Chapter 1 General introduction

1.1 Background

Buildings provide people with comfortable shelter for daily activities, such as sleeping, working, and relaxing [1–3], while they are characterized as highly intensive in the use of resources and energy and the generation of residues [4]. Currently, the building sector accounts for around 35% of global energy consumption and nearly 55% of global electricity is consumed by building operations [5]. Building operation and construction represent 38% of global greenhouse gas (GHG) emissions, mainly due to the combustion of fossil fuels (natural gas, oil, and solid fuels) for onsite space heating and cooking and offsite heat (e.g. district heating networks) and electricity generation [1,5]. 40-50% of globally extracted resources are used for constructing buildings and infrastructures [5–7]. In the European Union (EU), construction and demolition waste (CDW) accounts for 25-30% of the total generated waste, by weight [5,8]. The building sector thus has to play a significant role in ambitions concerning climate change mitigation [9,10].

Policies have been developed, from the EU to the national level, to accelerate the decarbonization of the EU building stock [11]. However, large-scale construction of new buildings and renovation of existing buildings with more complex technical systems will continue in the next decades [12], mainly driven by ongoing population increase, urbanization, and continuous increases in living standards, such as floor space per capita [13] and higher thermal comfort requirements for space heating and cooling [3,14,15]. This trend will inevitably pose great challenges for reducing the demand for primary materials and energy and the generation of CDW [16], which further emphasizes the urgency of reducing/decarbonizing the materials and energy consumed in the building sector to realize the circular economy, energy-neutral and climate-neutral targets [17–19].

1.2 GHG emissions in buildings

The GHG emissions of buildings are mainly composed of embodied and operational emissions [1,20]. Embodied emissions are primarily related to building material (component) manufacturing, transportation, installation, and end-of-lifespan treatment during construction, renovation, maintenance, and demolition processes [1,11,20,21]. The consumption of cement, concrete, bricks, and steel during initial construction accounts for the most embodied GHG emissions [1]. Operational emissions are from energy use, including the direct emissions from fossil fuel combustion for space heating, hot water, and cooking, and the indirect emissions from heat (heat networks) and public grid electricity generated by fossil fuels [22].

The amounts of life-cycle GHG emissions and the respective share of embodied and operational emissions are determined by many factors, such as the local climate, construction techniques, energy performance standards, and energy supply systems

[20]. The embodied GHG emissions from construction range from 250 to 400 kg CO_2-eq/m^2 [23], which occur in the relatively short construction phase (typically around one year) [20]. Renovation and maintenance during the operation phase can also lead to embodied emissions, but these emissions are less than 50% of the GHG emissions released during initial construction [1]. In contrast, the operational emissions per year range from 30 to 50 kg CO_2-eq/m^2 [23]. Since buildings are long-lifetime products [24] over the lifetime of the building, operational GHG emissions are more important than the embodied emissions related to construction. The proportion of operational GHG emissions can be changed by energy-efficiency renovations during the operation phase [25].

In addition to the building itself, the lifestyle of occupants can also greatly affect the living space per capita and energy demand per floor area. Greening lifestyles (e.g. shorter showers, more people living together in one house, and living in smaller houses) due to people's increased awareness of environmental protection can also be regarded as an important decarbonization strategy [26–28].

1.3 Towards climate-neutral building stock

According to the literature [1,28–31], decarbonization of the built environment can be pursued via three approaches: realizing a material transition, realizing an energy transition, and pursuing green lifestyles.

1.3.1 Material transition

Given the major contribution of building material production to embodied GHG emissions [32], it is critical to reduce the primary material extraction and decarbonize the building materials, i.e. material efficiency improvement and the substitution of carbon-intensive materials with low-carbon materials [33,34].

