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A bottom-up dynamic building stock model for residential energy transition: A case study for the Netherlands

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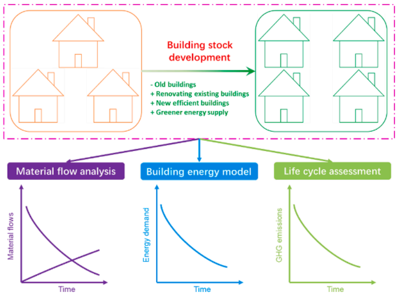
HIGHLIGHTS

- The presented model can simulate future material and energy demand and carbon emissions.
- The model builds upon real individual buildings from GIS data.
- Insulation contributes most to carbon reduction for space heating.
- Greening electricity mix plays a key role in residential decarbonization.
- Nearly 80% of electricity could be met if photovoltaic systems are installed on half of roofs.

GRAPHICAL ABSTRACT



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ABSTRACT

The building sector plays a key role in energy transition and carbon reduction while capturing the dynamic characteristics (e.g. materials, energy performance, and environmental impact) of building stock is a great challenge during the gradual process. This study presents a bottom-up dynamic building stock model that links dynamic material flow analysis with building energy modeling. The environmental impact of material and energy requirements is assessed by considering future electricity mix. The model is applied to evaluate the pathways to the climate-neutral energy supply of residential building stock in the Netherlands by 2050. Results show that space heating demand decreases by about 2/3 by 2050, while the energy for hot water increases to 92% of space heating demand. 80% of public grid electricity for appliances and lighting can be potentially substituted if rooftop photovoltaic (PV) systems are installed on 50% of renovated buildings and all the new buildings. Greenhouse gas (GHG) emissions of operational energy are reduced by approximately 60–90%, depending on the electricity mix. Annual GHG emissions from material production are not as important as those related to operational energy. Insulation materials account for a large proportion of the carbon footprint of material production. The model has a high spatial and temporal resolution and can be linked with local energy source availability (e.g. buildings or neighborhoods) to provide more accurate support for policymaking.

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1. Introduction

The building sector is responsible for about 40% of total final energy consumption and 36% of greenhouse gas (GHG) emissions in the European Union (EU) [1]. EU countries have set ambitious targets for realizing sustainable building stock, including improving envelope insulation [2], installing efficient energy systems [3], and replacing fossil fuels with renewable energy sources [4]. However, implementing these measures involves considerable construction activities (construction, renovation, and demolition), which will lead to large amounts of material consumption [5] and construction and demolition waste (CDW) [6]. It is necessary to understand the dynamics of building stock as well as the material flows and energy consumption [7], and quantitatively assess the performance (e.g. energy-saving effect, environmental impact, and cost) of various energy transformation policy strategies [8].

Dynamic building stock models (DBSMs) originate from dynamic material flow analysis (MFA) proposed by Müller [9] and account for the long-term evolution (construction, demolition, and renovation) of building stock as well as the changes of technologies [10], material flows [11], energy consumption [12], and carbon emissions [13] under different policy scenarios [14]. Many DBSMs have tried to disaggregate and characterize the building stock. For example, Sandberg et al. [15] present a segmented model that simulates the dynamics of each stock segment (defined by building type and cohort) with probability functions. Wiedenhofer et al. [16] model the nonmetallic material composition change of EU25 with typologies of buildings, roads, and railways. Heeren and Hellweg [17] develop a prospective bottom-up dynamic model that applies the GIS (geographic information system) data of buildings and the component-based inventory data of building typologies [18].

Apart from materials, some DBSMs track the evolution of energy consumption and environmental impact. Coffey et al. [19] discretize the US commercial building stock into different categories, simulate the stock growth with the rates of construction, renovation, and demolition, and estimate the energy consumption by energy-use intensity. Heeren et al. [12] propose a lifecycle-based building stock model (LC-Build) that combines construction activities and operational energy demand and includes the environmental impact from energy supply side. Pauliuk et al. [20] combine MFA and life cycle assessment (LCA) to determine the emission reduction potential of the Norwegian dwelling stock. Vásquez et al. [21] present a dynamic Type-Cohort-Time (TCT) stock-driven model to investigate the energy reduction levels of different policy scenarios in Germany and the Czech Republic. Koezjakov et al. [22] investigate the development of the Dutch building stock and the relationship change between embodied and operational energy.

The building stock is a complex and dynamic object constituted by long-lasting buildings [8] that will be updated by different building technologies (e.g. insulation and heating systems) over time [23]. However, the following shortcomings of previous DBSMs limit their ability to track the changes of building characteristics during the gradual energy transition process:

1. (1) They are mostly top-down models lacking the ability to consider technical details, or bottom-up models that disaggregate building stock at a very limited level (typically segmenting the total floor area stock by the proportion of construction periods or building types).
2. (2) Material and energy (empirical or modeled) intensities [24] of representative buildings are usually employed to estimate the total material and energy stock, which omits the specific characteristics of individual buildings and cannot accurately evaluate the energy and carbon reduction effect of energy-efficient measures.
3. (3) Most models have not combined materials and energy consumption together [24], while better insulation increases the relative importance of embodied environmental impact [25]. Integrated models are required to evaluate the overall impacts of both material and energy strategies on climate change target realization across different scales ranging from neighborhoods to cities, or an entire country.

This paper presents a bottom-up DBSM based on the basic principle of MFA to simulate the spatial–temporal development of the building stock, material flows, energy consumption, and environmental impact to evaluate the effects of policy strategies for the energy transition in the building sector. Individual buildings are mainly characterized by GIS data and building typologies. The space heating demand is simulated based on the model by Yang et al. [26]. The environmental impacts linked to building materials and energy supply of the energy transition are assessed by considering the likely development of future electricity production. The model is used to evaluate the Dutch national control scenario of the built environment [27] (hereafter named as national control scenario), which aims to ensure the transition towards a self-sufficient renewable energy supply, especially the electrification of the heat supply. The main research questions of the case study are:

1. (1) How close can the Netherlands get to the carbon–neutral residential building stock by 2050 under the national control scenario?
2. (2) Which are the drivers for GHG emission reductions in the building stock?

2. Materials and methods

2.1. Model overview

The structure of the model is shown in Fig. 1. The building stock (BS) is a dynamic object, and at time t it comprises 1) new buildings that will be constructed ($BS_{new,t}$), 2) existing buildings that will not be renovated ($BS_{no\_intervention,t}$), 3) existing buildings that will be renovated ($BS_{renovation,t}$), and 4) existing buildings that will be demolished ($BS_{demolition,t}$).

