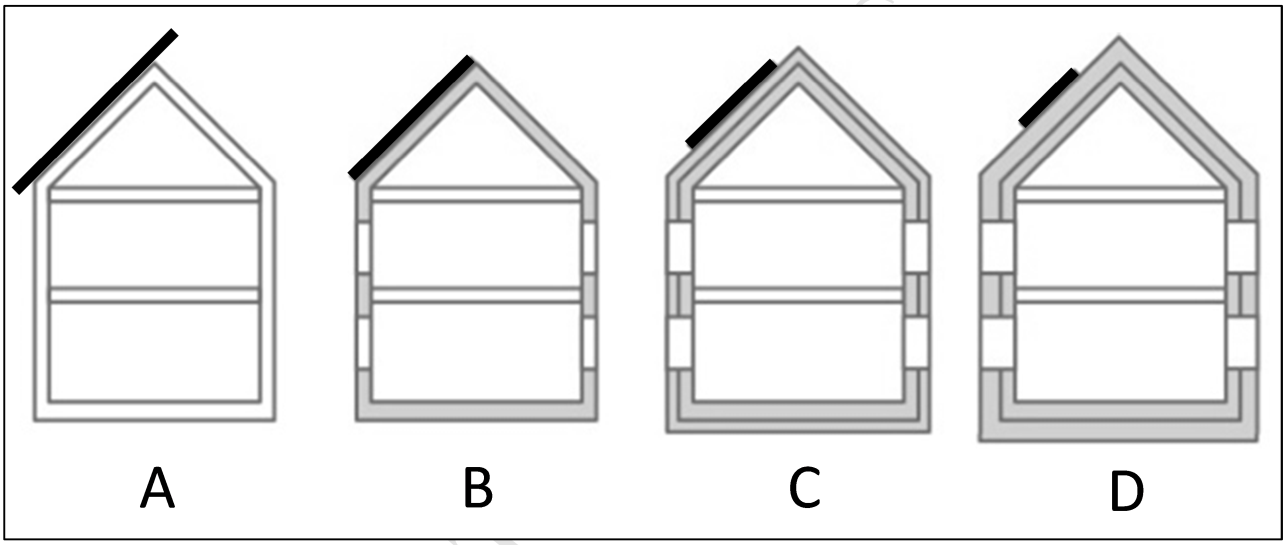

Fig. 7. Concept of adding insulation packages (grey) and PV modules (black) to the outside of the building envelope to transform existing dwellings into ZEB's.

2.2.1 Current situation – Scenario A

In the current situation, no insulation package has been added, as indicated in Fig. 8. The operational energy demand is completely generated by PV modules integrated in the roof. The average U values of the building envelope components are indicated in Table 4 and the applied materials are indicated in Table 5.

2.2.2 Scenario B

Insulation package B consists of insulating the existing building envelope, as indicated in Fig. 8. The air cavities in the cavity walls are filled with 40 mm wood fiber insulation. The cavities between the ground floor girders and the roof girders are filled with 160 mm wood fiber insulation and the roof is finished with 18 mm fiberboard on the inside. The existing glass is replaced by high insulation double pane glazing. The operational energy demand is completely generated by PV modules integrated in the roof. The average U values of the building envelope components are indicated in Table 4 and the applied materials are indicated in Table 5.

2.2.3 Scenario C

Insulation package C consists of an add-on to the insulated building envelope with package B, as indicated in Fig. 8. On the outside of the facades, 100 mm wood fiber insulation is added, finished with plaster. The roof tiles are removed in order to place 52 mm of wood fiber insulation and new battens, before the original and additional needed roofing tiles are replaced. Additionally, 160 mm of wood fiber insulation is placed underneath the ground floor, finished with 18 mm multiplex. The existing glass is replaced by high insulation double pane glazing and larch window frames replace the existing window frames. The operational energy demand is completely generated by PV modules integrated in the roof. The average U values of the building envelope components are indicated in Table 4 and the applied materials are indicated in Table 5.

2.2.4 Scenario D

Insulation package D consists of a wooden load bearing structure of 140 mm girders filled with 140 mm of wood fiber insulation on both the facades and the roof, in combination with the already added insulation packages B and C, as indicated in Fig. 8. An additional 52 mm wood fiber insulation is placed underneath the ground floor. The existing glass is replaced by high insulation triple pane glazing and insulated larch window frames replace the window frames. The operational energy demand is completely generated by PV modules integrated in the roof. The average U values of the building envelope components are indicated in Table 4 and the applied materials are indicated in Table 5.

