Spatiotemporal building stock modeling for residential decarbonization in the Netherlands

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Chapter 6 General discussion

The thesis aims to help policymakers understand how building stock in the Netherlands can be decarbonized and supports them in formulating relevant climate change mitigation strategies also for the residential building sector in the Netherlands. The research gaps, research questions, and corresponding answers covered by this study are shown in **Table 6.1**. To answer the research questions, I develop a series of bottom-up building stock models to characterize the current building stock, track building stock evolution, analyze materials flows, simulate energy demand, and account for environmental impacts. The models can be applied to support policymakers in making policies related to developing a circular economy, reducing energy demand, phasing out fossil fuels, and mitigating climate change. In the remainder of this chapter, I will summarize and discuss my main findings and provide some implications for policymakers. Finally, this chapter analyzes the uncertainties and limitations of my models and provides some suggestions for further improving bottom-up building stock modeling.

Table 6.1 Research gaps, research questions, and corresponding answers of this thesis.

Research gaps	Research questions	Answers
The potential development of the Dutch residential building stock in space and time	How will the residential building stock develop in the Netherlands? (**Chapter 3, 4, and 5**)	· Improved insight into building stock composition · Insight into material flows related to demolition and new construction · Insight into the spatial distribution of stocks and flows over time
Energy-saving potential and energy supply	How much can energy demand be reduced and what is the potential of rooftop PV to meet local electricity demand? (**Chapter 2, 3, and 5**)	· Developing an engineering-based building stock energy model for assessing energy-saving potential · Insight into future energy demand · Analyzing energy-saving effects of different measures · Exploring the electricity generation potential of rooftop PV
Linking material outflows with inflows in space and time	How much primary material consumption in the Dutch residential building sector can be potentially reduced by urban mining? (**Chapter 4 and 5**)	· Insight into the spatiotemporal distribution of material flows and stock · Analyzing the mismatch between material demand and secondary material supply
Overall decarbonization potential of combined strategies	To what extent can residential GHG emissions be reduced under different decarbonization strategies and scenarios? (**Chapter 3, 4, and 5**)	· Estimating the overall decarbonization potential · Comparison between the decarbonization potential of different strategies · Discussion on the relationships between strategies

6.1 Answers to research questions

Question 1: *How will the residential building stock develop in the Netherlands?*

Chapter 3 shows that the buildings constructed before 1964 will still form the largest share of the Dutch building stock during the considered time frame (from 2015 to 2050). The annual demolished floor area will increase as an increasing number of buildings will reach the end of their lifespan. The demolished buildings are mostly constructed before 1964. The annual newly constructed floor area will become less with time as a result of a slower population increase. The floor area of newly constructed buildings (defined as buildings constructed after 2015) will account for about 20% in 2050. Most existing buildings will remain in use until 2050 or later, meaning that improving the existing buildings is the most important task for realizing energy neutrality and climate change targets.

Chapter 5 conducts a case study for Leiden. The reference scenario uses a fixed floor area per capita value while the ambitious scenario assumes that the floor area per capita will linearly decrease by 15% from 2015 to 2050. Results show that with this ambitious scenario, the total floor area will increase before 2035 and then begin to shrink, but the total floor area in 2050 is still more than in 2015 (increased by 6%). This makes the share of new buildings in the ambitious scenario (18%) smaller than that of the reference scenario (30%) in 2050.

Question 2: *How much can energy demand be reduced and what is the potential of rooftop PV to meet local electricity demand?*

To assess the energy-saving potential of energy efficiency measures, Chapter 2 develops an engineering-based space heating demand model based on EN ISO 13790 [180]. The GIS data and building archetypes in the Netherlands are used to derive individual buildings' information, such as component geometries and physical properties. The spatial validation shows that the model can well estimate the space heating demand of the residential building stock of the Dutch city of Leiden. It can provide acceptable results at the postcode scale (containing 9 buildings on average). However, there may be considerable uncertainties regarding individual buildings as the model builds upon information derived from GIS and archetypes rather than real detailed information on individual buildings, such as insulation level, heating systems, and occupant behavior. Validation for individual buildings was not conducted because the measured energy consumption is reported at the postcode level. A stepwise approach that increases the sophistication of the space heating model by gradually including more parameters shows that past renovation and occupant behavior can greatly affect the model accuracy, and thus contribute most to the reliability of model results. In contrast, increasing the temporal resolution of weather data (from seasonal to hourly) leads to a limited accuracy increase. Future research should thus mainly focus on collecting the data on past renovation records and occupant characteristics to further improve the model accuracy.