The model builds upon individual buildings characterized by a series of attributes, mainly including basic building information, building geometries, envelope's thermal properties, occupant behavior, ventilation systems, heating systems, rooftop photovoltaic (PV) systems, annual energy demand (space heating, domestic hot water, electricity for appliances and lighting), and material composition. This study involves five types of residential buildings from TABULA [28] (single-family house, mid-terraced house, end-terraced house, apartment building, and multi-family house), which are differentiated into six construction periods (before 1964, 1965–1974, 1975–1991, 1992–2005, 2006–2014, and after 2015). Individual buildings are characterized by the method of Yang et al. [26], which assigns the attributes of archetypes to individual buildings in GIS datasets based on construction periods and building types. More details can be found in S1 in supporting information (SI).

New construction is driven by population and lifestyle (stock-driven [23]). Mass-balance principles [9] are applied to determine the annual construction activity by considering both demolition and floor area demand. Renovation is driven by activity (renovation rate) that reflects the aggressiveness of energy transition strategies. The energy transition measures mainly include saving energy (i.e. insulation and ventilation improvement) and installing efficient heating systems that use sustainable energy sources.

In the process of building stock evolution, individual buildings can be dropped (demolition) from the building stock, added (new construction) to the stock, or updated (renovation). The relevant attributes (e.g. U-values, materials, and energy demand) of all buildings in the building stock are considered over time.

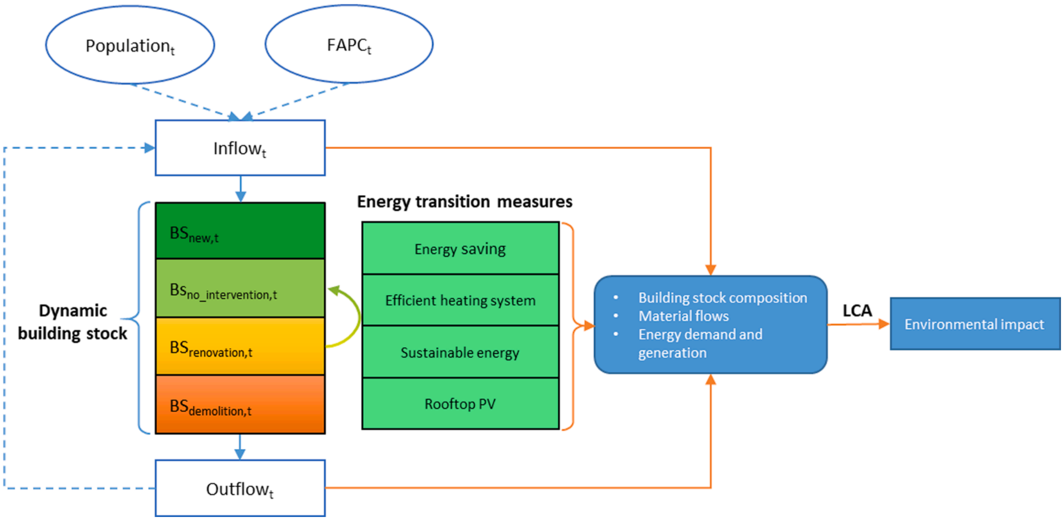

Fig. 1. Schematic overview of the dynamic building stock model. FAPC: floor area per capita, BS: building stock, t: year, $BS_{new,t}$: newly constructed buildings, $BS_{no\_intervention,t}$: buildings that will not be technically intervened, $BS_{renovation,t}$: buildings that will be renovated, $BS_{demolition,t}$: buildings that will be demolished.

2.2. Construction activities

2.2.1. Demolition

Building lifetimes are modeled with Weibull distributions [29]. The mean historical building lifetime (130 years) of buildings in the Dutch building stock and shape parameter (k = 2.95) are from Deetman et al. [30]. The scale parameter (λ) is derived based on the mean value equation of Weibull distribution:

$$\lambda = lifetime_{mean} \div \Gamma\left(1+\frac{1}{k}\right) \tag{1}$$

where $lifetime_{mean}$ is the mean lifetime of Dutch buildings.

There are many historical and monumental buildings in Western Europe [30]. Their ages vary significantly, so it is hard to find a reliable average lifetime for them. As their share in the whole building stock is very small (see Figure S2 in SI), we assume that buildings constructed before 1900 will not be demolished but renovated in the considered time frame. An array containing random lifetime values following the Weibull distribution is generated with Python, and the bound (mean ± 1.5 standard deviations [9], i.e. lower bound 58 and upper bound 202) is applied to avoid unrealistic lifetime values. The buildings are grouped by construction year, and for each group of buildings, their lifetimes are sampled from the lifetime array that filters the random values smaller than or equal to their current ages (current year minus construction year). The demolition year of each building is calculated as follows:

$$t_{dem} = t_{con} + lifetime \tag{2}$$

where t_{dem} is the demolition year, and t_{con} is the construction year.

2.2.2. Construction

The annual construction floor area is calculated based on population, floor area per capita, and the demolished floor area in year t:

$$A_{new,t} = FAPC_t \times P_t - S_{t-1} + \sum_{j=1}^{N_{dem,t}} A_{t,j} \tag{3}$$

where $A_{new,t}$ is the new construction area in year t. $FAPC_t$ is the floor area per capita. P_t is the population. S_{t-1} is the floor area stock of the previous year. $N_{dem,t}$ is the number of demolished buildings. $A_{t,j}$ is the floor area of the demolished building j in year t.

The number for each type of new building is calculated as:

$$N_{type,t} = round\left(A_{new,t} \times PP_{type,t} \div A_{type}\right) \tag{4}$$

where $N_{type,t}$ is the number of a building type of new buildings. $PP_{type,t}$ is the floor area proportion of a building type. A_{type} is the floor area of a TABULA archetype.

2.2.3. Renovation

According to the Dutch National Climate Agreement, municipalities will apply the neighborhood-oriented approach [31] to organize residents, building owners, and energy companies to collectively determine the best solution [32]. The residential buildings of the same neighborhood will be tackled together, and are likely to use the same heat source. Therefore, the existing building stock (excluding the buildings that will be demolished during the considered time frame) is grouped by neighborhood. The weighted average U-value of buildings in the same neighborhood is calculated as follows:

$$U_{neighborhood,weighted} = \frac{\sum_{1}^{N_{neighborhood}} U_{building,weighted} \times A_{building}}{\sum_{1}^{N_{neighborhood}} A_{building}} \tag{5}$$

where $U_{neighborhood,weighted}$ is the weighted average U-value of a neighborhood, $A_{building}$ is the floor area of a building, and $N_{neighborhood}$ is the number of buildings in a neighborhood. $U_{building,weighted}$ is the weighted average U-value of a building, which is determined as follows:

$$U_{building,weighted} = \frac{\sum_{1}^{N_{element}} U_{element} \times A_{element}}{\sum_{1}^{N_{element}} A_{element}} \tag{6}$$

where $U_{building,weighted}$ is the weighted average U-value of a building, $U_{element}$ is the U-value of an element, $A_{element}$ is the area of an element, and $N_{element}$ is the number of elements. In this study, the elements involve roof, external wall, window, door, and ground floor.