Material efficiency

Previous literature [3,34,35] suggests that strategies for material efficiency improvement mainly include:

(1) **Lifetime extension**. Increasing the lifetime of a building or component can reduce the life-cycle material demand [36]. New building construction will require large amounts of materials, especially for the foundation, structure, and walls, which consume the most carbon-intensive materials such as concrete, cement, bricks, and steel. Therefore, extending the lifetime of existing buildings by deep renovation rather than demolition and reconstruction can not only reduce the generation of CDW but also reduce new material demand. Demolition can be an option only when the building can hardly meet current function demand or its structure is seriously defective (e.g. foundation settlement), which makes the renovation too expensive or almost technically impossible. As for new buildings, advanced urban planning and better building design (increased durability of components) can greatly reduce the construction of short-lifetime buildings. This is an important lesson learned from China where the building lifetimes are very short [37,38] and large-scale demolition

and construction activities generate very high CDW amounts leading to unnecessarily high consumption of primary raw materials [39,40].

(2) **Material recovery**. This mainly encompasses reuse and recycling [41]. Some components can be directly reused for new construction or renovation [4], such as the components made of wood and steel. Some materials, such as metals, plastics, wood, and concrete, can be recycled and used to produce secondary materials. Concrete can be crushed into aggregate for new concrete manufacturing [42] although additional cement, sand, and water are required [43]. In practice, CDW is commonly used as road foundation or backfilling [43], which represents a form of downcycling and should be transformed into high-level recycling [44]. In addition, future building construction should develop towards manufacturing off-site prefabricated modular components [45] that are easy to disassemble [46,47] which will increase the closed-loop use of materials [5]. Standardized component libraries can be built and thus enhance component universality between different buildings, which can effectively reduce CDW generation and crushing works.

(3) **Lightweight design**. The structures account for a significant proportion of material consumption. Reducing the weight of structures without loss of mechanical properties and specific functionality should therefore be pursued [3,5]. Some components (e.g. non-load-bearing walls) can be constructed with lightweight materials. Innovative technologies for low-density material production can be of great benefit in the future [48] and are highly advocated as these materials have advantages of seismic resistance, fewer environmental impacts, and shorter construction time [49]. In addition, the building type choice can also affect the component weight, especially for high-rise buildings, which tend to use large amounts of concrete and steel for foundations, pillars, and beams.

Low-carbon materials

Raw material extraction and building material production cause a great impact in terms of biodiversity loss and carbon emissions [5,50]. It is therefore important to substitute carbon-intensive materials (e.g. metals, concrete, and masonry) with bio-based materials, such as wood [3,51]. Some bio-based materials can sequester CO_2 emissions during growing and can act as carbon storage [3,5,50]. Wood can be used in different parts of the buildings, such as structures, window frames, walls, and roofs. Bio-based materials can also become a good choice for insulating building envelopes [52]. Bio-based materials (e.g. bamboo or timber) have been the main building materials in human history but, with the fast population increase and urbanization in the process of the industrial revolution, other materials that can be produced on a large scale and have better properties began to be used in buildings in the past two to five hundred years. Given that the supply of bio-materials is limited due to the slow growth of forestry, using materials from fast-growing bio-based plants (e.g. bamboo, straw, hemp, and flax) can be a sound option as they can store carbon in less than 10 years and more easily keep pace with the material demand [53].

In addition to material substitution, decarbonizing the material production is also critical because wood can hardly meet the material demand in most countries [54], such as the Netherlands and China. Further, harvesting trees from unmanaged forests will harm the ecosystem [53]. The GHG emissions of building material production (e.g. metals and cement) are mainly related to the energy supply from fossil fuel combustion [39]. Therefore, increasing the energy efficiency during material production, developing low-carbon processes particularly cement and steel production [55,56], and enhancing the share of renewable energy in upstream energy systems can greatly reduce material-related GHG emissions [50].

1.3.2 Energy transition

The energy transition is regarded as an important measure in reducing GHG emissions in the building sector. The main reason is that energy-related GHG emissions related to the operational energy use of buildings account for the largest share of life-cycle emissions [1].