The space heating demand model in Chapter 2 is integrated into the bottom-up dynamic building stock model in Chapter 3 to estimate the energy-saving potential under the national control scenario of energy transition in the Netherlands. Results show that extensively renovating existing buildings, constructing high-energy performance buildings (nZEBs), and demolishing old energy-inefficient buildings can reduce annual space heating-related energy demand by more than 60%. In the assessed scenarios, energy-efficiency renovation contributes more to annual space heating demand reduction than demolishing old buildings, especially if it is possible to renovate buildings to the nZEB standard. As buildings with worse thermal properties are assumed to be renovated first, the marginal reduction of demand for space heating decreases with time. Constructing nZEBs instead of conventional new buildings avoids any increase in space heating demand.

The space heating demand model in Chapter 2 is also applied in the spatiotemporal building stock model in Chapter 5. Unlike the case in the dynamic building stock model in Chapter 3 where renovation is driven by exogenously defined annual renovation rates, in Chapter 5, the renovation is assumed to occur when a building component (e.g. windows) reaches retirement time. The model is used in the case study for Leiden. Results show that annual energy demand will decline by 50% by 2050 if the heat transition and green lifestyle strategy are deployed together. The reduction is mainly from lowering space heating demand due to extensive energy-efficiency renovation and lower room temperature.

Chapter 3 and Chapter 5 both show that in contrast to the development trend of space heating demand, the energy demand for domestic hot water, appliances, and lighting will experience a slight increase because these energy consumptions are driven by occupants, new construction, and installation of technical systems rather than the thermal properties of building envelopes. However, extensive installation of rooftop PV systems can greatly mitigate the dependence on public grid electricity and even generate surplus electricity. Chapter 3 shows that 80% of electricity demand can be potentially met by 2050 if 50% of building roofs are fitted with rooftop PV systems in the Netherlands. Chapter 5 shows that installing as many rooftop PV systems as possible would meet local residential electricity demand and generate 36% of surplus electricity.

Question 3: *How much primary material consumption in the Dutch residential building sector can be potentially reduced by urban mining?*

Chapter 4 shows that both material outflows and inflows of the Dutch building sector will, as expected, concentrate in big cities (e.g. Amsterdam and Rotterdam). Due to the expansion of the housing stock, material inflows outweigh material outflows. Urban mining can only supply limited amounts of specific types of building materials for annual new construction and renovation activities, meaning that additional consumption of primary raw materials is still required, such as concrete and sand. Even so, we show in Chapter 5 that the CDW reuse potential in terms of closing building material loops is much smaller than is usually suggested [112,248]. The reason is that most current studies simply check whether CDW is recycled. In the Netherlands the recycling rates of CDW are high, typically over 95% [304].

However, most of these materials are downcycled as filler or road foundation. Much more complex collection, sorting, and upgrading techniques are needed to use CDW again as primary building materials that meet the applicable legal quality standards.

The potential to meet future material demand is also determined by what kinds of and how many buildings will be built in the future. Chapter 4 shows that bricks will not be required as much as before because the brick intensities of building archetypes chosen in the case study for the Netherlands are very low. Extensive renovation will consume large amounts of insulation materials while such insulation materials are hardly present in CDW created by the demolition of very old buildings. Increasing the share of wood buildings will require more wood. Again, since wood was little used in the past, CDW from the demolition of old buildings cannot meet the specific supply of wood. Chapter 5 shows that the green lifestyle strategy (e.g. more intensive occupation of buildings) will reduce the material demand for new construction.

Question 4: *To what extent can residential GHG emissions be reduced under different decarbonization strategies and scenarios?*

Chapter 3 shows that GHG emissions in the Dutch residential building stock can be significantly reduced. Under the "National Control Scenario" of the Plan "Nederland klimaatneutraal in 2050" (Netherlands climate neutral in 2050) [156], climate neutrality of the building stock will almost be achieved by 2050. Extensive renovation, together with ceasing the use of natural gas for space heating and domestic hot water generation, reduces the annual energy-related GHG emissions by nearly 60%, but the decarbonization potential can increase to nearly 90% if the share of renewable electricity supply is significantly increased. Greening the electricity mix contributes mainly to a reduction of operational energy-related GHG emissions, but also, to a lesser degree, via the decarbonization of the production of building materials.