The neighborhoods are sorted by $U_{neighborhood,weighted}$ (descending), and then the top neighborhoods that contain $N_{ren,t}$ buildings are selected for renovation. These buildings are randomly divided into two parts. One part will be renovated with the conventional standard while the other part will be renovated with the nearly zero energy buildings (nZEB) standard. The numbers of buildings with different renovation standards are calculated as follows:

$$N_{ren\_i,t} = N_0 \times R_{ren\_i,t} \tag{7}$$

where N_0 is the total number of existing buildings to be renovated. $N_{ren\_i,t}$ is the number of renovated buildings for energy standard i in year t. $R_{ren\_i,t}$ is the renovation rate for energy standard i in the year t.

2.3. Materials, energy, and environmental impact

2.3.1. Building materials

The material amounts for a building are calculated as follows:

$$W_{mat} = A_{building} \times MI_{mat} \tag{8}$$

where W_{mat} is the weight of a material for a building. $A_{building}$ is the floor area of the building. MI_{mat} is the intensity of a material for each building type (see Table S7 and Table S8 in SI).

Glazing is renovated by replacing the existing glass with HR++ (double glazed with a coating and an insulating gas between the plates) for conventional standard and HR+++ glass (three glass plates with a coating and insulating gas) for nZEB standard [33]. The opaque elements (roof, external wall, door, and ground floor) are renovated by adding an insulation layer on top of the corresponding envelope element. The physical parameters of different renovation standards for each element can be found in TABULA [34]. The details on different insulation materials can be found in Table S9 in SI. The amount of an insulation material for renovating an opaque element is calculated based on insulation standards and the thermal conductivity of used insulation materials [35]:

$$W_{mat,ins} = \left(\frac{1}{U_{ren,ele}} - \frac{1}{U_{exi,ele}}\right) \times k_{mat,ins} \times A_{ele} \times D_{mat,ins} \tag{9}$$

where $W_{mat,ins}$ is the weight of an insulation material for a building. $U_{exi,ele}$ is the current U-value of an opaque element, and $U_{ren,ele}$ is the U-value after renovation. $k_{mat,ins}$ is the thermal conductivity of an insulation material.

2.3.2. Operational energy

The energy consumption of Dutch residential buildings is comprised mainly of space heating, domestic hot water (DHW), and electricity for appliances and lighting [36]. The space heating demand of the initial and renovated building is simulated based on Yang et al. [26]. The energy demand for DHW of existing buildings is estimated by the TABULA method [37]. For new buildings, the energy for space heating and hot water is calculated based on the energy intensities of corresponding TABULA archetypes [28]. The heat demand for space heating and DHW is converted into the final heat demand supplied by heating systems based on the TABULA method [37].

The annual electricity consumption for appliances and lighting is estimated by multiplying floor area with the sampled electricity intensities derived based on measured annual electricity consumption (CBS) and BAG (see Figure S6 in SI). Due to the lack of enough energy consumption data on buildings constructed after 2015, the electricity consumption of buildings after 2015 is estimated based on the electricity consumption of buildings built in the 2006–2014 period.

The potential annual electricity generation from rooftop PV (E_{PV}) is calculated based on the following equation [38]:

$$E_{PV} = G \times \eta \times R_{performence} \times A_{roof} \times R_{reduction} \tag{10}$$

where G is the annual cumulative solar irradiation, which is calculated by summing up hourly values from KNMI (Royal Dutch Meteorological Institute) [39]. η is the efficiency of rooftop PV. In this study, the modern crystalline Silicon panels are applied and its efficiency is 17% [38]. $R_{performence}$ is a reduction factor that considers, e.g., sub-optimal angels and inverter losses, to better reflect the efficiency in real life, and its value is 87% in this study [38]. A_{roof} is the roof area for solar panel installation. Considering the space left for maintenance and obstacles, A_{roof} is adjusted by an additional reduction coefficient ($R_{reduction}$) and its value is 60% [40] (i.e. only 60% of the roof surface of a building can be used for rooftop PV).

2.3.3. Environmental impact

The GHG emissions related to materials and energy in year t ($G_{me,t}$) are calculated by multiplying GHG emission factors in year t ($F_{me,t}$) with the quantity of materials or energy in year t ($Q_{me,t}$), as follows:

$$G_{me,t} = F_{me,t} \times Q_{me,t} \tag{11}$$

In this study, onsite construction processes are not included and only building materials are considered for the environmental impact assessment of construction activities. All materials and energies described in the previous sections are modeled using the ecoinvent database 3.6 (cut-off system model) [41] except for hybrid heat pumps and heat networks that use different energy sources. The hybrid heat pump consists of a green gas boiler and an electric heat pump. 35% of its heat is supplied by a green gas boiler (only used in cold weather) and 65% is from an electric heat pump [42]. According to the national control scenario [27], the heat in the heat network is from geothermal (70%), biogas (15%), wood chips (10%), and residual heat from waste treatment plants (5%). The GHG emission factors of hybrid heat pumps and heat networks are the weighted average GHG factors of their sub-energy technologies by proportion (see S5 in SI). This study selects climate change as the impact category, and then reports the results in GHG emissions measured as kg CO_2-eq (IPCC 2013 [43]).

With electric heat pumps replacing many natural gas boilers in the future, the electricity demand will increase [42], which means that the future electricity mix will highly influence the carbon emissions of the residential building stock. Therefore, the method by Beltran et al. [44] is applied to combine the ecoinvent and IMAGE 3.0 databases [45] to create future scenario databases. The IMAGE scenarios applied in this study are SSP2 (Shared Socioeconomic Pathway, Middle of the Road) [46] as the baseline scenario, and SSP2 450 representing the greener electricity mix (e.g. increasing shares of solar PV or wind offshore). We use these databases in the Activity Browser [47] LCA software to calculate the LCA results of future material production and energy consumption (for further details, please refer to Steubing and Koning [48]).