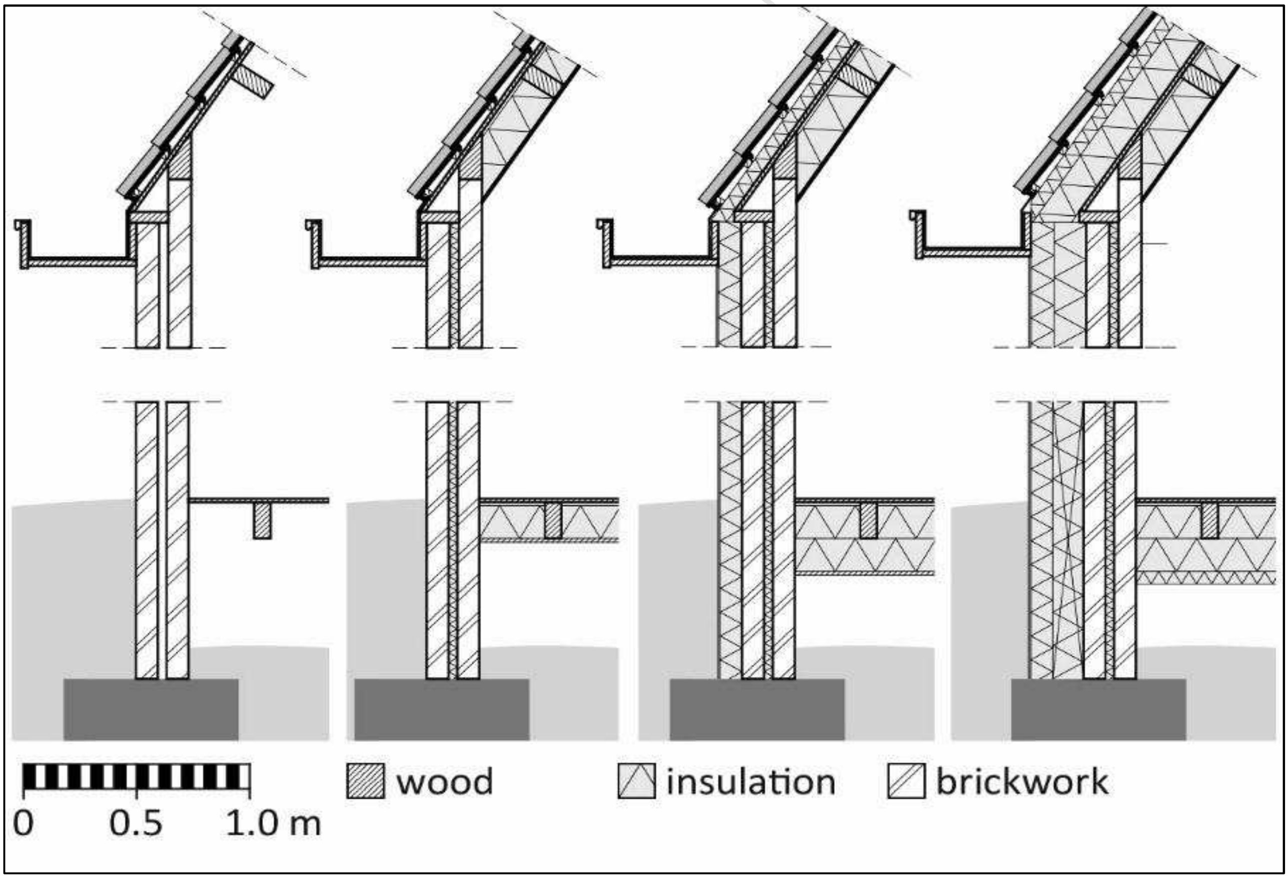

Fig. 8 FLTR: vertical sections of the outer cavity wall in the current situation A, insulation package B, insulation package C, and insulation package D.

Table 4. Achieved average U values (W/m²K) of the building envelope components in the different scenarios.

Component	Scenario			
	Current state A	Insulation package B	Insulation package C	Insulation package D
Façade	*2.6*	*0.83*	*0.29*	*0.15*
Ground floor	*4.4*	*0.25*	*0.13*	*0.09*
Roof	*4.2*	*0.25*	*0.14*	*0.10*
Glazing	*5.72 (single pane) / 2.77 (double pane)*	*1.3*	*1.1*	*0.7*
Window frames	*2.4*	*2.4*	*1.4*	*0.78*

Table 5. Applied materials in the different scenarios with their key indicators for this evaluation.

