THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

A comprehensive approach to building-stock modelling

Assessing the impact of renovating urban housing stocks

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Abstract

The existing building stock provide a possibility for cost-efficient energy efficiency measures and related reductions in greenhouse-gas emissions. As the rate of renewal in the building-stock is low, energy efficiency measures need to be applied when renovation is being done in order to reach climate goals. To increase the renovation rate and realise the potential for substantial reductions in energy use, several research and demonstration projects have been carried out on both a European and Swedish level. In order to evaluate the current state and renovation potential of the existing building stock on an urban level, a local approach is needed to understand challenges and possibilities associated with the transformation of the building-stock. To quantify the potential for reducing energy use and greenhouse-gas emissions, building-stock modelling is commonly used. However, these models are often based on using representative buildings and scaling factors. With increased spatial resolution, building descriptions based on representative buildings lose accuracy and as a result, stakeholders operating at a planning or policy level are commonly targeted. This study proposes a building-specific stock description where each building is treated individually to differentiate the renovation potential within the building-stock. For this purpose, available databases containing building-specific information has been gathered and processed for the multi-family building stock of the City of Gothenburg. The available data is used to create a building-specific stock description and renovation measures are modelled using a bottom-up engineering method and evaluated regarding energy use, environmental impact and cost-effectiveness. This thesis with appended papers shows that available data sources can be used to describe the characteristics of the stock on a building level and model the effect of renovation on energy use, environmental impact and cost-effectiveness in order to provide detailed information to policy makers, planners and property owners.

Keywords: Building-stock modelling, energy performance certificate, GIS, LCA, cost-effectiveness, building valuation, multi-family buildings, energy, renovation, refurbishment

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List of Publications

This thesis is based on the following four peer-reviewed journal papers:

I. **Österbring, M**., Mata, É., Thuvander, L., Mangold, M., Johnsson, F., & Wallbaum, H. (2016). A differentiated description of building-stocks for a georeferenced urban bottom-up building-stock model. Energy and Buildings, 120, 78-84.
II. **Österbring, M**., Thuvander, L., Mata, É., & Wallbaum, H. (2018). Stakeholder Specific Multi-Scale Spatial Representation of Urban Building-Stocks. ISPRS International Journal of Geo-Information, 7(5), 173.
III. **Österbring, M**., Camarasa, C., Nägeli, C., Thuvander, L., & Wallbaum, H. (2019). Prioritizing deep renovation for housing portfolios. *Energy and Buildings*, 109361.
IV. **Österbring, M**., Mata, É., Thuvander, L., & Wallbaum, H. (2019). Explorative life-cycle assessment of renovating existing urban housing-stocks. Building and Environment, 106391.

The following publications are not included in the thesis but listed here for further reading.

V. **Österbring, M**., Mata, É., Johnsson, F., & Wallbaum, H. (2014). A methodology for spatial modelling of energy and resource use of buildings in urbanized areas. In World Sustainable Building Conference WSB14 Barcelona.
VI. Mangold, M., **Österbring, M**., & Wallbaum, H. (2015). A review of Swedish residential building stock research. International Journal of Environmental Sustainability.
VII. Mangold, M., **Österbring, M**., & Wallbaum, H. (2015). Handling data uncertainties when using Swedish energy performance certificate data to describe energy usage in the building stock. Energy and Buildings, 102, 328-336.
VIII. Thuvander, L., **Österbring, M**., Mangold, M., Mata, E., Wallbaum, H., & Johnsson, F. (2015). Spatial exploration of the refurbishment dynamics of urban housing stocks. In Computers in Urban Planning and Urban Management CUPUM Cambridge.
IX. Mangold, M., **Österbring, M**., Wallbaum, H., Thuvander, L., & Femenias, P. (2016) Socio-economic impact of renovation and energy retrofitting of the Gothenburg building stock. Energy and Buildings, 123, 41-49.
X. **Österbring, M**., Thuvander, L., Mata, É., & Wallbaum, H. (2017). Renovation Needs and Potential for Improved Energy Performance Depending on Ownership – A Location Based Study of Multi-Family Building Stocks in an Urban Context. In World Sustainable Building Conference WSBE17 Hong-Kong.
XI. Mangold, M., **Österbring, M**., Overland, C., Johansson, T., & Wallbaum, H. (2018). Building Ownership, Renovation Investments, and Energy Performance—A Study of Multi-Family Dwellings in Gothenburg. Sustainability, 10(5), 1684.
XII. **Österbring, M**., Rosado, L., Wallbaum, H., & Gontia, P. (2018). An Approach to Identify Resource Patterns on a Neighborhood Level. In Factor X (pp. 317-323). Springer, Cham.
XIII. Gontia, P., Nägeli, C., Rosado, L., Kalmykova, Y., & **Österbring, M**. (2018). Material-intensity database of residential buildings: A case-study of Sweden in the international context. *Resources, Conservation and Recycling*, *130*, 228-239.