2.4. Case study

In the Netherlands, the majority of current residential buildings are not well insulated compared to modern building standards [49], and about 86% of houses are heated by natural gas [50]. The Dutch government wants to phase out natural gas and realize energy-neutral [51] and carbon–neutral [49] building stock by 2050. In the national control scenario [27], the target average insulation level is energy label A by 2050. 55% of existing buildings will be insulated to be suitable for electric heat pumps. 25% of buildings will be connected to heat networks (e.g. geothermal, green gas, or biomass), 20% installed with hybrid heat pumps (green gas boiler and heat pump), and 50% roof surfaces installed with solar PV. Along with this transition are large amounts of building material consumption (e.g. insulation materials) and CDW, which can significantly affect the realization of circularity of the built environment [52].

The time frame considered in this study is from 2015 to 2050. The population forecast (16.9 million in 2015 and 18.5 million in 2050) of the Netherlands [53] (see Figure S5 in SI) is from the Central Bureau of Statistics (CBS), and the conditioned floor area per capita is assumed constant (83 m^2, see details in S1 in SI). The building materials consist of 23 most common building materials (see Table 1) in the Netherlands.

New construction is differentiated by conventional new (CNEW) buildings and nZEBs from TABULA archetypes [28], including single-family house, mid-terraced house, end-terrace house, apartment building, and multi-family house. According to Dutch policy [54], all the new buildings constructed after 2020 must be nZEBs. Therefore, we assume that in 2016–2020 all new buildings are CNEW, while from 2021 all new buildings are nZEBs. Both of them are installed with balanced

Table 1
Building material labels [35].

Label	Material name
AC	Aerated concrete
Al	Aluminum
Ar	Argon
Bi	Bitumen
Br	Brick, clay
Ce	Ceramics
EPS	Expanded polystyrene
Gr	Gravel
GY	Gypsum plaster
HW	Hardwood
MW	Mineral wool
PC	Precast concrete
PG	Primary glass
Pl	Plywood
PUR	Polyurethane foam
PVC	Polyvinylchloride
RC	Reinforced concrete (including steel [35])
Sa	Sand
SC	Sand cement
SW	Softwood
WF	Wood fiber
XPS	Extruded polystyrene
Zn	Zinc

ventilation systems. Natural gas boilers are installed on CNEW buildings to supply the heat for space heating and DHW, while nZEBs are installed with electric heat pumps for space heating, and solar water heaters for hot water. Rooftop PV is installed on all new nZEBs. The floor area proportion of each building type is assumed the same as in 2015 (see Figure S3 in SI).

It is hard to determine the shares of different insulation levels for renovation based on the average label A in 2050 in the national control scenario [27], and the heating system choice is also related to the insulation level. For example, electric heat pumps are only applicable for very well insulated buildings as they cannot provide high enough temperature for poorly insulated houses [55]. For simplification, this study derives the shares of insulation levels based on the heating system proportions in the national control scenario [27], and defines two combinations of insulation and space heating system based on TABULA [28], which provides the renovation options (e.g. insulation levels, ventilation systems, space heating systems, and hot water systems) for buildings differentiated by types and periods:

(1) Conventional renovation. Buildings are insulated to conventional standard and heated with heat networks (district heating) or hybrid heat pumps.
(2) Advanced renovation. Buildings are insulated to nZEB standard and heated with electric heat pumps.

According to the step-by-step plan to cease residential natural gas use by Milieu Centraal [56], we summarize the energy transition measures into 4 layers: insulation, ventilation, heating systems, and rooftop PV. All the ventilation systems of renovation and construction are balanced ventilation systems. Table 2 shows the technical combinations and distributions.

Following Vásquez et al. [21], it is assumed that there will not be renovation for nZEBs in the considered time frame. CNEW buildings in 2016–2020 will not experience technical intervention in the considered time frame. The buildings that will be demolished in 2016–2050 will not be renovated while all the other existing buildings will be renovated to certain energy efficiency levels. The renovation task is evenly allocated to each year.

Table 2
Technical scenario parameters. In the brackets are periods or shares of technical options.

Activity	Insulation standard	Ventilation	Heat supply	Energy production
Construction	CNEW (2016–2020) nZEB (2021–2050)	Balanced ventilation (100%)	Natural gas boiler (100%) Electric heat pump + solar water heater (100%)	Rooftop PV (0%) Rooftop PV (100%)
Renovation	Conventional insulation (45%)	Balanced ventilation (100%)	1) heat networks (25%) 2) hybrid heat pump + solar water heater (20%)	Rooftop PV (50%)
	nZEB insulation (55%)		Electric heat pump + solar water heater (55%)	

3. Results

3.1. Building stock evolution

Fig. 2a and b show that with slower population growth in 2016–2050, the size of building stock only experiences a slight increase. For the current building stock, more than 1/3 of building stock is constructed before 1964, and even in 2050, the buildings before 1964 still have the largest share, which is followed by the buildings built in the 1975–1991 period. In 2050, most existing buildings will remain, and new buildings only occupy a small share (about 19%). The annual demolished floor area will increase and annual constructed floor area will decrease (see Fig. 2c and d), while new construction outweighs the latter. It is also found that the demolished buildings are mainly built before 1964, and the latest period of buildings that will be demolished is 1975–1991. Fig. 2e and f show that over time the renovation share of recently built buildings is increasing (recent buildings have better insulation and will be renovated later than old buildings). There are differences (e.g. peaks) in annual renovated floor areas while the numbers of renovated buildings every year are the same, which is due to the different sizes of individual buildings. The floor area of advanced renovation is significantly larger than that of conventional renovation due to past renovation (some existing buildings have already reached the conventional insulation standard), although the difference is not large (55% advanced renovation vs. 45% conventional renovation).

3.2. Material and energy

Fig. 3a shows that the material stock will continue to grow until 2050, albeit not to a great extent and at a slowing pace. Concrete (including prefabricated and reinforced concrete) accounts for the largest share in both material stock and flows (Fig. 3b and c), which is followed by sand. In 2050, the total material outflow is almost equal to the material inflow, which shows the potential for closing the building material loop.