Scenario	Material	Density	U value (W/m²K)	Embodied energy (EE)	Embodied land direct [B]	Circular embodied land and EE embodied land [B]
all	**PV modules**	14.3 kg/m^2 [C]	n.a.	4060 MJ/m^2 [C]	4.97 m^2·a	4299.9 m^2·a
B	**160 mm wood fiber ground floor insulation**	190 kg/m^3 [A]	0.24	17 MJ/kg [A]	0.47 kg/m^2·a	0 kg/m^2·a
B	**40 mm wood fiber cavity wall insulation**	55 kg/m^3 [A]	1.00	17 MJ/kg [A]	0.47 kg/m^2·a	0 kg/m^2·a
B	**160 mm wood fiber roof insulation**	55 kg/m^3 [A]	0.28	17 MJ/kg [A]	0.47 kg/m^2·a	0 kg/m^2·a
B	**18 mm multiplex boarding roof**	650 kg/m^3 [A]	0.09	15 MJ/kg [A]	0.47 kg/m^2·a	0 kg/m^2·a
B	**HR++ double pane glazing**	2600 kg/m^3 [C]	1.1	15 MJ/kg [C]	0.10 kg/m^2·a	0 kg/m^2·a
C	**100 mm wood fiber exterior wall insulation**	190 kg/m^3 [A]	0.44	17 MJ/kg [A]	0.47 kg/m^2·a	0 kg/m^2·a
C	**'Forel clay' lime plasterwork**	1300 kg/m^3 [C]	0.02	3 MJ/kg [C]	0.00 kg/m^2·a	0.53 kg/m^2·a
C	**52 mm wood fiber roofing insulation**	250 kg/m^3 [A]	0.32	17 MJ/kg [A]	0.47 kg/m^2·a	0 kg/m^2·a
C	**Additional row ceramic roof tiles**	2000 kg/m^3 [C]	n.a.	6.5 MJ/kg [C]	0.00 kg/m^2·a	0.53 kg/m^2·a
C	**Battens / counter battens**	460 kg/m^3 [C]	n.a.	7.4 MJ/kg [C]	0.47 kg/m^2·a	0 kg/m^2·a
C	**Larch window frame**	590 kg/m^3 [C]	1.4	7.4 MJ/kg [C]	0.47 kg/m^2·a	0 kg/m^2·a
D	**140 mm wood fiber exterior wall insulation**	55 kg/m^3 [A]	0.27	17 MJ/kg [A]	0.47 kg/m^2·a	0 kg/m^2·a
D	**Spruce wooden construction 140 mm exterior wall**	460 kg/m^3 [C]	1.22	7.4 MJ/kg [C]	0.47 kg/m^2·a	0 kg/m^2·a
D	**140 mm wood fiber roof insulation**	55 kg/m^3 [A]	0.32	17 MJ/kg [A]	0.47 kg/m^2·a	0 kg/m^2·a
D	**Spruce wooden construction 140 mm roof**	460 kg/m^3 [C]	0.27	7.4 MJ/kg [C]	0.47 kg/m^2·a	0 kg/m^2·a
D	**HR+++ triple pane glazing**	2600 kg/m^3 [C]	0.7	15 MJ/kg [C]	0.10 kg/m^2·a	0 kg/m^2·a
D	**Cork window insulation**	550 kg/m^3 [C]	0.78	4 MJ/kg [C]	0.02 kg/m^2·a	0 kg/m^2·a

[A] *product information producer [46]*
[B] *MAXergy report [42]*
[C] *ICE database [44]*

For a comparable environmental impact assessment of the different renovation scenarios of both dwelling types in this research, the following conditions and characteristics have been defined:

General conditions:

- Geographic location: Maastricht, the Netherlands (50° 51′ 0″ latitude, 5° 41′ 0″ longitude and 50 m altitude). Maastricht has a moderate sea climate (type Cfb according to the Köppen Climate Classification [52]) with relatively mild summers (17.5°C), mild winters (3.1°C) and annually 773 mm of precipitation [53]. The average annual temperature in Heerlen is 9.9 °C [53]. The annual direct solar irradiation is 1069 kWh/m^2 [45] and the location has 1480 solar hours yearly [53].
- Only the environmental impact of the added materials has been taken account, neglecting the current materials embodied in the dwelling types.
- The lifespan of the scenarios is 50 years.

Insulation characteristics:

- The insulation materials applied are fully based on renewable resources, such as wood, which might not be applicable in real-life circumstances.
- The impact of internal condensation and heat/cold bridges is neglected;
- The impact of small-scale construction materials such as nails and screws is neglected;
- Air permeability of 1 $dm^3/s{\cdot}m^2$ at pressure difference of 10 Pa (qv10);
- The crawl space has 0.4 m height and allows insulation of the floor of the heated spaces above.

Installation characteristics:

- The operational energy generation is based on all electric PV (240 Wp[5]/module, building integrated);
- The lifespan of the PV modules is 25 years;
- Heating by ground heat pump with a COP of the heat pump boiler 2.2 for warm tap water and a COP of the heat pump 4.3 for room heating;
- Heating by low temperature fluid floor heating (35-45 °C);
- Mechanical ventilation with natural entry, without heat recovery;
- The impact of materials in the heating and ventilation installation is neglected.

