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Key strategies for decarbonizing the residential building stock: Results from a spatiotemporal model for Leiden, the Netherlands

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ABSTRACT

Decarbonizing the building stock plays an important role in realizing climate change mitigation targets. To compare the decarbonization potential of different strategies, this study presents a spatiotemporal bottom-up dynamic building stock model that integrates material flow analysis, building energy modeling, and life cycle assessment. It can simulate future building stock evolution at the component level and track the associated material flows, energy demand and generation, and GHG emissions with the consideration of both endogenous factors (e.g. building energy efficiency upgrade) and exogenous factors (e.g. policies, occupant behavior, and climate scenarios). The model is applied in the residential building stock of Leiden, a municipality in the Netherlands. Results show that annual GHG emissions are reduced by about 40% under the reference scenario while annual GHG emissions can be reduced by about 90% under the ambitious scenario where all the decarbonization strategies are simultaneously implemented. Natural-gas-free heat transition and renewable electricity supply are the most effective strategies, respectively reducing the annual GHG emissions in 2050 by an additional 21% and 19% more than the reference scenario. Rooftop PV, green lifestyle, and wood construction have similar decarbonization potential (about 10%). Surplus electricity can be generated if rooftop PV systems are installed as much as possible. The decarbonization potential of demolition waste recycling is much smaller than other strategies. The model can support policymakers in assessing the decarbonization potential of different policy scenarios and prioritizing decarbonization strategies in advance.

1. Introduction

The building sector accounts for 30% of global final energy consumption (IEA, 2020) and nearly 50% of all resource extraction (United Nations Environment Programme, 2020). It also generates large amounts of construction and demolition waste (CDW), equivalent to nearly 40% of annual extracted construction materials (United Nations Environment Programme, 2020). The construction and operation phases contribute to 37% of greenhouse gas (GHG) emissions around the world (IEA, 2020), mainly from fossil fuel combustion for heat and carbon-intensive electricity consumption for appliances, lighting, and material production (United Nations Environment Programme, 2020; Xi et al., 2016). Ongoing urbanization and population growth (United Nations Population Division, 2018) further emphasize the urgency of drastically decarbonizing the building sector to achieve the Paris Agreement goals (GlobalABC et al., 2020).

GHG emission sources highlight the main decarbonization strategies in the built environment (United Nations Environment Programme, 2020). Demand-side strategies mainly include increasing material sufficiency (avoiding material demand and delivering human wellbeing within the biophysical limits of the planet) (Saheb, 2021) and operational energy efficiency (CE Delft, 2020). Supply-side strategies involve the transition towards renewable energy supply and low-carbon material production (e.g. bio-based materials) (EASAC, 2021). These strategies are coupled with each other during the development of the building stock (Roca-Puigròs et al., 2020). For example, the reconstruction and renovation wave (European Commission, 2020) would trigger considerable material flows and the deployment of high-quality CDW recycling (Roca-Puigròs et al., 2020). Besides technical strategies, lifestyle change (e.g. floor area per capita and room temperature) (Roca-Puigròs et al., 2020; Yang et al., 2020) influences the demand for materials and energy, and thus affects climate change target realization (Khanna et al., 2021).

Diverse models have been developed for evaluating the decarbonization strategies of building stock (Mastrucci et al., 2017; Röck et al., 2021), mainly including building energy modeling (BEM) (Oraiopoulos and Howard, 2022; Yang et al., 2020), material flow analysis (MFA)

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(Göswein et al., 2019; Lanau et al., 2019), and life cycle assessment (LCA) (Helena and Silvia, 2018; Yang et al., 2018). Dynamic building stock models further integrate these three tools to consider the overall material flows, energy demand, and environmental impact (Heeren et al., 2013; Yang et al., 2022a). Despite advances in modeling techniques, existing researches have the following limitations:

(1) There is a lack of comprehensive consideration of deploying different decarbonization strategies together. For example, circular economy and energy transition are usually considered separately although they are both essential strategies deployed simultaneously in construction practices (Kullmann et al., 2021). Besides, exogenous factors (e.g. technologies, policies, occupant, and climate) are usually assumed constant (Fathi et al., 2020; Roca-Puigròs et al., 2020; United Nations Environment Programme, 2020) and the interaction between them is typically neglected (IRP, 2020).
(2) Previous dynamic building stock models are mostly top-down models that depict the long-term trend of large-scale building stock (e.g. national or global) (Röck et al., 2021) and estimate material and energy quantities with intensities and floor area (Roca-Puigròs et al., 2020), limiting the evaluation of transformation strategies due to overlooking building heterogeneity (Mastrucci et al., 2021). To support governments in tackling local climate change issues, they have to shift towards the spatiotemporal bottom-up models that include more buildings and building technology details (Yang et al., 2022a).
(3) The decarbonization opportunity of materials (e.g. CDW recycling, low-carbon production, and bio-based materials) is usually ignored (Zhong et al., 2021), particularly for the materials consumed during renovation (Roca-Puigròs et al., 2020; United Nations Environment Programme, 2020), while embodied emissions gain more importance as a result of building energy efficiency upgrade (Akbarnezhad and Xiao, 2017; Göswein et al., 2019).
(4) While lifestyle changes can significantly influence material and energy consumption as well as the related GHG emissions, existing building stock models mainly focus on technical measures for material and energy aspects. We only identified a few top-down dynamic building stock models that consider lifestyle changes as either the intensive use of buildings or lower room temperature settings (Pauliuk et al., 2021; Roca-Puigròs et al., 2020; Zhong et al., 2021).

This study presents a spatiotemporal bottom-up dynamic building stock model that can track material flows, energy demand and generation, and environmental impact with the consideration of different decarbonization strategies. The building stock is composed of individual buildings characterized by a series of attributes that are updated every year due to the replacement of building components and the change in exogenous factors. The model is applied to the residential building stock of the Dutch city of Leiden to answer the following research question:

To what extent can primary materials, energy, and GHG emissions be reduced under different decarbonization strategies, namely a material transition, an energy transition, and a greener lifestyle?