Building energy efficiency improvement

Realizing climate change targets will be extremely challenging and expensive if the energy demand is not significantly reduced [57,58] because a substantial increase would be required in renewable energy infrastructure construction and carbon dioxide removal (CDR) technology adoption [58]. The GHG emissions during building operations mainly involve fossil fuel combustion for space heating, hot water, and cooking, and electricity consumption for cooling, lighting, and appliances [11]. In many EU countries, space heating is the dominant form of energy use (mainly in the form of natural gas), corresponding with about 66% of total household energy consumption [23], but this share can be larger in Northern Europe [1]. Considering that most EU countries' building stocks are rather aged and most existing buildings will continue to exist in the next decades [15], renovating existing buildings is regarded as an important strategy to reduce operational energy consumption [1,11,59]. This mainly encompasses insulating the building envelopes and replacing current heating systems with more efficient ones. In addition to heating systems, ventilation systems with heat recovery are also important to reduce heat losses. Smart ventilation systems are recommended as they can maintain a comfortable home in terms of both temperature and fresh air control [60]. Moreover, more energy-efficient appliances can also contribute to reducing household electricity consumption.

As regards the construction of new buildings, it is important to ensure that these are energy efficient. Many EU member states have made national plans to encourage the construction of "nearly Zero-Energy Buildings" (nZEB) [61,62], which are defined by the Energy Performance of Buildings Directive (EPBD) as "a building that has a very high energy performance, as determined in accordance with Annex I, and states that the nearly zero amount of primary energy required should be covered to a very significant extent by energy from renewable sources, including those produced on-site or nearby". According to EPBD [61], after 31 December 2018 buildings occupied and owned by public authorities must reach the nZEB energy standard and from 2021 all the new buildings have to be nZEBs.

Renewable energy supply

Increasing the renewable energy share in electricity generation can reduce the carbon emissions of many types of electricity uses, such as lighting, appliances, and electric cooking [63,64]. It can also contribute to the decarbonization of space heating and cooling systems. Phasing out the onsite fossil fuel use of buildings mainly involves installing new heating systems (e.g. heat pumps, heat networks, and green gas boilers) that do not directly combust fossil fuels [60]. Replacing water heaters based on electricity and fossil fuels with solar water heaters can greatly reduce GHG emissions as hot water is provided with energy from the sun. Besides, increasing the installation of electric cooking systems (e.g. induction cooking) instead of natural gas cookers is also an option to reduce natural gas use.

Rather than consuming energy, buildings can also produce energy onsite by installing solar panels [29,65]. In recent decades, solar panel technologies have become mature and their price and installation cost has dropped significantly [66]. Solar panels can be installed on the roofs of existing buildings and are commonly installed on new buildings heated with heat pumps [67], especially on the roofs of nZEBs [68]. The solar panel system can convert energy from the sun into electricity and is regarded as an important option for renewable electricity generation [66]. Compared with a conventional pattern where power plants are far from buildings, meeting electricity demand with locally generated electricity from rooftop PV (photovoltaics) has the advantage of saving the cost of electricity transmission and distribution infrastructure and reducing electricity losses in transmission processes [69]. A report [70] estimated that there are 892 km^2 of roof surfaces suitable for solar PV installation in the Netherlands, which can potentially meet half of the national electricity demand and greatly reduce the fossil fuel combustion for electricity generation. Given that the electricity generation of solar panels is limited by the weather and sun, the supply peaks are usually not in line with the demand peaks [71]. Therefore, the combination of solar panels with energy storage technologies (e.g. lithium-ion batteries) can balance the different peaks of demand and supply [66]. When the electricity generated from solar panels exceeds buildings' demand and can supply surplus electricity to the public grid, such buildings or neighborhoods are named positive energy buildings (PEBs) or positive energy neighborhoods (PENs) [1,72].

1.3.3 Green lifestyles

In addition to technical measures, the GHG emissions of building stock can also be reduced by changing occupants' lifestyles [57,73]. Reducing the demand for floor area per capita (more intensive use of buildings [3]) can directly reduce the consumption of both materials and energy. Along with economic development and urbanization, house prices are increasing, which leads to decreasing family size (partly due to a lower marriage rate and birth rate than before) and the demand by individuals for increasing living space [3]. Policymakers and urban planners can mitigate this trend by constructing more multi-family houses rather than single-family houses. The size of single-family houses can also be reduced by constructing smaller buildings. Further, the greener lifestyles of building occupants can also lead to a reduction in the demand for energy and water, such as lowering room temperature and reducing shower time. Imposing taxes on fossil fuels and increasing the cost of energy can also contribute to the decrease in energy consumption [74].