3. Results

3.1 Energy performance

The effect of the insulation packages on the primary energy consumption (PEC) and is calculated using BINK software [43]. The output of the PV modules has been calculated in PVGIS, resulting in 129 kWh/m^2a in the detached dwelling case and 134 kWh/m^2a in the terraced dwelling case due to the different inclination of the roof [45]. The primary energy values provided by BINK software are used to calculate the final energy consumption (FEC), which is the actual energy provided to the end-user after conversion and transportation losses [54]. In the Netherlands, the current average electricity conversion yield for coal power plants is 40% and the conversion factor from kWh to MJ is 3.6 [3]. The main results covering the energy performance are indicated in Table 6.

[5] Wp indicates the nominal power of a PV module.

Table 6: Operational energy (OE) and amount of PV modules (m^2) of the different scenarios in the two dwelling types.

	Average U- value of the building envelope (W/m²K)	OE PEC (MJ/a)	OE FEC (MJ/a)	OE FEC (kWh/a)	OE heating demand PEC (MJ/a)	OE heating demand FEC (MJ/a)	Surface of PV modules to generate OE FEC (m^2)
Terraced dwelling							
Scenario A	2.78	82,811	33,124	9,201	64,151	25,660	68.8
Scenario B	0.29	42,134	16,854	4,682	27,695	11,078	35.0
Scenario C	0.17	38,682	15,473	4,298	24,258	9,703	32.1
Scenario D	0.12	36,950	14,780	4,106	22,541	9,016	30.7
Detached dwelling							
Scenario A	3.03	165,341	66,136	18,371	142,301	56,920	142.0
Scenario B	0.29	86,773	34,709	9,641	65,154	26,062	74.5
Scenario C	0.17	75,738	30,295	8,415	53,940	21,576	65.1
Scenario D	0.12	63,316	25,326	7,035	40,342	16,137	54.4

As the available south facing roof surface of the terraced dwelling is 28.5 m^2 none of the scenarios would be practically feasible without higher efficiency modules and/or PV modules facing north. As the available south facing roof surface of the detached dwelling is 64.0 m^2, scenario A and B would not be practically feasible without higher efficiency modules and/or PV modules facing north.

3.2 Mass and embodied energy

The first step in calculating towards embodied energy and eventually towards embodied land is to calculate the mass of the insulation packages and the PV modules. The mass of insulation is based on the applied materials mentioned in Table 4 and Table 6 for the amount of PV modules. In the calculations the impact of the PV modules has been doubled in the project lifespan of 50 years because the PV modules have an expected lifespan of 25 years. The mass and embodied energy results for both dwelling types are shown in Table 7 and Fig. 9 and Fig. 10.

Table 7: Mass, embodied energy (EE) and PV surface needed for EE generation of the different scenarios in the two dwelling types over a lifespan of 50 years.

	Mass insulation (kg)	Mass PV modules (kg)	Mass total (kg)	EE insulation (MJ)	EE PV modules (MJ)	EE total (MJ)	Surface of PV modules to generate EE (m^2)
Terraced dwelling							
Scenario A		989	989		558,607	558,607	5.8
Scenario B	2,834	503	3,337	45,950	284,228	330,178	3.4
Scenario C	6,364	462	6,826	92,100	260,938	353,038	3.7
Scenario D	9,176	441	9,617	140,261	249,256	390,682	4.1
Detached dwelling							
Scenario A		2,041	2,041		1,153,041	1,153,041	12.4
Scenario B	4,586	1,071	5,657	74,034	605,130	679,164	7.3
Scenario C	12,141	935	13,076	166,489	528,175	694,664	7.5
Scenario D	16,566	782	17,348	236,887	441,543	680,391	7.3

To minimise building related environmental impact, a building should generate the embodied energy as well, resulting in a Life Cycle Zero Energy Building (*LC-ZEB*). A *LC-ZEB* is a building whose operational energy consumption and the embodied energy in materials and systems is compensated by the renewable energy production within the building itself, on a yearly base (based on [8, 55]. To fulfill the demand of *LC-ZEB* an additional 3.4 -12.4 m^2 of PV modules should be embedded in the redesign, as indicated in Table 7, which would affect the outcomes of the environmental impact calculations. In this study,