2. Materials and methods

2.1. Model overview

The modeling approach is shown in Fig. 1. It encompasses three parts with temporal dimensions: decarbonization strategies and scenario definition, dynamic building stock model, and assessment of material and energy consumption and environmental impacts. Decarbonization

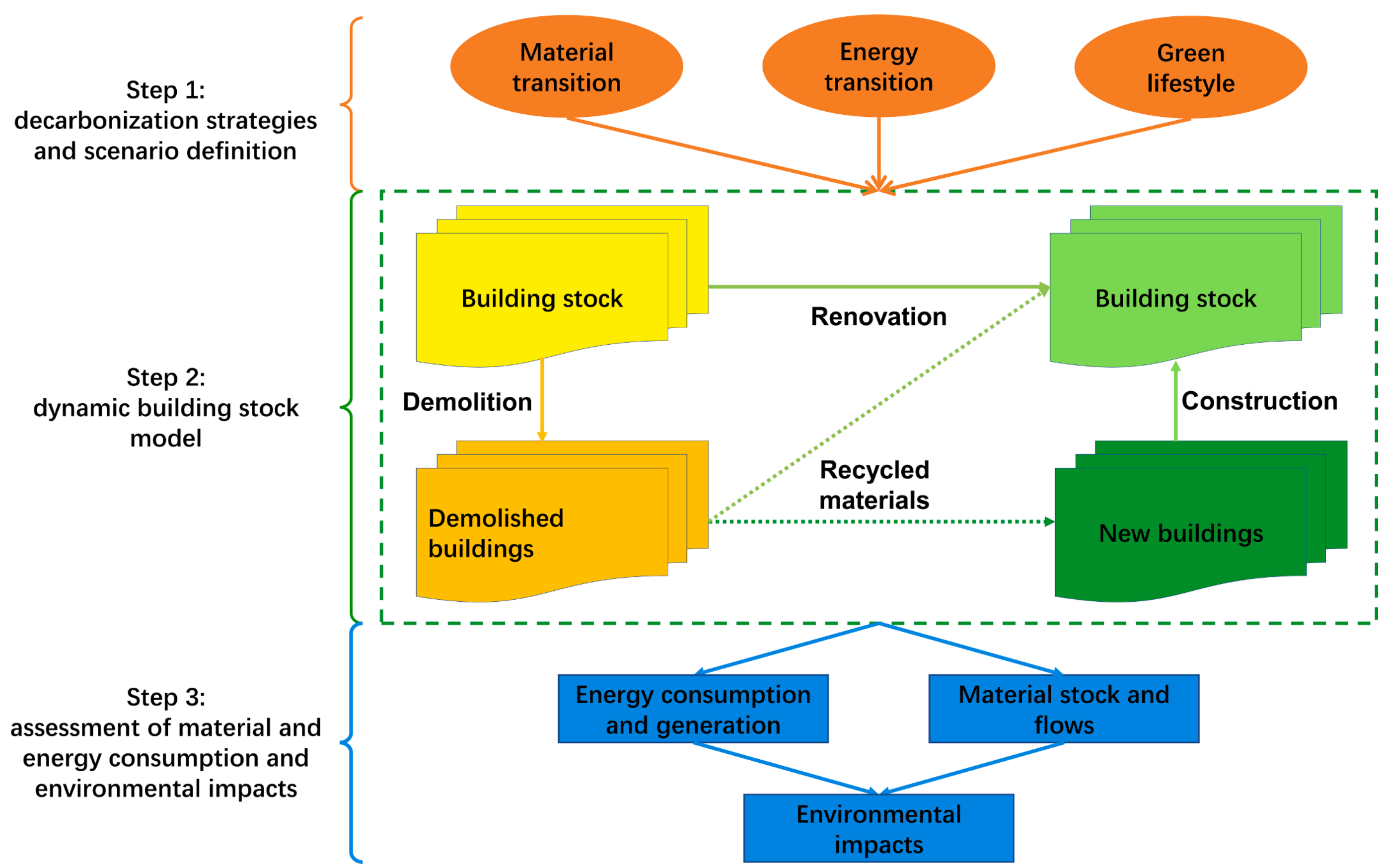

Fig. 1. The model overview.

strategies mainly consist of material transition (e.g. circular economy and bio-based construction), energy transition (e.g. energy efficiency improvement and renewable energy supply), and green lifestyle (e.g. less floor area per capita). Scenarios are differentiated by the combination of decarbonization strategies. We analyze the potential building stock development under different decarbonization strategies or scenarios that affect building stock size and composition, material flows, energy demand and generation, and the related environmental impact. The recycled materials from CDW are reused in annual construction activities. The environmental impact of material flows and energy consumption and generation during building stock development are further calculated by LCA.

The building stock is composed of individual buildings from the geographic information system (GIS) data (BAG, 2018), which contains the construction year of each building in the Netherlands. The building typologies from TABULA (TABULA, 2013) are employed to classify buildings (see **Table S1** in supporting information (**SI**)) and derive building information (e.g. envelope component geometries, and physical properties) based on (Yang et al., 2020). Buildings are characterized by several kinds of attributes, mainly including basic building information (e.g. construction year and floor area), location, components, material composition, annual energy demand and generation, and environmental impact (see more in **Table S2**).

2.2. Decarbonization strategies and scenario definition

The Dutch government wants to reach carbon-neutrality (Dutch government, 2019) and full circularity (Government of the Netherlands, 2016) by 2050, including the building sector. Most existing residential buildings in the Netherlands have relatively low thermal insulation standards (Visscher, 2019) and almost 90% of them rely on natural gas for space heating and hot water(CE Delft, 2020), suggesting its untapped decarbonization potential. Leiden, a medium-sized city in the Netherlands, has various types of residential buildings (29,030 in total), including both historical buildings and new buildings (Teun J Verhagen et al., 2021). The municipality of Leiden hopes to realize a natural-gas-free heat supply (Municipality of Leiden, 2017) and a circular economy (Municipality of Leiden, 2019) in the building sector. Here we use the residential building stock of Leiden as a case study. The timeframe of this study is from 2015 to 2050.

Based on literature (EASAC, 2021; Göswein et al., 2021; Hietaharju et al., 2021; Roca-Puigròs et al., 2020; Röck et al., 2021) and relevant Dutch policies (CE Delft, 2020; Dutch government, 2019; Rijksoverheid, 2018a; Teun Johannes Verhagen et al., 2021), this study involves several main decarbonization strategies and defines two scenarios, i.e. reference scenario and ambitious scenario (see **Table 1**). The reference scenario follows a conservative development pattern. In the ambitious scenario, all the strategies are simultaneously adopted to investigate the maximum decarbonization potential of the residential building stock. Given the importance of prioritizing optional strategies for policymakers and other stakeholders (EASAC, 2021), the decarbonization potential of each strategy is investigated by independently deploying them in addition to the reference scenario.

This study considers two insulation standards: conventional insulation and nZEB (nearly Zero Energy Building) insulation (TABULA, 2013). The alternative space heating systems in each neighborhood are from the heat vision of Leiden (Municipality of Leiden, 2017), including natural gas boilers, electric heat pumps, low-temperature heat networks, and high-temperature heat networks. The natural gas boiler is excluded when the heat transition strategy is deployed in the neighborhood. The thermal performance of envelope elements (e.g. roof and window) can greatly affect the efficiency of space heating systems (Ende, 2017; Milieu Centraal, n.d.; Yang et al., 2022a). Therefore, buildings using electric heat pumps and low-temperature heat networks are insulated with the nZEB standard while buildings using natural gas boilers and high-temperature heat networks are insulated with the conventional standard. The details of insulation standards and technical systems and their combinations can be found in section **S4** in **SI**.

2.3. Dynamic building stock model

2.3.1. Demolition

The buildings constructed before 1920 are regarded as historical buildings (Municipality of Leiden, 2017), which will not be demolished in our model. The demolition year of individual buildings is estimated as follows:

$$t_{dem} = t_{con} + t_{lifetime,building} \quad (1)$$

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

Table 1
Description of strategies and scenarios.