1.4 Methods for analyzing building stock

The tools for analyzing building stocks include building stock models, which are usually based on material flow analysis (MFA), and life cycle assessment (LCA) [29]. In this thesis, the development of building stocks is calculated by combining an Urban mining model that analyses how much materials are stocked at a point in time in the built environment, with a Dynamic building stock model based on MFA that calculates material inflows and outflows per unit of time, and as a result, development of the building stock. We further use a Building stock energy model to analyze the energy requirements of the building stock, while we use LCA to assess the life cycle impacts of material and energy flows. These methods and their applications are introduced below.

1.4.1 Urban mining model

Urban mining models quantify how many, where and what kinds of materials are stocked in the current buildings and infrastructures [75,76]. They are mostly used to assess the potential of current anthropogenic material stock to provide secondary material to meet future material demand, such as concrete, bricks, wood, steel, and copper [76,77]. The amounts of building materials are usually estimated by multiplying the floor area of different types of buildings with the corresponding material intensities (kg/m^2) [78,79]. Many of these models apply GIS (geographical information system) data of buildings and infrastructures to estimate the floor area stock or the length of roads. For example, Mastrucci and colleagues [80] developed a bottom-up material stock model based on GIS and combined it with LCA to assess the end-of-lifespan scenarios of demolition wastes in a city in Luxembourg. Arora and colleagues [77] proposed a model framework for investigating the urban mining, recovery, and reuse potential of building materials on a city scale and demonstrated the framework in the public building stock of Singapore. Guo and colleagues [81] conducted a case study for Beijing, China, which quantifies the material stock in different kinds of roads. Arbabi and colleagues [82] presented a framework that can estimate the material stock at the building component level based on a mobile-sensing approach. Peled and Fishman [83] used nightlight radiance values as a proxy for built-up volume and linked it with the material stock distribution of Europe based on regression analysis. It is worth mentioning that Heeren and Fishman [84] created a comprehensive and harmonized material intensity database differentiated by climate and socioeconomic indicators by extracting data from 33 worldwide studies, which greatly helps data provided for use in urban stock models. Based on an extensive survey (813 sample buildings), Yang and colleagues [85] created the material intensity data of buildings differentiated by structure, function, construction period, and provinces in China. These datasets can increase granularity and consider the heterogeneity of buildings, which benefits model accuracy [10]. Nasir and colleagues [75] and Fu and colleagues [86] have provided an overview and comparison of approaches to urban mining models.

1.4.2 Building stock energy model

The end-use energy can be grouped into space heating, space cooling, domestic hot water, appliances, and lighting [87,88]. The end-use energy types can be very different, depending largely on the climatic and socioeconomic conditions [89]. For example, most residential buildings in the Netherlands do not have air conditioning systems for space cooling (moderately warm summers) while air conditioning systems are installed in most buildings in southern China (hot summers).

Building stock energy models (or urban building energy models) estimate the energy demand on a large scale to support decision-making in energy performance improvement and climate change mitigation [90]. This mainly involves assessing and comparing the energy-saving effects of different renovation measures, especially for reducing the space heating demand. Modeling the building stock energy demand is hindered by a lack of data on so many heterogeneous buildings on an urban or national scale, such as building geometries, physical properties, and occupant behavior.

Swan and Ugursal [87] classified building stock energy models into two categories: top-down models and bottom-up models. Top-down methods usually link aggregated energy consumption data from statistics with socioeconomic variables such as population, economic indicators, fuel prices, and income [91]. This kind of model mostly conducts a retrospective analysis of the relationship between sectoral energy consumption and macroeconomy [87] and estimates the potential change in energy demand and GHG emissions under certain policy scenarios in the future [92]. The technical details and end energy uses are usually omitted. In contrast, bottom-up approaches consider the end-use energy consumption intensities (kWh/m^2a) of archetypical buildings that are usually differentiated by construction periods and building types [93,94]. The energy demand of representative buildings is mostly aggregated to the building stock based on the distribution proportion of building archetypes [95].

