# Spatiotemporal building stock modeling for residential decarbonization in the Netherlands

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# Summary

The building sector accounts for large amounts of material consumption, demolition waste generation, fossil fuel energy consumption, and greenhouse gas emissions. Decarbonizing the building stock plays an important role in realizing the climate-neutral target for the Netherlands. Dutch residential buildings are mostly relatively old and energy-inefficient and rely heavily on natural gas for space heating and domestic hot water supply, which occupy the largest share of annual residential energy consumption. This means that decarbonization policy strategies need to understand the characteristics of the current building stock and its future evolvement patterns. Accordingly, this thesis employs multi-source data, mainly including GIS data of building footprints and the archetypes representative of Dutch residential buildings, to develop a series of bottom-up building stock models to track future material stock and flows, energy demand, electricity generation, and GHG emissions.

Chapter 2 develops a bottom-up building stock energy model based on GIS data and archetypes of residential buildings differentiated by building types and construction periods. Archetypical information on buildings, such as geometries (e.g. window to wall ratio), thermal properties of envelope elements, and parameters of technical systems, is mapped to the individual buildings from GIS data, which provides a method to characterize the residential building stock in the Netherlands. At the same time, to investigate what kinds of information contributes most to model accuracy improvement, the detailed data (e.g. hourly climate data) is added stepwise to the basic model. The model is spatially validated against the measured natural gas consumption reported at the postcode level. Results show that past renovation and occupant behavior can greatly affect the modeled space heating demand. While uncertainties exist for individual buildings due to a lack of detailed individual building information, the modeled results are acceptable at the building stock level.

Chapter 3 presents a bottom-up dynamic building stock model capable of simulating future building stock development and accounting for the associated material and energy flows, and annual GHG emissions. Contrary to previous bottom-up dynamic building stock studies, the model builds upon archetypical building types retrieved from GIS data and simulates the potential energy demand taking into account (future) energy-efficient building renovation. The model is applied to assess the effect of the "Nederland klimaatneutraal in 2050" (Netherlands climate neutral in 2050) scenario, which aims to realize renewable energy supply systems in the Netherlands. Results show that the annual GHG emissions can be reduced by nearly 90% by 2050 if existing buildings undergo a thorough renovation, phase out natural gas boilers, and use a renewable electricity mix. Rooftop PV can potentially supply 80% of the annual electricity demand for appliances and lighting if solar panels are installed on 50% of roofs. The annual material-related GHG emissions are much less than annual energy-related emissions. The cumulative material-related GHG emissions from construction and renovation activities will be counteracted by the cumulative reduced space heating-related emissions by 2035.

Chapter 4 further develops the bottom-up dynamic building stock model in Chapter 5 by linking material inflows and outflows during construction, demolition, and renovation in space and time to explore the urban mining potential to reduce primary material consumption and GHG emissions. The CDW collection rates and the recycled content potentials are used to account for the amounts of recycled CDW that are used in construction and renovation processes. Results show that most building materials and floor areas are stocked in big cities, such as Amsterdam, Rotterdam, and The Hague. These cities also dominate future material inflows and outflows, but there are fewer outflows than inflows, meaning that urban mining can only provide limited amounts and kinds of materials for construction and renovation, especially for the insulation materials that most old buildings do not contain. There is a large temporal mismatch between material demand and secondary material supply; consequently, some materials have a deficit in the early years but have a surplus in later years. The limited ability of urban mining to substitute primary materials leads to limited GHG emission reduction potential. Greening the electricity mix for material production has a much bigger effect on GHG emission reduction than urban mining.

Chapter 5 integrates the models in the previous chapters to investigate the overall GHG emission reduction potential of combined policy strategies and compare the decarbonization potential of different strategies, such as material transition (CDW recycling and wood construction), energy transition (heat transition, renewable electricity mix, and rooftop PV), and implementing green lifestyles. Results show that if all the strategies are effectively implemented together, the overall GHG emission reduction potential can be over 90%. The energy transition strategy, especially the heat transition and renewable electricity supply, plays the most important role. Rooftop PV can supply surplus electricity if as many roofs as possible are fitted with solar panels. The material transition strategy contributes much less to GHG emission reduction than the energy transition strategies. The green lifestyle strategy has a similar decarbonization potential to a wide installation of rooftop PV systems.

Together, the chapters of this thesis demonstrate the great potential for GHG emission reduction, while the decarbonization strategies should be effectively and extensively implemented. Saving space heating energy consumption is the most direct way to reduce annual GHG emissions. Considering that most existing residential buildings will still be in use in 2050, renovating them with high energy performance standards is required. Despite the great potential of renovation, it alone is not enough to realize the climate-neutral target in the residential building stock because the upstream fossil fuel-based energy systems still emit large amounts of GHG. Replacing fossil fuels with renewable energy sources is a critical path, mainly involving onsite natural gas combustion for space heating and offsite natural gas and coal combustion for electricity and heat (in heat networks) generation. Urban mining cannot contribute to as much emission reduction as energy transition strategies, but it should nonetheless still be implemented as it can reduce the primary material consumption and generation of CDW. In addition to the technical aspects considered in this thesis, it is also necessary to develop feasible policies in terms of socioeconomic aspects to guarantee the effective and quick deployment of these technical strategies.