Decarbonization strategies		Reference scenario	Ambitious scenario
D1. Material recycling	Materials recycled from CDW are applied to substitute the primary raw materials for construction activities (Yang et al., 2022b).	Current recycling practices in the Netherlands (Teun J Verhagen et al., 2021).	CDW is completely recycled for construction and renovation (Government of the Netherlands, 2016; Rijksoverheid, 2018b).
D2. Wood construction	Wood buildings (Takano et al., 2015) are introduced to represent the use of bio-based materials in new construction (IRP, 2020; United Nations Environment Programme, 2020).	The share of wood buildings in annual construction is 20% (Bronsvoort et al., 2020).	The share of wood buildings in annual construction will linearly increase from 20% to 80% by 2050 (Bronsvoort et al., 2020).
D3. Heat transition	Natural gas boilers are replaced by electric heat pumps or heat networks and envelope elements are additionally insulated with the nZEB standard to improve energy performance standards (Municipality of Leiden, 2017; Yang et al., 2022a).	Current heating system types remain unchanged (**Table S8**).	The share of neighborhoods implementing a natural-gas-free plan will linearly increase to 100% by 2050 (Municipality of Leiden, 2017; Ouden et al., 2020). The buildings in the natural-gas-free neighborhoods will be installed with natural-gas-free heating systems after the old heating systems retire.
D4. Renewable electricity	The share of renewable electricity in the public electricity grid is increased (Mendoza Beltran et al., 2018; Yang et al., 2022a).	Conservative development of public electricity grid.	Greener public electricity grid.
D5. Rooftop PV	Solar PV systems are installed on roofs to substitute the public grid electricity consumption (towards positive energy buildings or neighborhoods) (EASAC, 2021; Ouden et al., 2020).	The share of roofs with solar panels linearly increases from 4.4% (Broersen et al., 2018) to 30% (Ouden et al., 2020) by 2050.	The share of roofs with solar panels linearly increases from 4.4% (Broersen et al., 2018) to 100% (Ouden et al., 2020) by 2050.
D6. Green lifestyle	The floor area per capita and room temperature gradually decrease due to the increase in environmental protection awareness and the reduction of vacancy rates (Roca-Puigròs et al., 2020; Zhong et al., 2021).	Floor area per capita remains unchanged (62 m^2 per person in 2015) (BAG, 2018; Municipality of Leiden, 2020). The room temperature is set as 20 °C (Yang et al., 2020).	Floor area per capita linearly decreases by 15% in 2050 compared with 2015 (Roca-Puigròs et al., 2020). The share of buildings heated at 18 °C in conditioned areas linearly increases to 100% by 2050 (Roca-Puigròs et al., 2020).

$t_{lifetime,building}$ is the randomly assigned lifetime following the Weibull distribution (Nägeli et al., 2020) based on (Yang et al., 2022a).

2.3.2. Construction

Annual constructed floor area is driven by future population (see **Table S7**), floor area per capita, and demolition (B. Müller, 2006). New buildings are represented by TABULA archetypes (TABULA, 2013). According to Dutch policy (RVO, 2021), all the new buildings built from 1 January 2021 have to meet the nZEB standard. This applies to both the reference and ambitious scenario. The annual constructed floor area of a type of building ($A_{con,type,t}$) is estimated as follows:

$$A_{con,type,t} = \left(FAPC_t \times P_t - S_{t-1} + A_{dem,t}\right) \times PP_{building\_type} \quad (2)$$

Where $FAPC_t$ is the floor area per capita in year t. P_t is the population in year t. S_{t-1} is the floor area stock of the previous year. $A_{dem,t}$ is the total demolished floor area in year t. $PP_{building\_type}$ is the proportion of a type of building. This study uses the building type proportions in 2015 (Yang et al., 2020) to segment the annual constructed floor area. Considering that the buildings in Leiden are relatively crowded due to limited land supply, new buildings are likely to be built in the original places. Therefore, the neighborhood codes of new buildings are randomly sampled from the neighborhood codes of the buildings demolished in the same year.

2.3.3. Renovation

This study models renovation at the building component level, mainly including envelope elements (roof, window, external wall, door, and ground floor), ventilation systems, space heating systems, domestic hot water systems, and rooftop PV systems. Existing studies typically consider renovation with exogenously defined annual renovation rates based on recent trends or policy targets (Nägeli et al., 2020; Sandberg et al., 2017). Nevertheless, the payback time of renovation is very long due to high investment and relatively low energy bill savings (Knobloch et al., 2019), making it usually occur during the "natural" aging process for component replacement, maintenance, or upgrading (Filippidou, 2018; Sandberg et al., 2014). Considering that our model contains high-resolution information for individual buildings, this study simulates the renovation of envelope elements based on their lifetimes, meaning that renovation will occur after a component retires. As the ages of existing components are usually unknown, we estimate the retirement time of existing components as follows:

$$t_{retirement,existing} = t_{con} + \left\lfloor \frac{t_{start} - t_{con}}{t_{lifetime,component}} \right\rfloor \times t_{lifetime,component} + t_{lifetime,component} \quad (3)$$

Where $t_{retirement,existing}$ is the retirement year of an existing building component. t_{start} is the start year of the considered timeframe (i.e. 2015). $t_{lifetime,component}$ is the lifetime of the component (see section **S4** in **SI**). "$\lfloor x \rfloor$" is the floor function and gives as output the greatest integer less than or equal to the real number "x".

The retirement year of a newly installed component is calculated as follows:

$$t_{retirement,new} = t_{current} + t_{lifetime,component} \quad (4)$$

Where $t_{retirement,new}$ is the retirement year of a new building component. $t_{current}$ is the current year.

Buildings in the same neighborhood tend to have similar characteristics (e.g. construction years, building technologies, and heat sources) and can be upgraded with similar solutions (Municipality of Leiden, 2017). In the Netherlands, municipalities are required to make a heat transition plan based on the neighborhood-oriented approach (Klimaatakkoord, n.d.; PAW, n.d.; Yang et al., 2022a), which determines when and which neighborhoods will be tackled with what kinds of solutions, i.e. the dynamic heat transition map (see **Figure S1**). The heating system choice sets of individual buildings are linked to the corresponding neighborhood and updated every year.

2.4. Analysis of material and energy flows and related environmental impacts

2.4.1. Material flows

This study involves 25 kinds of common building materials in the Netherlands (see **Table S4**). The initial material stock of individual buildings is determined by multiplying material intensities (**Table S5** and **Table S6**) with the floor area. The material flows during renovation are accounted for based on (Yang et al., 2022b). The material composition of individual buildings is recorded every year (**Table S3)** and will be updated during envelope renovation. Individual buildings' material stock and flows are aggregated to the building stock level. The future material demand and potential supply of secondary materials from CDW are calculated based on (Yang et al., 2022b).