Abbasabadi and Ashayeri [96] further classified bottom-up models into data-driven (statistical) and simulation (engineering-based) approaches. Data-driven models typically use statistical and artificial intelligence techniques (e.g. machine learning) to identify the mathematical relationship between energy use and the characteristics of end-users, such as urban attributes, occupant features, and building properties, while this method regards the building stock as a “black box” and relies on large-scale historical end-user datasets that are usually unavailable and need to be collected from questionnaires [96]. Engineering-based approaches use the physical properties of buildings, climate data, and occupant data to model the balance of heat transfer according to thermodynamic equations [97]. While it is almost impossible to collect so much detailed information on individual buildings, Buffat and colleagues [98] simulated the building stock heat demand building by building based on building energy modeling standards (engineering-based model) and comprehensive use of various GIS datasets in Switzerland such as building footprints and high-resolution climate data. There have already been several review articles [91,96,97,99–107] on building stock energy models.

1.4.3 Dynamic building stock model

Müller [108] developed a dynamic MFA model to determine the future product demand based on lifetimes, per capita demand, and population (stock driven). The model was applied to model the building stock development of the Netherlands and the corresponding concrete inflows, outflows, and stocks. After this, the model was widely used to model the production routes and embodied emissions of building and construction materials in general. Bergsdal and colleagues [109] employed MFA to model concrete and wood usage in residential buildings from 1900 to 2100. Material intensities differentiated by building type and vintage cohorts are multiplied with floor areas to quantify the material composition of the building stock. Hu and colleagues analyzed [110] the urban and rural floor area demand and predicted the oscillation of new construction and demolition activities in China. Hu and colleagues [111] applied MFA to estimate the amounts of CDW generation in Beijing. They found that the CDW generation will unavoidably rise and the lifetime of buildings is a key factor affecting future CDW figures. Using a cohort-based and stock-driven dynamic model developed by Deetman and colleagues [37], Zhong and colleagues [34] explored the material-related emissions for residential and commercial buildings in the world and compared the decarbonization potential of different material efficiency strategies. Heeren and Hellweg [112] applied a three-dimensional and geo-referenced building dataset to characterize the building geometries and combined this with detailed building inventory data to track future material flows and stocks in the Swiss residential building sector. They found that material outflows would be almost equal to material inflows in 2055, meaning that for the Swiss case CDW recycling has great potential to meet future material demand for construction activities, i.e. closing building material cycles. Wiedenhofer and colleagues [113] used an inflow-driven dynamic stock-flow model to analyze 14 kinds of materials in the building sector around the world and found that the rising levels of stocks in the future will lead to more waste outflows and higher material demand for maintenance, renovation, and replacement. Further information can be found in several review articles [24,114–118], which provide a comprehensive overview and comparison of modeling techniques in MFA.

Apart from material aspects, some models include the energy demand and environmental impacts in dynamic building stock analyses [79,90,119]. Heeren and colleagues [95] developed a lifecycle-based building stock framework (LC-Build) that classified the building stock according to construction periods, building types, and technical systems (e.g. heating and ventilation systems) and can assess the effect of climate change mitigation strategies on material flows, energy demand, and environmental impact. McKenna and colleagues [120] modeled the likely house stock development in Germany and modeled the energy performance change with the consideration of floor area demand, demolition and renovation rates. Roca-Puigròs and colleagues [28] developed a dynamic stock-driven model to quantify the future energy consumption and GHG emissions under different technology and lifestyle combinations in Switzerland. Recently, some researchers integrated building stock models with system dynamics models [121–123], agent-based models [124,125], and machine learning [126,127]. For instance, Nägeli and colleagues [128] employed an agent-based building stock model to explore the potential effects of different policies aimed at realizing national GHG emission reduction targets in Switzerland. There have already been some review articles [29,129,130] that classify the different building stock models and compare their modeling approaches.