From Fig. 3d, we can see that due to extensive insulation and installation of balanced ventilation systems, the energy for space heating drops by nearly 2/3. Natural gas boilers are almost phased out by 2050 and the heat supply for space heating is dominated by heat networks and electric heat pumps. In contrast, the energy for hot water (Fig. 3e) and the electricity for appliances and light (Fig. 3f) show an opposite trend. Both their absolute amount and relative share increase. In 2050, the heat demand for hot water is almost equal to the heat demand for space heating. Solar water heater occupies the main supply for domestic hot water, which is followed by heat network. In Fig. 3f, the electricity

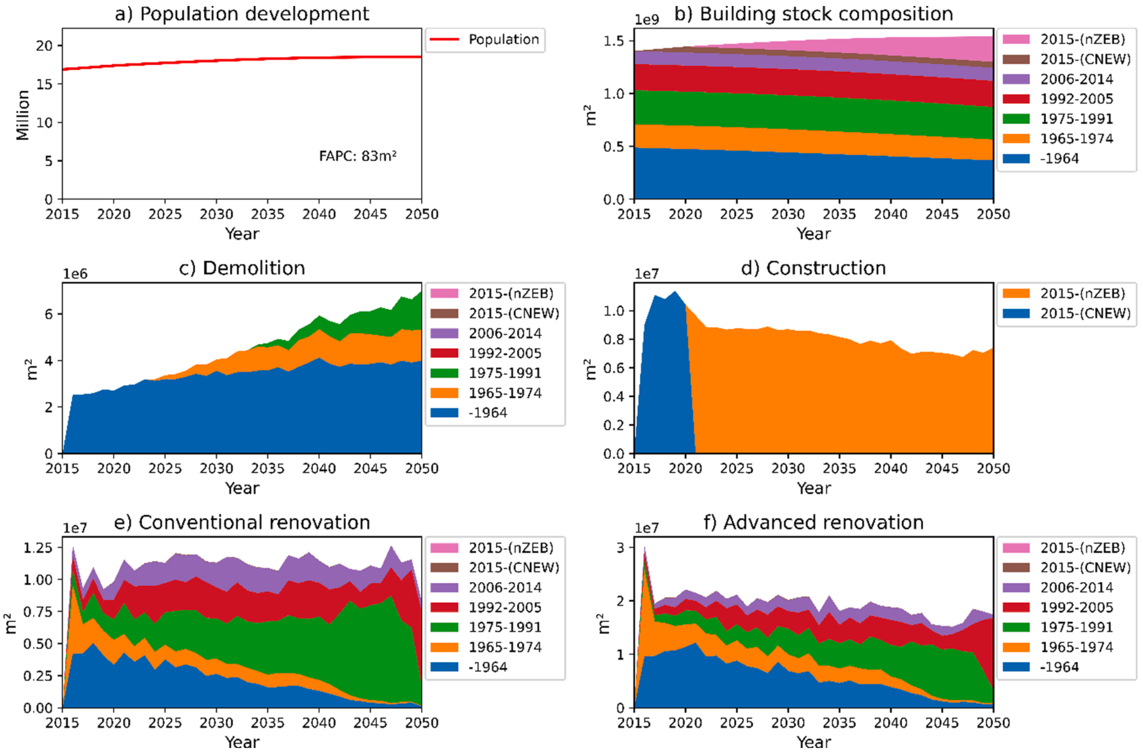

Fig. 2. The evolution of building stock composition. 'FAPC' is short for floor area per capita. The floor area here refers to the conditioned floor area. 'CNEW' is short for conventional new, and 'nZEB' is short for nearly Zero Energy Building.

generated by rooftop PV reaches more than 80% of the residential electricity demand in 2050, showing the great potential of rooftop PV to realize self-sufficient building stock in terms of electricity.

3.3. *GHG emissions*

From Fig. 4a and b, we can find that GHG emissions are mainly from the production of mineral wool and concrete (precast and reinforced). Mineral wool dominates the total GHG emissions of materials, while its share of weight (Fig. 3c) is pretty small (low density). This shows the necessity of applying more low-carbon insulation materials. In contrast, sand contributes a relatively smaller share of GHG emissions although their shares of weight are very large. The electricity under SSP2 450 is considerably less GHG intensive than SSP2, but the GHG emissions of material production only decrease slightly, showing that electricity is less important in the supply chain of most building materials.

Fig. 4c shows that the GHG emissions of operational energy supply are reduced by 57% under the SSP2 scenario. GHG emissions from heat supply (space heating and hot water) decrease by 79%. The heat supply emits about 57% of total GHG in 2015, while in 2050 the electricity for appliances and lighting contributes the most GHG emissions under the SSP2 scenario (72%). In Fig. 4d, the GHG emissions of operational energy supply significantly decline (93%) under SSP2 450 scenario, and the carbon–neutral target by 2050 is almost realized in the residential building sector in terms of operational energy.

Fig. 4e and f show that both material production GHG and operational GHG emissions decline. The GHG emissions of material production are much smaller than operational emissions, while the share of emissions of material production increase with time, especially under the SSP2 450 scenario, meaning that GHG emissions associated with construction materials will gain in relative importance in the future. The GHG emissions of renovation are much smaller than that of construction.

3.4. *Effects of different measures*

Fig. 5a shows the change of space heating demand by different construction activities. We can find that from 2021 the annual increase of heat demand drops more than 50% due to the introduction of nZEBs. The heat demand decrease by demolition and renovation is more than the increase by new construction, which makes the overall space heating demand decrease (Fig. 3d). Advanced renovation reduces much more space heating demand than conventional renovation while the marginal energy-saving effect gradually declines for both conventional and advanced renovation. The space heating demand reduction effect of demolition increases with time (more buildings are demolished). From Fig. 5b we can find that in 2050, the reduction of annual space heat demand is mainly due to advanced renovation and demolition.

In the 'BAU' scenario of Fig. 5c, the GHG emissions increase at first but gradually decline after 2020 due to the introduction of nZEBs, despite the increasing size of building stock due to population growth. In the 'saving' scenario, energy-saving measures reduce GHG emissions by about 66%. Replacing natural gas boilers with other space heating systems reduces roughly another 12% of GHG emissions by 2050 for 'saving + SHS (SSP2)' scenario and 22% for 'saving + SHS (SSP2_450)' scenario, respectively. Energy-saving measures contribute the most to total GHG reduction among different measures. In Fig. 5d, we can see that the cumulative GHG reduction increases and this trend becomes faster with time. In about 2032, the cumulative GHG emissions of building material production begin to be paid off by cumulative operational GHG reduction. By 2050, the cumulative GHG reduction reaches 1.04 (saving), 1.23 (saving + SHS (SSP2)), and 1.38 (saving + SHS (SSP2_450)) times the total GHG emissions of the Netherlands in 2015 (202 Mt [57]), respectively.