2.4.2. Energy demand and generation

The energy consumption of Dutch residential buildings mainly includes space heating, domestic hot water, and electricity for appliances and lighting (Majcen et al., 2013; Yang et al., 2022a). Annual energy demand for space heating is calculated using the hourly physical energy requirement simulation method of the standard EN ISO 13,790 (International Organization for Standardization, 2008). The energy demand for hot water is calculated based on the TABULA method (TABULA Project Team, 2013). Further details are given in (Yang et al., 2020). The annual electricity demand for appliances and lighting is calculated by multiplying floor area with measured electricity consumption intensities (Yang et al., 2022a). For buildings installed with rooftop PV, the annual generated electricity is calculated based on (Yang et al., 2022a). Considering the effect of future weather change on space heating demand and electricity generation from rooftop PV (Buffat et al., 2019; Lombardi et al., 2022; Streicher et al., 2021), the climate scenario from KNMI (Royal Netherlands Meteorological Institute, 2015) is used to represent the future weather change in the Netherlands. The temperature will linearly increase by 0.035 °C every year and the solar radiation will increase by 0.04% every year, from 2015 to 2050. Individual buildings' annual energy demand and generation are accordingly updated every year.

2.4.3. Life cycle assessment

Climate change is selected as the environmental impact category and measured as kg CO2-eq (IPCC, 2013). The current and future environmental impact for all materials and energy services is modeled based on future scenario background life cycle inventory databases as described by (Mendoza Beltran et al., 2018). These databases are constructed from a combination of data from the IMAGE model (O'Neill et al., 2014) and the ecoinvent database (cut-off system model) (Wernet et al., 2016). Here, we have updated these databases to version 3.6 of ecoinvent and calculated climate change impacts using the superstructure approach (Steubing and de Koning, 2021) as implemented in the LCA software Activity Browser (Steubing et al., 2020). This data represents two scenarios: the SSP2-base (Shared socioeconomic Pathway) scenario, which represents the middle of the road following a representative concentration pathway (RCP) of 6 W/m^{2,} and the SSP2–2.6 scenario, which represents a more ambitious middle of the road scenario, characterized by a greener energy mix and limiting global warming to just below 2 °C° by 2100 (Romainsacchi, n.d.). SSP2-base corresponds to the reference scenario and SSP2–2.6 corresponds to the ambitious scenario (**Table 1**). Annual GHG emissions are calculated by multiplying the amounts of materials and energy with the related GHG emission factors (see section **S5** in **SI**). Details on quantifying the GHG emissions related to material transportation and end-of-life treatment can be found in (Yang et al., 2022b).

3. Results

3.1. Building stock

Fig. 2a shows that the building stock of Leiden is very old, with nearly 50% of neighborhoods older than 1964, while there is only one neighborhood where the buildings' average construction year is after 1992. The city center (inside the moat) is the oldest and densest area (Fig. 2b). In Fig. 2c and d, the buildings constructed before 1964 occupy a large share (above 30%), suggesting the necessity and potential of decarbonizing the existing building stock. In the reference scenario, the building stock sees a continuous increase of 24% by 2050, making new buildings account for 30% of the total building stock. In the ambitious scenario, the building stock size increases at the start and reaches its peak at 8.1 km^2 in 2035 but begins to drop until 2050, with only 6% more than in 2015. In 2050, the proportion of new buildings is only 18%, much smaller than the reference scenario.

3.2. Material demand and supply

In Fig. 3, the material demand is mainly composed of concrete and sand, regardless of scenarios and strategies. Compared with the reference scenario (Fig. 3a), the total material demand (2016–2050) declines by about 55% in 2050 for the ambitious scenario (Fig. 3b) and 51% for the green lifestyle (Fig. 3c). The wood construction strategy reduces material demand by 15% due to the use of low-density wood materials and less concrete. The heat transition strategy slightly increases material demand as a result of more insulation material use.

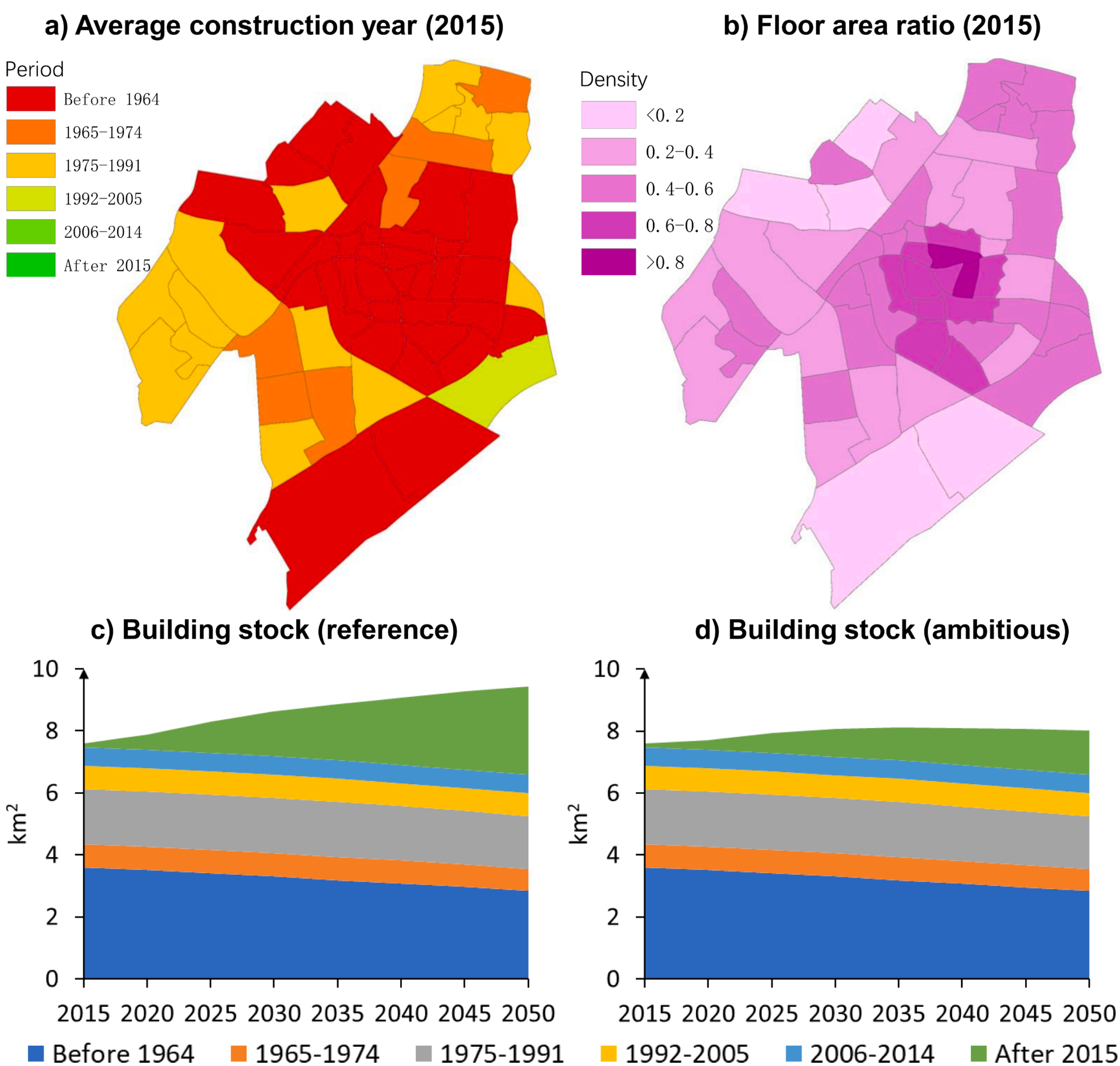

Fig. 2. Current building stock and its future development (using "floor area" not "buildings"). In Fig. 2a, the average construction year is weighted by floor area to represent the age of building stock in each neighborhood. In Fig. 2b, the floor area ratio (Joshi and Kono, 2009) is calculated by dividing the total floor area per neighborhood by the neighborhood's land area. Fig. 2c and d show the evolution of building stock composition (total floor area of each construction period).