1.4.4 Life cycle assessment

LCA is a method that accounts for the potential environmental impact of products and services during their life cycle [131,132]. It can help designers and policymakers to make decisions at the early stage of products, services, and policy strategy making [1,20]. ISO 14041 divides LCA into four steps: goal and scope definition, inventory analysis, environmental impact assessment, and interpretation [133]. When LCA is applied to individual buildings, it covers the product stage (raw material supply, transport, manufacturing), process stage (transport and construction), use stage (use, maintenance, repair, replacement, refurbishment, operational energy use, and operational water use) and end-of-life stage (deconstruction, transport, waste processing, disposal) [134]. The commonly used life cycle inventory databases are, e.g., ecoinvent, Gabi, ELCD, and CLCD [135–138]. The most commonly used LCA software include SimaPro, Gabi, OpenLCA, brightway [139], and the Activity Browser [140–142]. In the past decade, the ever-wider application of building information modeling (BIM) systems proved to be supportive to provide Life Cycle Inventory (LCI) data for buildings concerning detailed material and energy consumption data during building construction and operation [20,143–146].

The review by Mastrucci and colleagues [129] shows that LCA application in building stock models mainly involves: 1) assessing the performance of current building stock to inform current issues; 2) exploring the improving potential of certain measures (e.g. renovation) in comparison with the current state; 3) the environmental target realization potential during building stock evolvement. The production-construction and use stages are included in most studies while the end-of-life stage is usually omitted [29,129]. Instead of quantifying the annual environmental impact of individual buildings one by one, current building stock models usually regard the building stock as a “virtual product” providing humans with comfortable living spaces (meeting floor area demand) over a specific time frame. The material flows and energy consumption information from building stock models are typically aggregated, after which LCA is used to calculate the life cycle emissions and impacts related to these material and energy flows. Results are usually reported as annual environmental impacts or accumulated impacts in the considered time frame. For example, Göswein and colleagues [31] translated material and energy needs into an emission inventory reflecting GHG emission coefficients. Heeren and colleagues [95] used the emission factors extracted from the ecoinvent database in their dynamic building stock model to calculate both direct and indirect GHG emissions (upstream processes).

1.5 Building stock modeling in the Netherlands

Several studies have developed building stock models in the Netherlands. The building stock model developed by Müller [108] is the earliest one, which presented the basic modeling principles and applied the model to analyze concrete flows and stock. Based on the material intensity data [147] collected from demolition companies in the Netherlands, Verhagen and colleagues [44] modeled the building stock dynamics based on government plans and compared the amounts of recycled materials from demolition wastes with the material demand for construction. Zhang and colleagues [148] extended the ODYM (Open Dynamic Material Systems Model [149]) by including a renovation function and explored the potential of new technology for manufacturing prefabricated concrete elements (PCEs) from recycled CDW. Zhang and colleagues [43] further conducted a static MFA to analyze the contribution of different end-of-life scenarios to circular construction.

In addition to material usage, some other studies focused on saving energy and reducing environmental impact. Verhagen and colleagues [74] characterized the building stock with GIS data and compared the environmental and financial impact of alternative sustainable heating options to natural gas boilers. Yücel [150] presented a dynamic simulation model to analyze the importance and inertia of the existing Dutch residential stock for the energy transition. Mastrucci and colleagues [151] linked measured natural gas and electricity consumption with several variables (e.g. building type, construction year, and floor area) through multiple linear regression, and assessed the energy-saving potential of typical renovation measures in Rotterdam. Wang and colleagues [152] presented a data-driven residential heating demand model based on GIS data and Bayesian calibration and applied the model in Amsterdam. Filippidou and colleagues [153] estimated the renovation rate between 2010 and 2014 based on the SHAERE (Sociale Huursector Audit en Evaluatie van Resultaten Energiebesparing), involving 856,252 Dutch residential buildings. Liu and colleagues [154] conducted a case study for the city of Utrecht to assess the current and future energy system in 2050 under different sustainable heating scenarios.