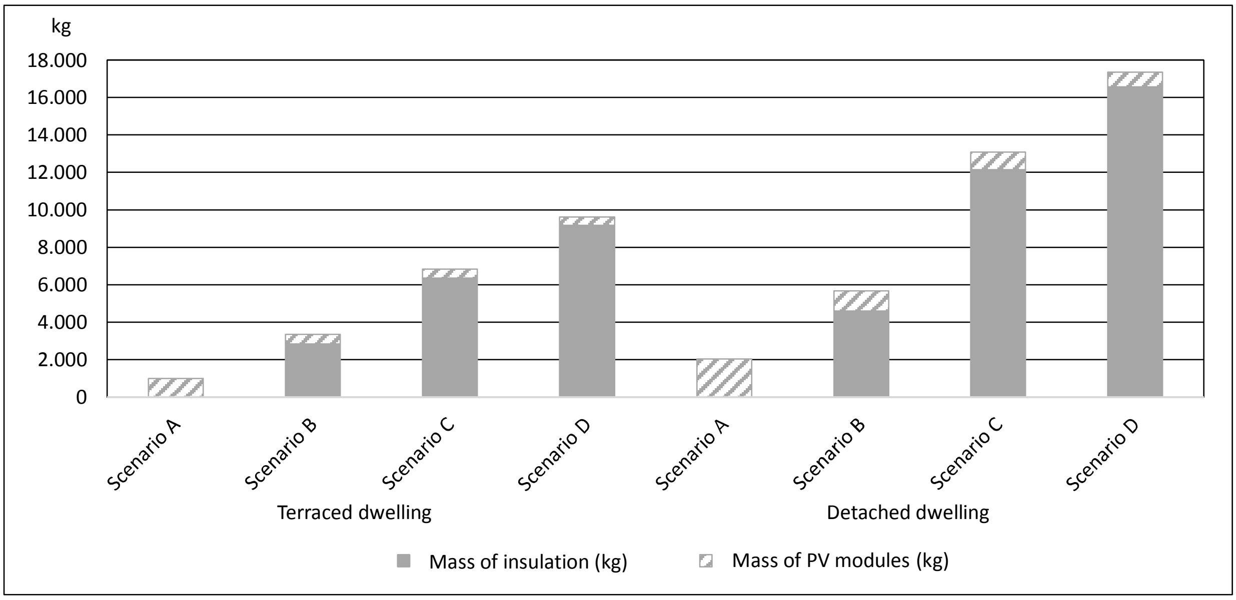

Fig. 9. Mass (kg) of the different scenarios in the two dwelling types.

Considering mass, scenario A, consisting of only adding PV modules has the lowest result, as shown in table 7 and Fig. 9. The mass of the PV modules is relatively small compared to the mass of the insulation packages.

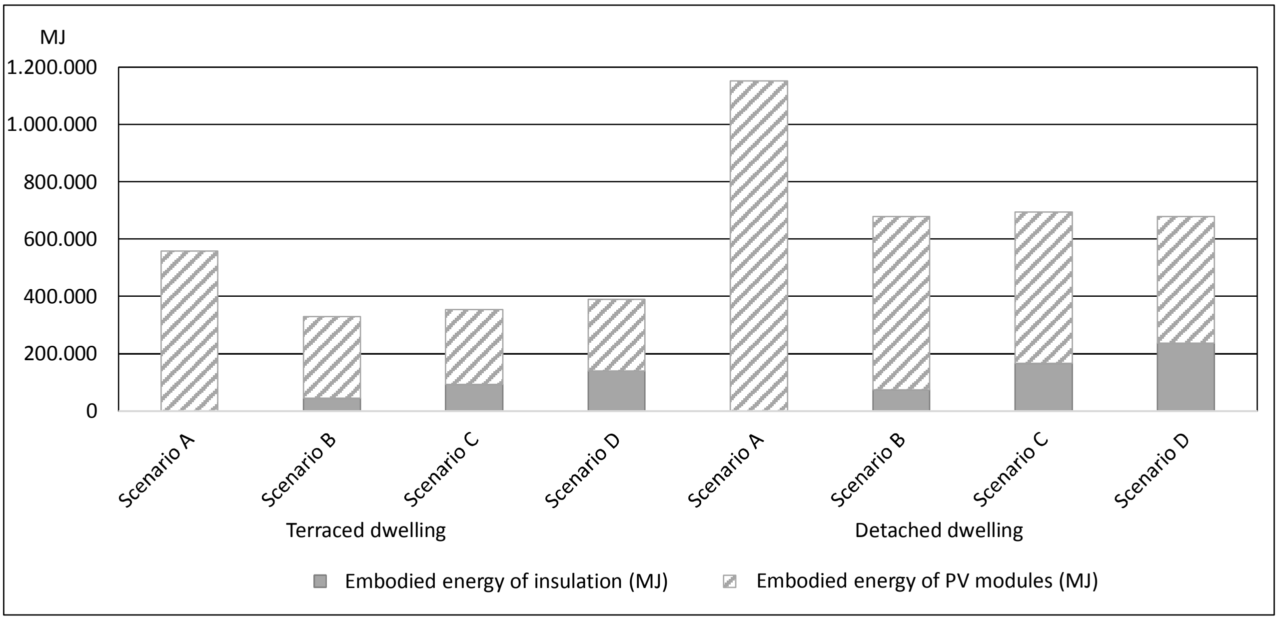

Fig. 10. Embodied energy (MJ) of the different scenarios in the two dwelling types.