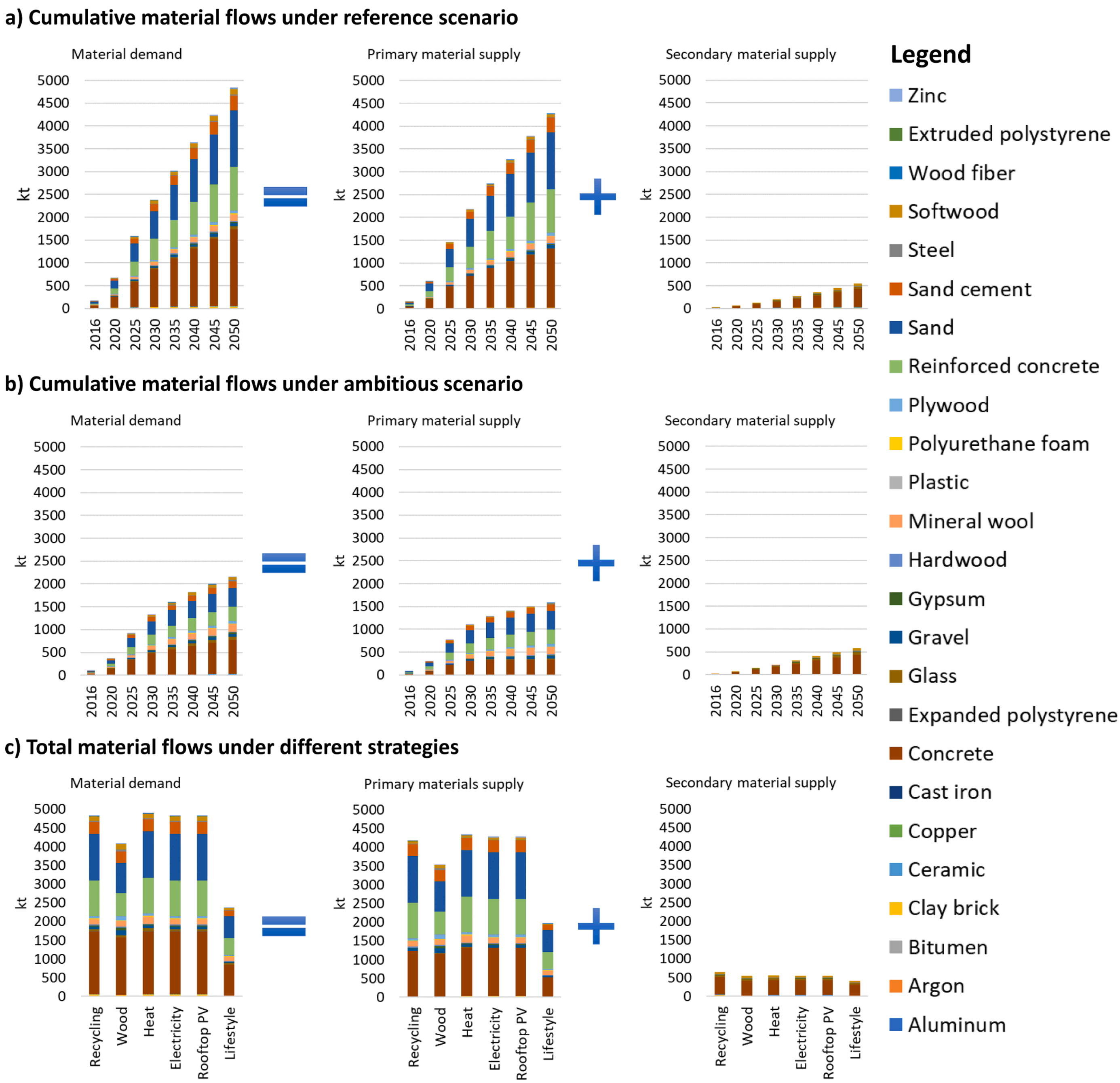

Fig. 3. Cumulative material demand and supply. The material demand is supplied by primary and secondary materials. The amounts of materials in Fig. 3c are the sums of material flows in the 2016–2050 period.

Considerable primary materials are still required because the secondary materials supplied from CDW can only provide very limited amounts and kinds of materials (mainly concrete). Even though the recycling strategy is fully implemented, only about 13% of material demand can be met by secondary materials. The green lifestyle strategy reduces the new construction and thus consumes much fewer materials, around 17% of which can be supplied from secondary materials. In the ambitious scenario, around 27% of material demand is met by recycling and more than half of consumed concrete is secondary.

3.3. *Energy demand and generation*

Fig. 4a shows that in 2015, the energy intensities of about half of the neighborhoods are more than 120 kWh/m^{2}a and the energy intensities of three neighborhoods are even higher than 160 kWh/m^{2}a. In the reference scenario, the energy intensities of most neighborhoods (77%) are below 80 kWh/m^{2}a in 2050. In the ambitious scenario, the energy intensities decrease dramatically in 2050 when the energy intensities of all the neighborhoods are lower than 80 kWh/m^{2}a.