1.6 Research gaps

Despite the progress in data application and modeling techniques, there are several limitations:

(1) **The potential development of the Dutch residential building stock in space and time**. Against the background of energy transition and climate change mitigation, the Dutch building stock composition will see substantial change due to demolishing old energy-inefficient buildings, constructing energy-efficient buildings, and upgrading the energy performance of existing buildings. To develop optimal decarbonization strategies, it is important to track this dynamic process and understand how many and which buildings will be involved with what kinds of solutions. However, previous dynamic building stock models mostly disaggregated the building stock based on statistical floor area. While the Netherlands has high-resolution GIS data of buildings that contains georeferenced information, geometries, construction year, and function, the potential of this data has not been fully explored in dynamic building stock modeling to simulate the spatiotemporal development pattern of building stock yet.

(2) **Energy-saving potential and energy supply**. Reducing energy demand and greening the energy mix is critical for the decarbonization of the residential sector. It is necessary to assess the energy-saving potential of different measures (e.g. envelope insulation and heating system replacement) and explore the potential change in energy supply structure in the building sector, particularly with the consideration of wide installation of rooftop PV. The macro policy targets (e.g. climate change mitigation) and corresponding strategies have to be realized by implementing specific measures (e.g. envelope insulation and technical system replacement or installation) that influence the material and energy use of individual buildings. However, existing dynamic building stock models are mostly top-down and usually estimate energy consumption by multiplying floor area with energy intensities of a limited number of archetype (or sample) buildings, which is too rough to capture the complex and gradual development of individual buildings in terms of material composition, technical system parameters, energy performance and environmental impact under different technical combination scenarios.

(3) **Linking material outflows with material inflows in space and time**. Previous urban mining models mainly analyze the spatial distribution of retrospective material flows and current material stock and have not yet adequately depicted the spatial distribution of future material flows, while the spatial distribution of material flows will significantly influence the cost and GHG emissions of transportation processes. In addition, the models focusing on future perspectives usually estimate the potential of CDW recycling to meet future material demand by directly comparing material inflows with material outflows. However, the amount of CDW that is recycled and comes back to the building stock is not only limited by the composition of the collected CDW but also by secondary material production practices and future building types, and associated material demand.

(4) **Overall decarbonization potential of combined strategies**. Previous studies mostly focused on either material or energy aspects separately, whereas material-related strategies (e.g. circular economy) and energy-related strategies (e.g. heat transition) are intertwined with each other and deployed together in reality. For

example, the large-scale energy-efficiency renovation of existing building stock will require large amounts of building materials, particularly insulation materials. In addition, replacing old energy-inefficient buildings with energy-efficient buildings will lead to large amounts of CDW generation and material consumption. Moreover, the lifestyle of occupants has not been well considered although it can significantly influence resource and energy consumption. It is, therefore, necessary to consider different factors together to help policymakers understand what the overall decarbonization potential of the building stock is and which strategies should be given priority.

1.7 Aims and research questions

The government of the Netherlands has established ambitious targets related to the circular economy [155], energy transition [156], and climate change mitigation [157]. This research aims to provide policymakers with the knowledge related to building stock decarbonization and support them in making reasonable climate change mitigation strategies. It involves tracking the building stock development and accounting for the associated material flows, energy demand, and environmental impacts under different scenarios. The overarching research question is:

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

To answer the overall research question, the following sub-questions are developed:

(1) *How will the residential building stock develop in the Netherlands?* (Chapter 3, 4, and 5)

(2) *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)

(3) *How much primary material consumption in the Dutch residential building sector can be potentially reduced by urban mining?* (Chapter 4 and 5)

(4) *To what extent can residential GHG emissions be reduced under different decarbonization strategies and scenarios?* (Chapter 3, 4, and 5)

1.8 Thesis outline

The thesis consists of six chapters (see **Figure 1.1**).

Chapter 1 introduces the characteristics and existing challenges of the building sector in terms of material use, CDW generation, energy consumption, and GHG emissions. It reviews the main policy strategies and technical measures to reduce the GHG emissions of the building stock. An overview of relevant methods for analyzing building stock is provided, including urban mining, LCA, and building stock models. Finally, the research gaps, aims, research questions, and outlines of the thesis are presented.