Chapter 5 assesses the decarbonization potential of deploying several main strategies in the residential building sector of Leiden, including CDW recycling, wood construction, heat transition, renewable electricity mix, rooftop PV, and green lifestyle. Results show that the annual GHG emissions of the residential building stock can be reduced by about 90% if all decarbonization strategies are implemented simultaneously [5]. The strategies of heat transition and greening the public electricity grid have similar decarbonization potentials (about 60%). Rooftop PV, green lifestyle, and wood construction strategies respectively reduce annual GHG emissions by about 50%. Chapter 4 shows that implementing a CDW recycling

[5] Note that the overall decarbonization potential of deploying strategies together is not equivalent to the aggregation of decarbonization potential of implementing each strategy independently. The reason is that the strategies can be mutually exclusive. For example, buildings are assumed to first use the locally generated electricity from rooftop PV. In that case, greening grid electricity only partially can give additional reductions, i.e. for the fraction of electricity that is used from the grid.

strategy would contribute only to limited GHG emission reductions due to the limited substitution potential of secondary materials recycled from CDW. Greening the public electricity mix leads to more material-related GHG emission reduction than CDW recycling. Implementing these two strategies together can reduce annual material-related GHG emissions by about 40% in 2050 in comparison with 2020 (Chapter 4).

Chapters 3 and 5 show that only reducing space heating demand through energy-efficiency renovation is not enough. Replacing natural gas boilers with alternative heating systems (e.g. electric heat pumps, heat networks, green gas boilers, and solar water heaters) can additionally lead to annual space heating-related GHG emission reduction. Along with the increased installation of electric heat pumps, the total electricity demand will also grow. Therefore, increasing the share of renewable electricity generation is also critical for reducing space heating-related GHG emissions.

Chapters 3 and 5 also show that the material-related GHG emissions area is much smaller than the GHG emissions of the operational energy supply. In the 2015-2050 period, the cumulative material-related GHG emissions from renovation and construction can be paid off by cumulatively reduced energy-related GHG emissions. However, the relative share of material-related GHG emissions in annual total GHG emissions increases over time.

The relationships between different decarbonization strategies are very complex and they can have co-benefits and mutual adverse side effects [34,298]. For example, green lifestyles and energy-efficiency renovation can reduce the energy demand, but increasing the share of renewable energy can further reduce both material and energy-related GHG emissions due to less carbon-intensive upstream processes. On the contrary, a large-scale energy-efficiency renovation will consume large amounts of materials, especially carbon-intensive insulation materials (e.g. mineral wool), leading to increased material-related GHG emissions. In addition, increasing the share of wood buildings in annual new construction will require more wood materials, which might entail difficulties in closing the building material loops. While CDW recycling can only supply very limited amounts and kinds of secondary materials and thus contribute very little to GHG emission reduction, it is still an important option for CDW management and primary material substitution.

Overall research question: *What is the potential to reduce energy demand, close material loops, and decarbonize in the residential building sector of the Netherlands?*

The thesis answers this question by developing a series of bottom-up building stock models to track future building stock development and account for the associated material flows, energy demand and supply, and the related GHG emissions. Results show that the energy use of the residential building stock can be significantly reduced, depending on what kinds of measures are deployed. While gas for space heating is assumed to be largely replaced by electricity use for heat pumps, electricity consumption will only slightly increase since well-insulated buildings have a low to zero heating demand per square meter. More intensive use of buildings and lower room temperature settings for space heating can considerably reduce the demand for both space heating and electricity. Wide installation of rooftop PV is a promising option to significantly reduce the dependence on public grid electricity and potentially meet local electricity demand.

Closing material loops in the residential building sector is challenging. Urban mining can only supply limited amounts of specific primary materials needed for renovation or new buildings. The main reason is that many new buildings will have to be built due to the population increase in the Netherlands. The building types and corresponding material inventory can also influence the potential of urban mining to meet future materials demands. For example, increasing the construction of wood buildings will consume more wood-based materials, which CDW recycling cannot adequately provide. In addition, extensive renovation activities will demand more building materials, especially insulation materials that recycling CDW from demolishing old buildings cannot supply. More intensive use of buildings can greatly reduce the material demand for new construction and, thus, to some extent help close the material loops.

In sum, the residential building stock can be almost fully decarbonized by deploying various strategies together. Reducing space heating demand by renovation and building nZEB besides phasing out natural gas boilers are both key strategies for realizing the climate-neutral residential building stock in the Netherlands. Greening the public electricity grid is also very important as it can greatly reduce both embodied and operational GHG emissions. Due to the relatively small share of material-related emissions in annual total GHG emissions, material decarbonization can only make a limited contribution to reducing GHG emissions related to the residential sector. However, the share of material-related GHG emissions will increase along with the decreased share of operational emissions, which will increase the relative importance of decarbonizing building materials. For example, increasing the proportion of wood buildings can considerably reduce GHG emissions.