The annual energy demand decreases by 27% in the reference scenario (Fig. 4b) and 53% in the ambitious scenarios (Fig. 4c), particularly for space heating demand, which is reduced by 49% in the reference scenario and 80% in the ambitious scenario. This leads to a lower proportion of space heating energy in annual energy demand, dropping from 72% in 2015 to 50% (reference scenario) and 30% (ambitious scenario) in 2050. In contrast, the shares of electricity and hot water energy experience a great increase. The proportion of electricity grows from 15% to 28% (reference scenario) and 39% (ambitious

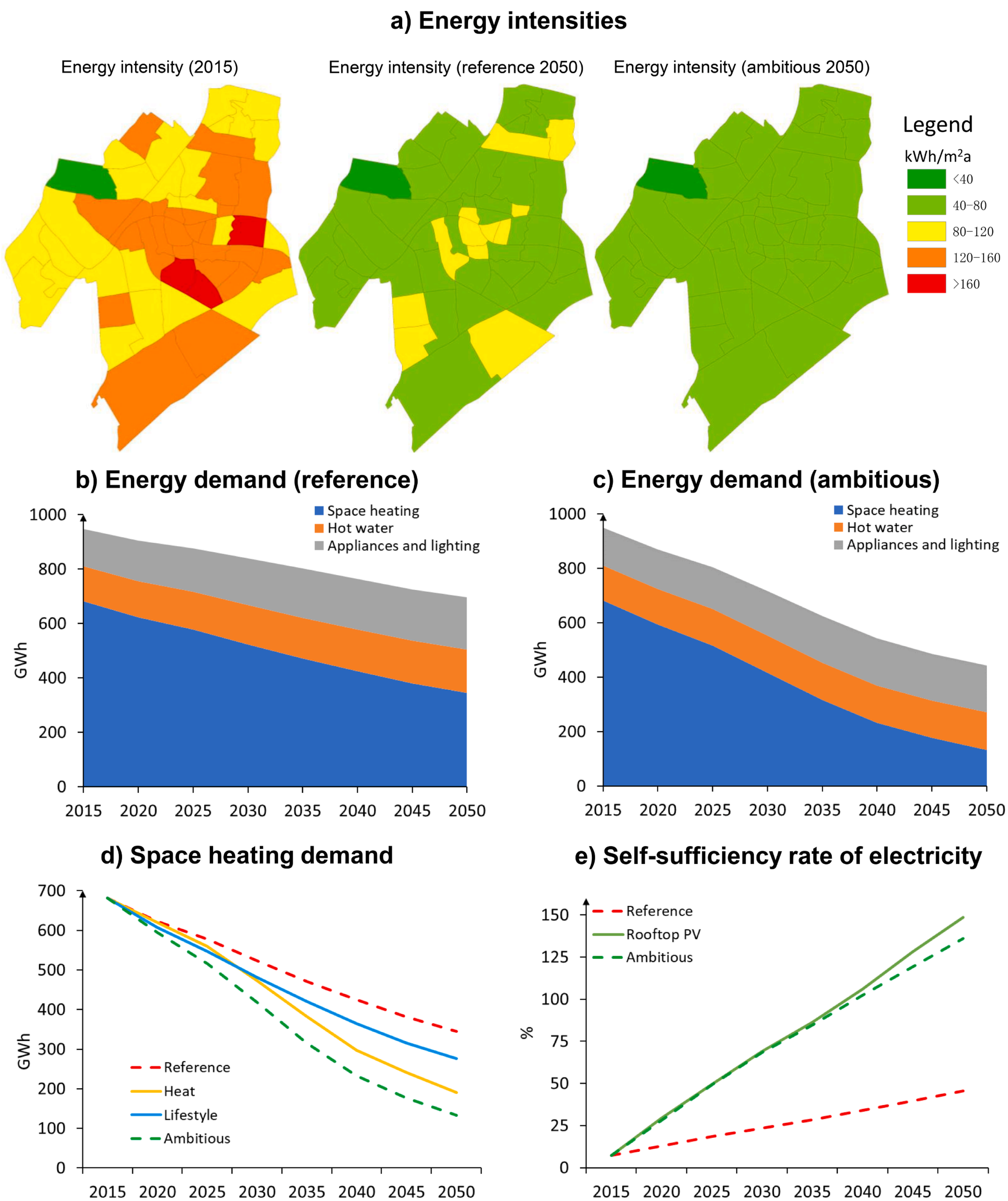

Fig. 4. Energy demand and the electricity generated from rooftop PV.

scenario). The share of hot water energy rises from 14% to 23% (reference scenario) and 31% (ambitious scenario).

Comparing different strategies (Fig. 4d), we can find that heat transition has a greater effect on reducing annual space heating demand than a green lifestyle, but the effect of a green lifestyle is bigger than heat transition at the early stage. In Fig. 4e, rooftop PV systems can only meet about 46% of annual electricity demand in 2050 in the reference scenario. When rooftop PV systems are installed as much as possible, the building stock not only becomes self-sufficient in electricity but also has an electricity surplus (36% with 62 GWh in the ambitious scenario).

3.4. GHG emissions

Fig. 5a shows that in 2015, the GHG intensities of most neighborhoods are above 30 kg CO_2-eq/m^{2}a and in some neighborhoods, the intensities are even more than 40 kg CO_2-eq/m^{2}a. Only three neighborhoods' intensities are below 20 kg CO_2-eq/m^{2}a. The city center is a carbon-intensive area where the GHG intensities are mostly above 40 kg CO_2-eq/m^{2}a. In 2050 of the reference scenario, the GHG intensities of most neighborhoods are below 20 kg CO_2-eq/m^{2}a while the intensities of 36% of neighborhoods are still between 20 and 30 kg CO_2-eq/m^{2}a. In the ambitious scenario, the GHG intensities are significantly reduced in 2050 when the GHG intensities of most neighborhoods are below 10 kg CO_2-eq/m^{2}a except for one neighborhood with intensities between 10 and 20 kg CO_2-eq/m^{2}a.

Comparing Fig. 5b with c, we can find that annual GHG emissions decrease by 40% (reference scenario) and 88% (ambitious scenario) by 2050, meaning that the carbon-neutral building stock target is nearly reached if all decarbonization strategies are deployed together. The GHG emissions of space heating occupy the largest share in all scenarios and periods, ranging from 47% to 75%. The share of GHG emissions from electricity generation is stable in the reference scenario (25–30%) but in the ambitious scenario, it ranges from 12% to 29%. In the ambitious scenario, the GHG emissions of hot water decline to nearly zero due to the extensive adoption of solar water heaters. Material-related emissions only account for a small share of annual GHG emissions (below 20% in both reference and ambitious scenarios).

Fig. 5d shows that the heat transition strategy has the largest impact on annual GHG reduction (21% more than the reference scenario), which is closely followed by the renewable electricity strategy (19%). Rooftop PV strategy, green lifestyle strategy, and wood construction have similar decarbonization potential (about 10%). The effect of fully implementing the recycling strategy is almost negligible. Fig. 5e suggests that the ambitious scenario realizes the most cumulative operational GHG reduction with the least material-related GHG emissions, which is followed by heat transition, renewable electricity, and rooftop PV.

4. Discussion

This study presents a spatiotemporal bottom-up building stock model to evaluate the GHG emission reduction potential of the building stock. The model builds upon real individual buildings from GIS data characterized by a series of parameters (including technical details) and tracks the development of individual buildings at the component level. Future material flows, energy demand and generation, and GHG emissions are accounted for every year building by building with the consideration of both endogenous factors (e.g. building component replacement or upgrade) and exogenous factors (e.g. material and energy policies, population and occupant lifestyle, and climate change scenarios). The model can prioritize decarbonization strategies by comparing the effects of different policy strategies on the overall decarbonization potential of building stock. The employment of local and high-resolution data further strengthens its reliability and capability to support decision-makers in making neighborhood or city-specific strategies for climate change mitigation.