Chapter 2 presents an engineering-based, bottom-up building stock energy model that can estimate the current energy demand and assess the energy-saving potential of certain energy efficiency measures. An approach to derive building information (e.g. geometries and physical properties) from GIS data and building archetypes is proposed. The model accuracy is spatially validated against statistical energy consumption. The marginal accuracy improvement due to including more parameters is explored.

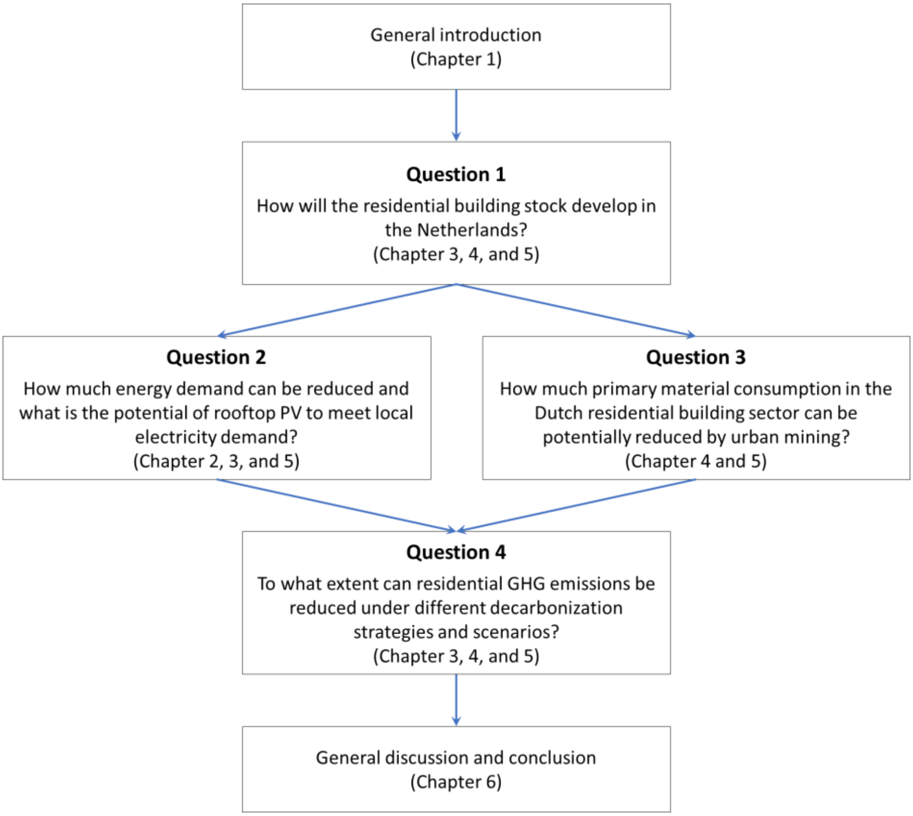

Figure 1.1 Outline of the thesis.

Chapter 3 develops a bottom-up dynamic building stock model that tracks the change in floor area composition, material stocks and flows, energy demand and supply, and GHG emissions under energy transition scenarios in the Netherlands. The overall energy and GHG emission reduction potential are analyzed. The effects of different measures on GHG emissions from space heating are compared. The potential of rooftop PV systems to meet the electricity demand for appliances and lighting is investigated.

Chapter 4 estimates the urban mining potential to substitute primary materials and reduce GHG emissions. It is based on the model from chapter 3, while it adds a module linking material inflows with material outflows. The spatial distribution of material stocks and material flows in different cities are mapped. The spatiotemporal mismatch between material demand and secondary material supply is analyzed. The decarbonization effects of urban mining and renewable electricity transition are accounted for.

Chapter 5 presents a bottom-up dynamic building stock with both spatial and temporal dimensions to assess the decarbonization potential of different strategies, mainly including material transition, energy transition, and green lifestyle. Renovation is driven by building component lifetimes instead of exogenously defined renovation rates. The maximum decarbonization potential of implementing all kinds of strategies is estimated. The effects of different decarbonization strategies are compared.

Chapter 6 answers the research questions, discusses the findings, and provides implications for making policies. The limitations of the thesis and recommendations for future research are given.