6.2 Methodological advances

The building stock models in this thesis build upon real data about buildings from a Dutch GIS dataset called "Basisregistratie Addressen en Gebouwen (Base registration of Addresses and Buildings; BAG)" [172]. The GIS data contains the georeferenced information, geometries, construction year, and functions of individual buildings. However, it does not contain information on thermal properties and heating systems. TABULA [68] contains such information on Dutch building archetypes that are differentiated between building types and construction periods. To fill in the data gaps of BAG, the residential buildings in BAG are grouped according to TABULA archetypes and the information of TABULA archetype buildings is then mapped to the buildings in BAG. The material intensities of Dutch archetype buildings are further included to estimate the material composition of these individual buildings. Considering the importance of renovation in residential decarbonization, an engineering-based bottom-up space heating demand model is developed to simulate the space heating demand building by building (Chapter 2). The model is validated against the measured natural gas consumption data to guarantee the model accuracy.

To track the future building stock development and account for the associated material flows, energy demand and generation, and GHG emissions, Chapter 3 develops a bottom-up dynamic building stock model that builds upon the individual parametric buildings and integrates MFA, space heating model, and LCA. Renovation is driven by exogenously defined annual renovation rates. Chapter 4 further develops the model by linking material inflows and outflows with the consideration of recycling practices. Considering that the payback time of renovation investment is long and renovation likely occurs as a result of the natural aging process of building components, different from the dynamic model in Chapter 3, renovation is driven by the building component lifetimes in Chapter 5. Following the neighborhood-oriented approach, heat system choice sets of individual buildings are linked to the heat source availability per neighborhood.

Compared with previous building stock models, the models in this thesis build upon individual buildings with detailed information. They can capture the change in material composition, technical system parameters, energy performance, and GHG emissions of individual buildings under different technical combination scenarios and outside weather conditions. Macro policy strategies can be translated into specific technical measures for individual buildings. In addition, each building contains georeferenced information, making my models able to depict the spatiotemporal material and energy flows along with the construction, renovation, and demolition of individual buildings. It can comprehensively assess the decarbonization effects of combined policy strategies, such as material transition, energy transition, and green lifestyle. However, the models mainly focus on technical aspects. Future research can include socioeconomic aspects by integrating other related analyzing methods, such as Life cycle costing (LCC) [305] and agent-based modeling [125].

6.3 Model applicability and transferability

The models in the present thesis can support policymaking in terms of the circular economy, energy transition, and carbon reduction in the residential building sector. The modeling approach can also be applied to analyze the non-residential building stock and infrastructure stock as long as the required data is available. The GIS data of non-residential buildings are available in the Netherlands, but the archetypes of non-residential buildings with detailed attributes are, as far as I know, unavailable. The main reason is that non-residential buildings are too diverse, depending on their functions, such as office buildings, hospitals, train stations, airports, and plants. Their energy consumption patterns and material composition are too complicated and time-consuming for data collection.

The proposed building stock models can theoretically be applied in other countries if the required data is accessible. The GIS data of individual buildings are available in many countries, such as Switzerland [98], China [306], the United States [307,308], Portugal [31], Luxembourg [309], Belgium [310], Ireland [311], and Austria [312], while the amounts of building attributes (e.g. construction year and function) are different. The building archetypes are available in many countries, especially for the building material inventory. It is worth mentioning that Heeren and Fishman constructed a material intensity database of different countries from published papers [84]. In China, governments of different provinces publish the building construction inventory for the required materials, energy, and construction machinery [20]. As for the energy modeling, TABULA is notable as it contains thermal properties, technical systems, and energy intensities of building archetypes of many EU countries [313]. The model of this thesis has not yet included the module for space cooling energy demand calculation, so this module should be added if the models are applied in the countries where air conditioning systems are widely installed.

6.4 Policy implications

Most existing buildings will still be in use until 2050 and beyond. Measures for saving energy are the most direct ways to reduce annual GHG emissions, mainly through energy-efficiency renovation and conscious energy-saving behaviors of occupants. Buildings are long-lasting products and the renovation or replacement cycles of building components ranges from 15 to 40 years [74,278]. To avoid arriving at a lock-in [292,314] situation where further energy-efficiency renovation and heating systems replacement are too late and uneconomical, measures related to the heat transition (energy-efficiency renovation and phasing out natural gas boilers) should be implemented in each neighborhood before 2030 (Chapter 5). Financial tools (e.g. low-interest loans, grants, and incentives) and innovative business models should be developed to encourage the residents or landlords to renovate their houses (increasing annual renovation rates) because the renovation investment is relatively high in comparison with the saved energy bills [12,315,316]. For example, the buildings in the same neighborhoods are likely to have similar technical characteristics and can be renovated together to reach an economy of scale (neighborhood-oriented approach [207]).