However, concerning embodied energy, the effect of the PV modules is significantly higher than the effect of the insulation package, due to the higher energy density of the PV modules compared to renewable insulation materials. Table 6 and Fig. 10 show that scenario B has the lowest embodied energy in both dwelling types, but that the differences between the scenarios in the detached dwelling are relatively small.

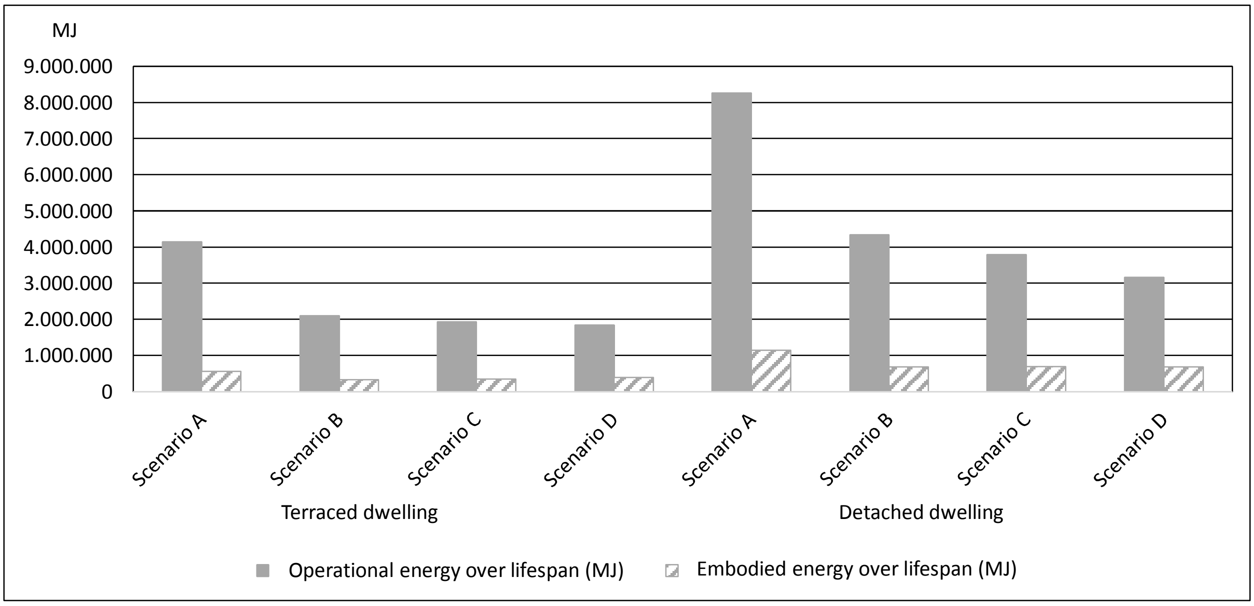

Fig. 11. Embodied energy and operational energy (MJ) of the different scenarios in the two dwelling types with lifespan 50 years.

Considering embodied energy set against operational energy, as is shown in Fig. 11, with every successive scenario the sum decreases, and the embodied energy is relatively small compared to the operational energy.

3.3 Embodied land

Table 9 and Fig. 12 indicate the amount of embodied land in total, the land surface involved to generate the energy from solar radiation: the solar module surface (including extra land for conversion losses due to seasonal storage of electricity), and for processing the materials for the insulation options.

Table 9. Embodied land of the different scenarios in the two dwelling types.

	Embodied land PV modules ($m^2 \cdot a$)	**Embodied land insulation ($m^2 \cdot a$)**	**Total Embodied Land ($m^2 \cdot a$)**
Terraced dwelling			
Scenario A	591,666	0	591,666
Scenario B	300,993	7,784	308,777
Scenario C	276,054	82,460	358,514
Scenario D	264,014	106,225	370,239
Detached dwelling			
Scenario A	1,221,172	0	1,221,172
Scenario B	640,685	12,959	653,644
Scenario C	559,847	226,018	785,865
Scenario D	467,829	264,860	732,689