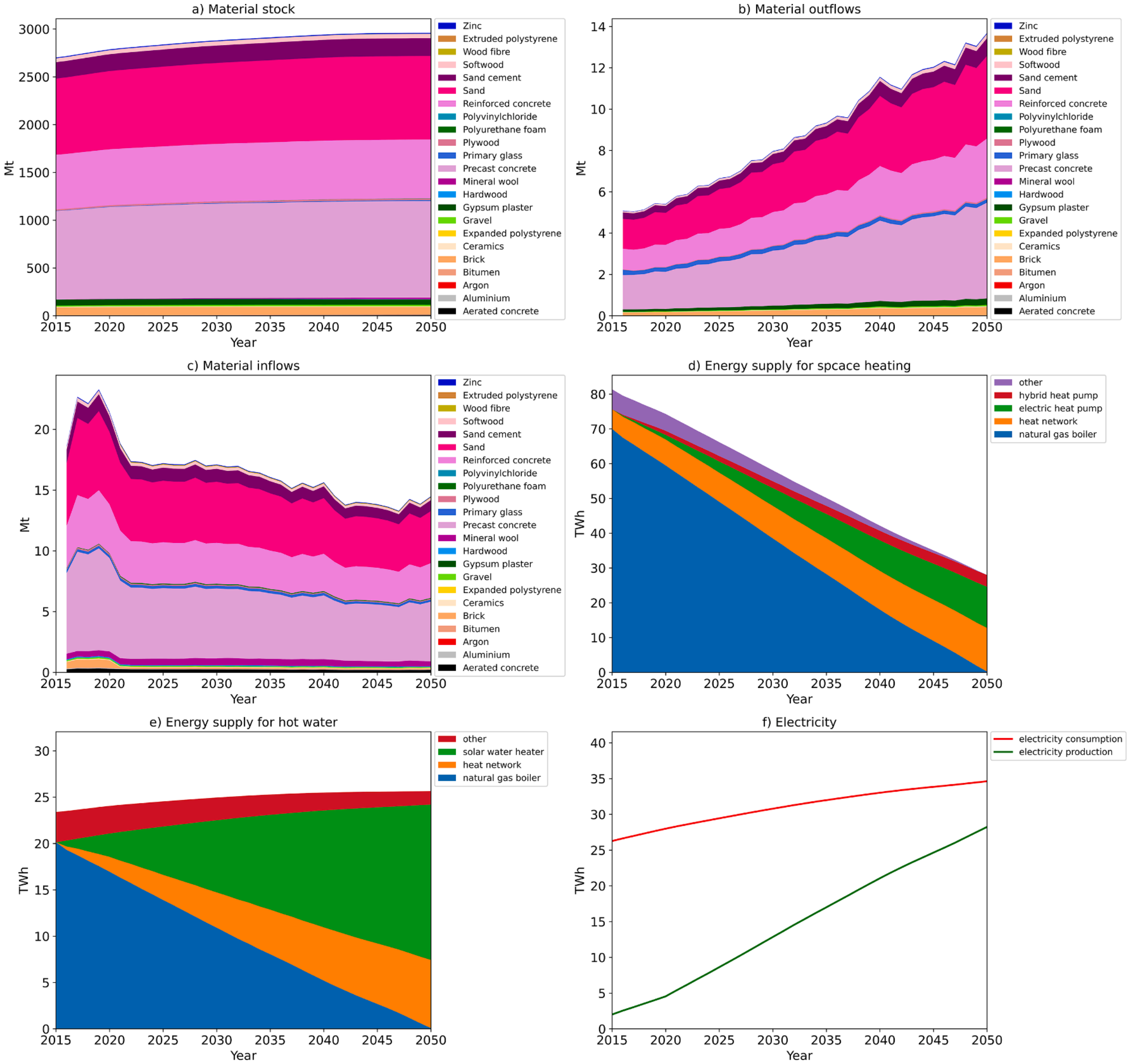

Fig. 3. The material stock and flows, and operational energy. Steel is included in reinforced concrete [35]. The electricity consumption by heat pumps is not included in the electricity for appliances and lighting. In f), the electricity is consumed by appliances and lighting, and the electricity production is from rooftop PV.

4. Discussion

4.1. Target realization potential

The national control scenario evaluation shows that the annual operational GHG emissions of residential buildings are reduced by more than 90% (about 19% of Dutch total GHG emissions in 2015 [57]), which is very close to realizing climate-neutral residential building stock. However, it requires extensive insulation, heating system replacement, and sustainable energy source application. Apart from the technical aspects, the feasibility of implementing these measures in the real world is not analyzed, especially the willingness of homeowners to adopt energy efficiency measures, e.g. financial [58] and legal aspects [59]. For example, the energy efficiency of existing buildings can differ substantially, and thus implementing energy-saving measures can lead to diverse savings of energy bills. Scaling up the energy transition measures (e.g. insulation and renewable energy sources) may lead to an economy of scale, i.e. lowering the average cost and potentially also direct environmental impacts related to energy-efficiency measures and energy infrastructure [49]. The tax on fossil fuels will also increase the competence of renewable energy sources. These factors would affect the choices of house owners, which also stresses the need for flexible and innovative business modes that can accelerate the implementation of policy strategies.

4.2. Drivers for GHG reduction

Fig. 5d shows that energy-saving measures contribute more GHG reduction (especially insulation) than sustainable energy supply for the national control scenario. However, both energy-saving measures and renewable energy supply technologies are important for reducing the GHG emission of the building stock, and neither of them can achieve a near carbon–neutral building stock alone. One reason is that insulation levels can seriously affect the efficiency of heat supply systems. For example, before installing electric heat pumps, buildings have to be well insulated, because heat pumps cannot provide enough heat or will be very energy inefficient in very cold weather for badly insulated buildings [60]. Buildings heated by low-temperature heat networks (50–55 °C) have to be well insulated although the insulation does not have to reach nZEB level [61]. Another reason is that generating enough sustainable energy to heat badly insulated buildings can be a great challenge [61]. For example, green gas from biomass cannot be a large-scale solution for the Netherlands [62]. Following the steps into natural gas-free buildings by Milieu Centraal [60], saving energy demand (through good insulation and balanced ventilation) is the first step, after which is the installation of more efficient heating systems based on