4.1. Overall decarbonization potential

Our study shows that the carbon-neutral building stock goal cannot be achieved in the reference scenario (conservative development pattern) where only around 40% of the annual GHG emissions are reduced in comparison with 2015. This demonstrates that simply upgrading building energy efficiency by envelope insulation is not enough for realizing the carbon-neutral target and replacing natural gas with lower-carbon heat sources is also necessary. When all the decarbonization strategies are simultaneously deployed to their furthest potential, annual GHG emissions can be reduced by nearly 90%, meaning that there is still some distance to the carbon-neutral building stock. It is worth noting that these strategies involve greening the energy system and thus a wider effort than just within the building sector is required. Although the introduction of wood construction and renewable electricity generation can have positive climate effects, e.g. from temporary carbon storage (Guest et al., 2013), their absolute values are small in our study compared to other emissions.

4.2. The key role of energy transition

Heat transition contributes the most to reducing energy demand and GHG emissions. Even in the reference scenario where the energy efficiency of buildings follows a natural improvement pattern, the annual energy demand and GHG emissions of space heating both decline by about 50%. A sensitivity analysis is conducted to evaluate how faster heat transition (Walter and Mathew, 2021) influences future GHG emissions (**Figure S2**). It shows that early deployment of the natural-gas-free plan can gain more GHG reduction, which is in line with the finding of (Walter and Mathew, 2021). This highlights the need for taking action earlier to realize "no regrets" renovation (Bernstein and Hoffmann, 2019; Dutch government, 2019; Müller, 2015; Reyna and Chester, 2014). The heat transition is followed by the strategy of greening the public electricity grid, which reduces annual emissions by 59%. Its distinctive feature is that it can reduce both embodied and operational GHG emissions (Potrč Obrecht et al., 2021; Zhong et al., 2021), so it plays a key role in decarbonizing the building stock, which is also confirmed by some other studies (de Oliveira Fernandes et al., 2021; Göswein et al., 2021; Vahidi et al., 2021; Yang et al., 2022a). Large-scale installation of rooftop PV systems has great potential for mitigating the dependence on public grid electricity and decarbonizing the building stock, which is also confirmed by some previous studies (Broersen et al., 2018; Lausselet et al., 2021; Lu et al., 2021; Yang et al., 2022a). The green lifestyle strategy has a similar decarbonization effect to the wide installation of rooftop PV systems. It can be achieved by, for example, more intensive use of buildings (e.g. constructing smaller houses, increasing the number of residents per housing unit, or a combination of both), shorter shower time, and lower room temperature settings. However, great uncertainties exist as the occupant behavior changes are diverse and hard to capture.

4.3. Limited effect of material-related strategies

The material recycling strategy has a very limited potential for reducing and decarbonizing materials. In addition, there are some technical and legal limitations (e.g. ensuring material quality) to be overcome in completely recycling CDW for construction and renovation (Teun J Verhagen et al., 2021), e.g. the suitable and permissible proportion of recycled aggregate use in new concrete (Schiller et al., 2017), making the decarbonization potential of CDW recycling further questionable. Wood construction has the potential for reducing annual GHG emissions, yet a sustainable supply of sufficient quantities may be the bottleneck (Bronsvoort et al., 2020). In this study, material-related strategies have a much smaller effect on decarbonization than energy-related strategies during the considered time frame. The reason is that embodied GHG emissions make up only a small proportion of annual GHG emissions (Fig. 5), which is also demonstrated by (Vahidi et al., 2021; Yang et al., 2022a). It is commonly believed that the relative share of embodied GHG emissions will increase in the future (Röck et al., 2020; Yang et al., 2022a), which is also shown in Fig. 5c. However, this share is also determined by what kinds of strategies are implemented to what extent. For example, greening the energy systems (e.g. renewable public electricity grid and rooftop PV installation) can significantly

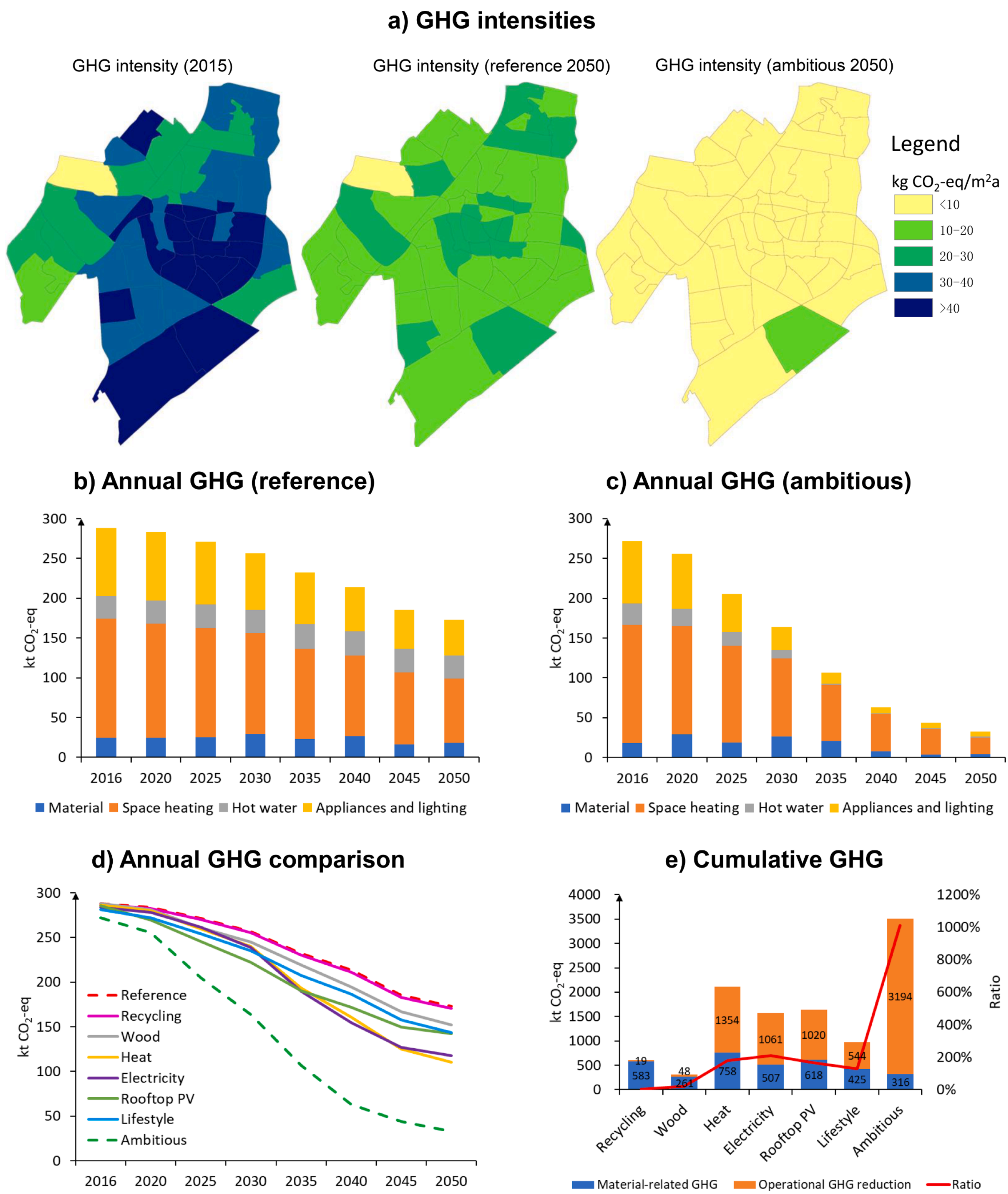

Fig. 5. GHG emissions. Fig. 5a and b show the annual operational GHG intensities. The percentages in Fig. 5e are the ratios of cumulative operational GHG reduction potential in comparison with the reference scenario to cumulative material-related GHG.