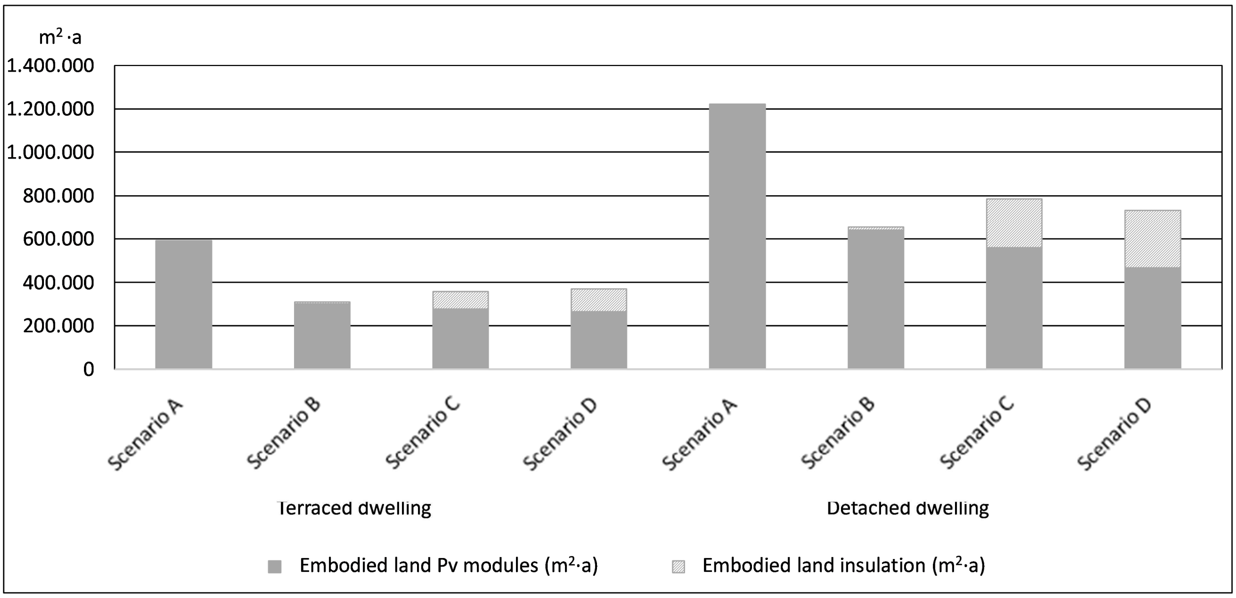

Fig. 12. Embodied land (m^2·a) of the different scenarios in the two dwelling types.

In both dwelling types, the scenario B correspond with the lowest amount of embodied land, indicating that the current strategy to renovate towards very high insulation values is from the point of carrying capacity not the solution with lowest environmental impact.

However, to relate the embodied land to the typical lifespan of a dwelling, Table 10 and Fig. 13 indicate the result for a 50 years lifetime. In this calculation, the PV modules are replaced after 25 years, increasing their impact.

Table 10. Embodied land of the different scenarios in the two dwelling types with lifespan 50 years.

	Embodied land PV modules (m^2)	Embodied land insulation (m^2)	Total embodied land (m^2)
Terraced dwelling			
Scenario A	11,833	0	11,833
Scenario B	6,020	156	6,176
Scenario C	5,521	1,649	7,170
Scenario D	5,280	2,125	7,405
Detached dwelling			
Scenario A	24,423	0	24,423
Scenario B	12,814	259	13,073
Scenario C	11,197	4,520	15,717
Scenario D	9,357	5,297	14,654