Extensive renovation for building energy efficiency improvement (renovation wave [29]) will consume large amounts of carbon-intensive insulation materials (e.g. mineral and fossil-derived materials [317]) that CDW recycling cannot provide. Therefore, the use of alternative insulation materials with low embodied carbon emissions is recommended to reduce annual embodied GHG emissions [1,318].

Rooftop PV can be a good option to substitute public grid electricity as it can potentially produce enough electricity to meet the electricity demand for appliances and lighting. However, the electricity generated by rooftop PV is intermittent and inherently affected by weather conditions, which implies that peak electricity production (e.g. daytime) is not in line with the peak electricity consumption (e.g.

evening) [319]. Energy storage technologies (e.g. batteries [13] and hydrogen vector energy [320]) could be applied to balance the mismatch between local demand and supply [230,321], but have in themselves implications for the demand for materials and embodied GHG emissions.

Residents are the users of buildings, so their daily activities can drive future material consumption and energy consumption. However, the implementation of a green lifestyle strategy can in reality be challenging because occupant behavior and preferences are affected by many complicated factors, such as affluence levels, house prices, and land use planning, and are not susceptible to rapid and direct change. Increasing the price of energy, particularly increasing the carbon tax on fossil fuels, could probably reduce energy consumption [74]. Poor families might be more sensitive to this policy, and such a policy could also widen the living standard gap between the poor and rich. In addition, the government could also limit the construction of new buildings to slow the growth of floor area per capita, thus reducing the consumption of materials and energy. Moreover, helping people to gain knowledge and awareness of saving energy through education and media, particularly for children, should be a long-term strategy.

The above policy strategies may not in themselves be sufficient to ensure that the residential building stock reaches the climate-neutral target. In that case, other technologies, such as CCS (carbon capture and storage) [88,322] and green hydrogen (e.g. used for space heating) [196], would be required to reach the climate-neutral target in the residential building sector.

6.5 Limitations and future perspectives

The research in this thesis has some limitations, such as:

(1) Representativeness of archetype buildings. Although this research has tried to apply as much data as possible, the current building stock remains a “black box”. The uncertainties come mainly from the systematic drawbacks of the archetype-based derivation and aggregation approach. The building footprints and registered building information (e.g. construction year and function) from BAG/GIS data are relatively accurate to derive building geometries. However, some of the existing buildings have already undergone some renovation while this is not recorded in the BAG database. Future research can focus on neighborhood or city-scale data collection on building characteristics with the help of local governments, which will improve the accuracy of modeled results.

(2) Gaps between actual and estimated reduction. Apart from the uncertainties due to the insufficient understanding of current building stock, the energy performance and occupant use patterns of post-renovated buildings are still unknown. The building energy model in this thesis uses standard values (e.g. the operation time of heating systems [168] and room temperature [323]), which can result in large gaps between the modeled and real energy and GHG emission reduction. Increased thermal comfort demand after energy efficiency renovation (“rebound effect”

[233,324–326]) is thought to be a common phenomenon that requires further attention. Future research can conduct some experimental case studies to collect some empirical data and calculate the reduced energy consumption and GHG emissions, which might provide more plausible support in policymaking.

(3) Insufficient consideration of socioeconomic aspects. The thesis mainly focuses on the technical aspects to reduce material consumption, energy demand, and GHG emissions while the socioeconomic aspects are also critical for successfully implementing the decarbonization strategies. Policymakers have to analyze the climate-neutral transformation pathways of the building stock from the perspectives of different stakeholders to overcome socio-economic barriers and to ensure potential risks are shared, such as fuel poverty and gaps between high and low-income groups. Future research can focus on developing socio-economic tools to guarantee the effective implementation of technical measures.

(4) Extending the scope to other buildings and sectors. The thesis focuses on the residential building stock while non-residential buildings also account for a large share of GHG emissions. CDW recycling is only considered for the residential building sector, while non-residential buildings and infrastructures (e.g. roads and railways) use many similar materials (e.g. concrete and steel) to residential buildings. Renewable electricity is critical for decarbonizing the building stock, but it will trigger large-scale construction of relevant infrastructures for generating renewable electricity. This thesis reveals the great potential of rooftop PV to meet local electricity demand, while its relationship to public grid electricity in terms of stable power supply to buildings remains to be studied.

(5) Future electricity demand. The energy efficiency improvement of appliances and lighting (e.g. increased inventions in LEDs [88]) is not considered in this study, so the future electricity demand and the overall decarbonization potential may be underestimated. Future studies can integrate the future residential electricity consumption estimation in dynamic building stock modeling.