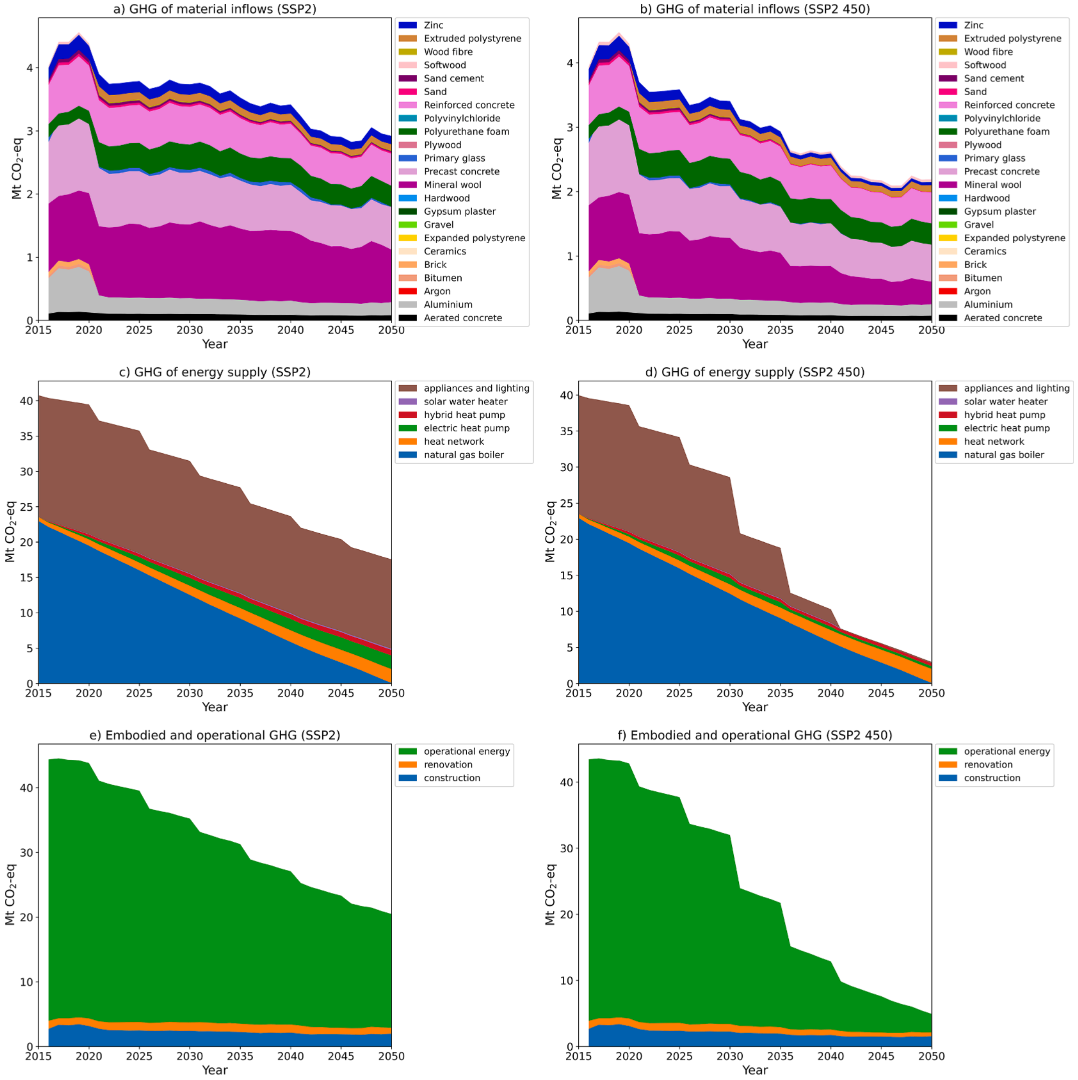

Fig. 4. The GHG emissions of material and energy supply.

renewable energy sources. However, the marginal effect of energy-saving measures decreases with time (Fig. 5a). The combination of insulation standards and heating systems is also influenced by the available energy sources (e.g. heat networks). Therefore, energy-saving measures and energy supply technologies are required in conjunction. Moreover, with the increase of electricity consumed by electric heat pumps, a greener electricity mix is important for reducing residential GHG emissions.

4.3. Limitations and future research

Compared with previous models, the presented model builds upon individual buildings, and includes potential future developments such as the energy transition as part of the underlying LCA model, providing the possibility for comprehensively assessing the material flows and energy demand and the related environmental impact of detailed technical measures. It can be applied to assess the performance of different energy efficiency strategies at a large scale (e.g. city or country). Our research comes with several limitations that could provide future research opportunities:

(1) In this study, the energy transition solutions for neighborhoods are randomly assigned due to lacking data on energy source availability for a specific building or neighborhood. This can lead to a mismatch between energy demand and supply. For example, the heat networks can only be available for certain areas, depending on the availability of industries or geothermal. Solar water heaters and solar PV panels are limited by the amount of sunshine [63]. High-rise buildings in dense urban areas are likely to be connected with heat networks while rural areas are suitable for electric heat pumps [49]. Municipal authorities can collect such data at the neighborhood scale to make an alternative energy source map with temporal dimension (in which year what kind of energy sources would be available for which neighborhood).
(2) Some factors will probably change in the future while they are not accounted for in the case study. The lifestyle of people [64], such as the floor area per capita [65], rebound effect (higher room setpoint temperature and longer heating time after renovation) [66], and the technologies of appliances, lighting, and energy generation, will be probably different from now. Besides, the climate will change [67] (e.g. temperature) but we use the constant climate data. Although the presented model has the availability to simulate the energy demand change due to these mentioned dynamic factors, they are not considered in this study.
(3) The developed model can, in theory, track the material flows in space and time, but we lack spatially and temporally differentiated building material inventory data. Wood construction is