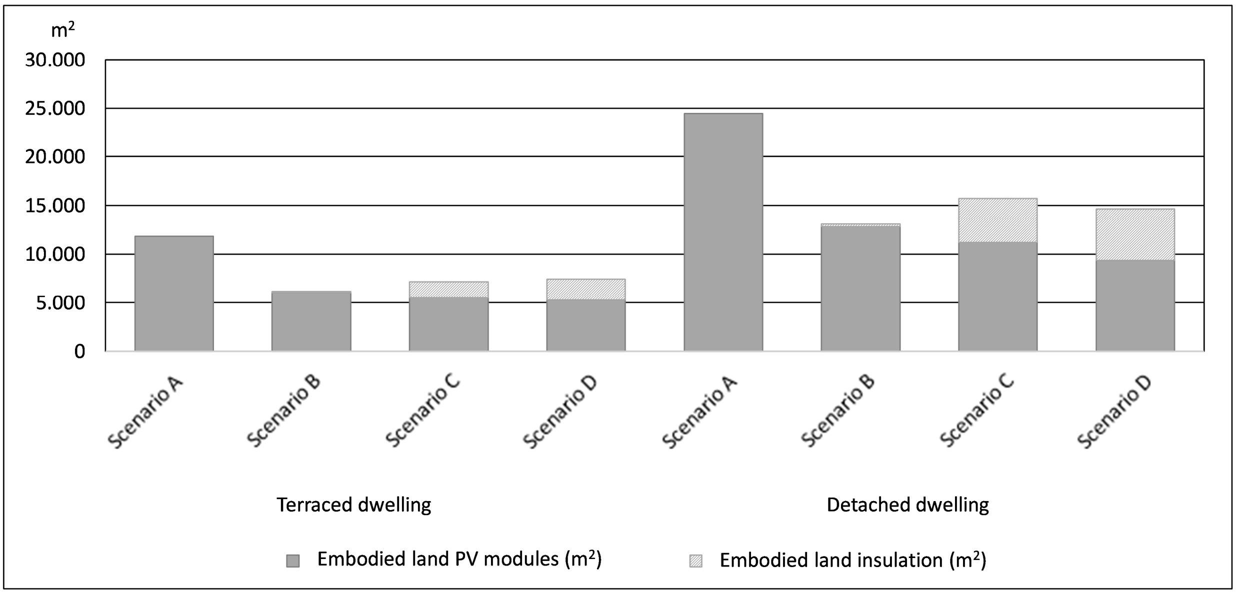

Fig. 13. Embodied land (m^2) of the different scenarios in the two dwelling types with lifespan 50 years.

Over a lifespan of 50 years, between 6,176 and 11,833 m^2 is needed to generate all the resources necessary for the *ZEB* renovation of the terraced dwelling type. Considering the detached dwelling type, between 24,423 and 13.073 m^2 is needed to reach the same level of energy performance.

In the calculations the land needed to generate the resources itself and to compensate for its use by re-growing the resources is included, applicable for the bio based insulation materials. To assess the impact of the use of non-renewable materials, minerals, and metals the 'circular embodied land' (Table 5) is introduced, the embodied land needed to restore concentrated material from dispersed resources, such as the clay, plaster and PV modules.

4. Discussion

In this study the environmental impact of different zero energy renovation scenarios for two Dutch dwelling types have been assessed, expressed in embodied energy and related to the carrying capacity, expressed in embodied land. In this theoretical exercise, different methods have been applied for the energy performance calculations and environmental impact calculations of insulation strategies based on renewable materials. However, in practice, occupant behaviour, construction traditions and technical possibilities will affect the outcomes.

Considering the energy aspect, even scenarios with high insulation levels result in an amount of PV modules exceeding the roof surface, emphasizing necessary improvements in the field of PV development.

Due to the scope of this research, other PV technologies, insulation materials and installation solutions might result in different optima. Moreover, social-economic aspects and maintenance have not been taken into account.

One of the main considerations regarding the carrying capacity based calculations is similar to the considerations regarding embodied energy and LCA calculations, namely the methodology, availability of data and uncertainty of calculated results due to differing input data. Considering the methodology, data from embodied energy databases is used and translated into time-land. This translation depends on numerous factors, such as solar radiation (inclination, orientation, and geographic location), soil type, etc. Considering the data used, this is often from other geographic location, depending on innovations (such as in the solar industry) and shows a large bandwidth (for instance on the field of embodied energy of solar modules). These factors lead to uncertainty of the calculated results. In future research, this has to be addressed more elaborately to provide clear guidance in the field of renovation the existing dwelling stock towards *LC-ZEB*.

Considering the carrying capacity of the Netherlands, 41,526 km^2 of territory is available. A total of 17,539 km^2 of the territory would be necessary to generate the materials and energy for the 2.84 million terraced dwellings and a total of 12,537 km^2 of the territory would be necessary to generate the materials and energy for the 959 thousand detached dwellings. 11,450 km^2 of the territory would remain for water, growing food, living and generating materials and energy for the other dwellings. This implicates that if the Netherlands has the ambition to realize a zero energy built environment based on its own carrying capacity, generating the necessary materials will conflict with other interests regarding land use.

5. Conclusions

Renovation of the existing dwelling stock is one of the key developments to decrease the, mainly fossil based, energy consumption and increase the level of renewable energy generation in the built environment. However, focusing on only energy in the operational phase does not cover the full scope to reach a sustainable built environment and both embodied energy and embodied land are useful indicators in a framework of complete impact assessment.

The lowest environmental impact is in both dwelling types created with an average building envelope U-value of 0.29 W/m^2K in combination with 35 and 74.5 m^2 of PV modules for the terraced and detached dwelling type, respectively. To renovate the terraced dwelling type in this scenario to *ZEB* level, this would result in 3.8 GJ/m^2 embodied energy and 6,176 m^2 land would be necessary for a period of 50 years. To renovate the detached dwelling type in this scenario to *ZEB* level, this would result in 5.2 GJ/m^2 embodied energy and 13,073 m^2 land would be necessary for the same period.

Taking into account *LC-ZEB*, an additional 3.7-12.4 m^2 of PV modules should be added to the dwelling types to compensate for the energy embodied in materials.

This evaluation demonstrates the added value of a joint assessment of materials and energy in the building envelope to indicate the overall environmental impact. Moreover, indicating environmental impact in embodied land generates insight in the effect of the built environment related to the carrying capacity.

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