reduce operational emissions while its impact on decarbonizing building materials is relatively smaller (Yang et al., 2022a). More intensive use of buildings can greatly reduce material-related GHG emissions but also reduce operational emissions. The wood construction can greatly reduce material-related emissions and thus makes the share of embodied emissions remain very small (**Fig. 5**d). Some other studies (Pauliuk et al., 2021; Zhong et al., 2021) find that the lifetime extension of buildings and components is very effective in reducing GHG emissions. We plan to explore this by including the lifetime extension strategy in our model in future research.

4.4. Relationships between decarbonization strategies

It is worth noting that the decarbonization strategies may sometimes have co-benefits and adverse side effects on each other (Luderer et al., 2019; Zhong et al., 2021). For example, implementing heat transition and wood construction strategies will require some new materials (e.g. insulation materials and wood) that CDW recycling cannot supply, which lowers the recycling rate and decarbonization potential. On the contrary, a renewable electricity mix can further enhance the effect of heat transition by decarbonizing the electricity consumed by widely installed heat pumps. In the ambitious scenario, the electricity generated from rooftop PV in 2050 can provide about 46% of the total electricity consumption of Leiden in 2015 (1821 TJ (Rijkswaterstaat, n.d.)). It has an electricity surplus (31%) for appliances, lighting, and electric heat pumps under the assumption that the heat pump's coefficient of performance (COP) is 3.5 (Teun Johannes Verhagen et al., 2021). However, there will also be a trade-off between the GHG emission factors of rooftop PV electricity and public grid electricity for the SSP2–2.6 scenario in about 2040 (**Table S23**). Therefore, the aggregated GHG reductions of each strategy are not equivalent to the reduced GHG emissions in the ambitious scenario where all strategies are simultaneously implemented. Besides, this study compares the decarbonization potentials of different strategies but it doesn't mean that the strategies with limited decarbonization potentials are unimportant. Instead, different policies are made to resolve different issues. The material recycling strategy, for example, can to some extent reduce the extraction of primary materials from nature and the generation of CDW and related environmental effects, yet its overall GHG reduction potential is rather small.

4.5. Model applicability and implications

The spatiotemporal model integrates MFA, BEM, and LCA, enabling it to comprehensively simulate the impacts of multiple aspects (e.g. policies, technologies, occupants, and nature) on the future development of floor area stock, technology distribution, material flows and stock, energy demand and generation, and GHG emissions. It can help policymakers prioritize the strategies for decarbonizing building stock by evaluating their performance in advance with the consideration of detailed technical practices. In theory, the model can be applied on larger scales (e.g. countries or regions) and in other countries as long as the required data is available. However, the space cooling demand model could also be included in future research as in some regions air conditioning systems are widely installed. The comparison between different strategies shows the descending order of their priority in terms of decarbonization potential for residential building stock in Leiden: heat transition, greener electricity mix, rooftop PV, green lifestyle, wood construction, and material recycling. The results might apply to some other Dutch cities because most residential buildings in the Netherlands are heated by natural gas boilers. However, the effects or order of decarbonization strategies might be very different considering the area-specific climate, building stock composition, energy supply systems, and socioeconomic circumstances, as a recent study (Vahidi et al., 2021) shows.

4.6. Limitations and future research

Some potential limitations are associated with our study:

(1) The study mainly considers the effect of policy strategies from a technical perspective (e.g. lifetime-driven building component renovation) while in reality, socioeconomic factors can greatly affect the implementation of strategies. For example, the residents might be reluctant to renovate the building to a higher efficiency level and transit to low-temperature heating systems, because investments may not pay off quickly enough (Galimshina et al., 2021; Streicher et al., 2019; Yang et al., 2022a; Zuberi et al., 2021). The financial initiatives from the government and the legislation for building technologies can also affect the pace of implementing strategies. Future research should investigate transformation patterns that are affordable and beneficial for everyone with the consideration of potential governments actions (Dutch government, 2019).
(2) Our model only considers the energy-efficiency renovation while in practice, it often happens in combination with non-energy renovations (Directorate-General for Energy, 2019). Thus, it is important to consider them together as non-energy renovation requires large amounts of building materials.
(3) This study has not considered the increasing efficiency of appliances and lighting (Ouden et al., 2020) as well as the rapid growth in the use of appliances in buildings, so the future electricity demand from appliances, combining projected use and efficiency, is subject to high uncertainty. It would be interesting to investigate future electricity demand as well as its decarbonization potential.
(4) Dynamic carbon accounting and the effect of carbon storage, as well as the wood availability and potential supply, are not included in this study, which could be explored in the future.

5. Conclusion

In this study, we present a bottom-up dynamic building stock model that builds upon individual buildings from GIS datasets and integrates MFA, BEM, and LCA. It is capable of tracking the building stock development and the associated material flows, energy demand and generation, and the corresponding environmental impact in space and time. Both building energy upgrade and exogenous factors (e.g. policies and occupant behavior) are considered to assess the potential effects of different policy strategies on the realization of future building stock decarbonization goals. The model is applied in a Dutch city to explore the overall decarbonization potential of the residential building stock and compare the decarbonization effects of different policy strategies. Results show that the annual GHG emissions can be reduced by above 90% if all strategies are effectively deployed together. Energy transition plays the most critical role. Heat transition and a greener public electricity grid have similar decarbonization potential, while this is beyond the building sector itself. Wide installation of rooftop PV systems can generate surplus electricity for residential electricity consumption. Material-related strategies contribute less to GHG emission reduction than energy-related strategies due to the small share of embodied emissions in annual total GHG emissions. The decarbonization potential of CDW recycling is almost negligible as it can only provide limited amounts and kinds of materials to substitute the primary materials. Increasing the construction of wood buildings can reduce much more GHG emissions than CDW recycling. The study demonstrates that the residential building stock has great decarbonization potential whereas different kinds of strategies need to be effectively implemented simultaneously. Reducing energy demand through wide renovations cannot lead to climate-neutral building stock. It should be accompanied by increasing the share of renewable energy in the energy mix. Future research should focus more on the socioeconomic aspects to promote the early and effective implementation of decarbonization strategies because faster energy transition can reduce more GHG emissions.

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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Supplementary materials

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