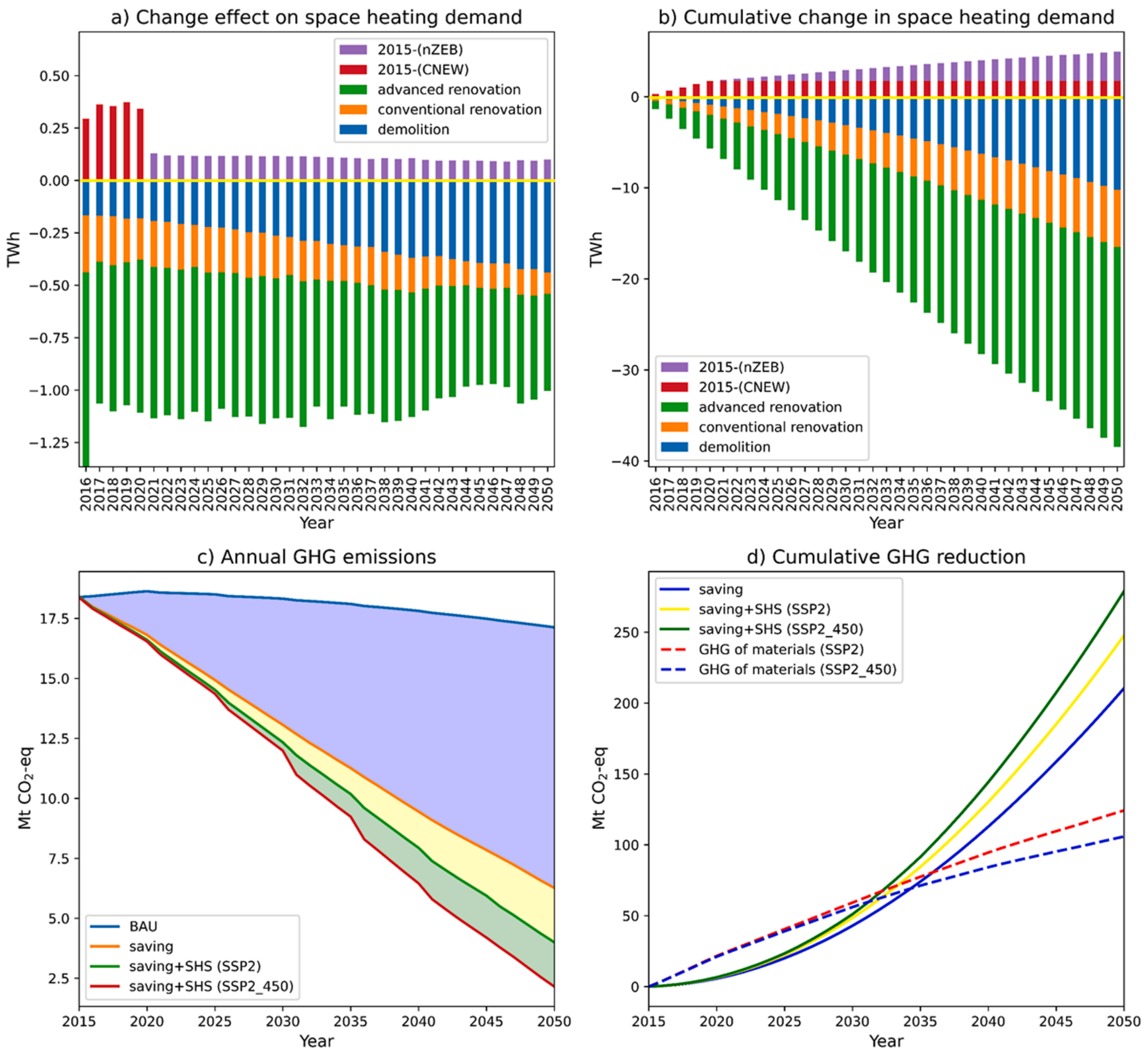

Fig. 5. Changes in space heating and GHG emissions. Fig. 5a shows the change effect of different construction activities on annual space demand. Fig. 5b shows the cumulative energy decrease or increase by construction activities from 2015 to 2050. In Fig. 5c, ‘BAU’ (business as usual) means that neither energy-saving measures nor space heating system (SHS) replacement is implemented on existing buildings, and new buildings are heated with natural gas boilers. ‘saving’ means that only energy-saving measures are implemented on existing buildings, while the SHSs for existing buildings remain unchanged and new buildings are heated with natural gas boilers. ‘saving + SHS (SSP2)’ means that both energy-saving measures and SHS replacement are implemented, and the GHG emissions are calculated with the ecoinvent database SSP2. In contrast, ‘saving + SHS (SSP2_450)’ means that the ecoinvent database SSP2_450, representing a quicker energy transition, is used for GHG emission calculation. The area in blue represents the carbon reduction by energy-saving measures ‘saving’. The yellow area represents the carbon reduction by SHS replacement under SSP2 scenario ‘saving + SHS (SSP2)’. The green area represents the carbon reduction by SHS replacement under SSP2 450 scenario ‘saving + SHS (SSP2_450)’. Fig. 5d shows the cumulative GHG savings compared to BAU. The dash lines show the cumulative GHG emissions from building material production. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

currently high on the political agenda in the Netherlands and the share of wood construction has recently increased [68]. Therefore, it would be interesting to explore the material composition change of future buildings and their effect on GHG emission reduction. Also, the secondary materials from CDW recycling will reduce the future raw material demand, while our model does not address this, meaning that this study might overestimate the future raw material demand. Future research can focus on sensitivity or uncertainty analysis to account for how much materials are overestimated.

(4) The presented model combines a building energy model with MFA and LCA, and builds upon a series of data sources to characterize individual buildings and the future development pattern of building stock. The uncertainties of sub-models can accumulate and thus result in considerable uncertainties for the results presented in this paper. Within the context of this paper, it was not possible to quantify these uncertainties and to validate the results. However, some of the underlying models, e.g. the building energy model [26] that we built upon has been validated with measured energy consumption data. Future research could attempt further validation [69] and should aim at further reducing model uncertainties, e.g. by collaborating with government agencies and companies to collect additional local data [70] and by developing more specific scenarios for the development of the building stock.

5. Conclusion

This study presents a bottom-up dynamic building stock model that can simulate the development of the building stock as well as the associated materials flows, and operational energy transition due to insulation, renewable energy sources, and rooftop PV panels. Compared with previous models, it builds upon individual buildings characterized by GIS data, and includes potential future developments such as the energy transition as part of the underlying LCA model, providing the possibility for comprehensively assessing the energy demand and material flows and the related environmental impact of detailed technical measures at a large scale. The national control scenario evaluation shows that energy-saving measures together with greener heat sources can reduce about 2/3 of the energy and 60–90% of GHG emissions for space heating, depending on the electricity mix. However, with the decrease of space heating demand, the share of energy for hot water, appliance, and lighting will increase significantly. About 80% of residential electricity for appliances and lighting can be potentially met by rooftop PVs if they are installed on the roof surfaces of about half of the building stock. The material outflows will be almost equal to the inflows in 2050, showing the potential of reducing raw materials by recycling the material outflows. The GHG emissions of material production will be leveled off by cumulative GHG emission reduction from operational energy in 2030–2035. The model can be applied in other countries or regions if the required data is available.

CRediT authorship contribution statement

Xining Yang: Conceptualization, Methodology, Software, Validation, Investigation, Writing – original draft, Writing – review & editing. **Mingming Hu:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Arnold Tukker:** Writing – review & editing. **Chunbo Zhang:** Resources, Writing – review & editing. **Tengfei Huo:** Writing – review & editing. **Bernhard Steubing:** Conceptualization, Methodology, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2021.118060.

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