XIV. Mata, É., Wanemark, J., **Österbring, M**., Thuvander, L., Wallbaum, H. (2018). Decision-Making in Building Retrofitting: Lessons from Dynamic Modelling of Scenarios for Gothenburg City, in 5th European Conference on Behaviour and Energy Efficiency, 2018.

XV. Nägeli, C., Farahani, A., **Österbring, M**., Dalenbäck, J. O., & Wallbaum, H. (2019). A service-life cycle approach to maintenance and energy retrofit planning for building portfolios. Building and Environment, 106212.

XVI. Eriksson, S., Waldenström, L., Tillberg, M., **Österbring, M**., & Sasic Kalagasidis, A. (2019). Numerical Simulations and Empirical Data for the Evaluation of Daylight Factors in Existing Buildings in Sweden. Energies, 12(11), 2200.

Acronyms and nomenclature

Acronyms

BSM – Building-stock modelling

DHW – Domestic hot-water

EAC – Equivalent annual cost

EEM – Energy efficiency measure

EPC - Energy performance certificates

GIS – Geographic information systems

HFA – Heated floor area

LCA – Life-cycle assessment

MFB – Multi-family building

SH – Space heating

Definitions

Deep renovation – A comprehensive renovation of a building aiming at considerable reductions in energy use.

Energy conservation measure – A measure that reduces energy demand and may impact the function, i.e. reducing indoor set-point temperature.

Energy cost saving – The monetary savings from reducing energy use.

Energy efficiency measures – A measure that reduces energy demand without impacting the function, i.e. improving the thermal insulation of a building component. Energy efficiency measures are a subsection of energy conservation measures.

Final energy – Energy delivered to the building for heating, domestic hot-water and auxiliary electricity use. It does not include household electricity use.

Multi-family building – The Swedish definition of a multi-family building is a building with three or more apartments.

Renovation – A change to a building or a building component in order to restore or improve the original function.

Contents

1. Introduction

In Europe, buildings account for about 40 % of the final energy use and 36 % of CO_2-emissions [1] and provide an opportunity for cost-efficient energy efficiency measures (EEM) [2]. The European Energy Performance of Buildings Directive defines efficiency standards for both new and existing buildings targeting these efficiency opportunities [3], [4]. On a national level, the Swedish government has set policy which strives for substantial reductions in energy use by 2020 and 2050 [5], [6]. As a result of the EU energy efficiency directive [4], energy performance certificates (EPC) were introduced in Sweden in 2006 in order to encourage energy efficiency in buildings. On a local level, more ambitious targets on energy savings have voluntarily been adopted by cities and municipalities. The city of Gothenburg has implemented such targets and aims to reduce energy consumption in residential buildings by 30 % by 2020 compared to 1995 levels [7]. For developed countries it is estimated that most of the buildings that will be in use in 2050 have already been built [8]. Meanwhile, the renewal rate of the Swedish residential stock is only 0.6% [9] which implies a need for EEM in the existing stock if these targets are to be met.

According to Statistics Sweden [10], the Swedish residential building stock consists of roughly 4.9 million apartments of which 2.5 million are found in the multi-family building (MFB) stock. The MFB stock is old with 75 % of apartments having been built before 1980 and 51 % of apartments being built between 1951 and 1980. Many of these apartments were built as a result of a governmental programme in 1965, the million homes programme, aiming at one million new apartments in the coming decade [11]. During this time period, roughly 700 000 apartments in MFBs were constructed. Furthermore, many of these buildings have not been renovated and there have been a few attempts to quantify the renovation need. In 2011, a survey conducted with property owners came to the conclusion that roughly 75 % of the MFBs from 1961-1975 were due for renewal, with 320 000 apartments needing thorough renovation [12]. A similar conclusion was made by a study in 2013, estimating 614 000 apartments needing renovation in the near future of which 471 000 needing major renovation [13]. A follow-up study was done in 2018 by accounting for major renovation activities since 2013 and concluded that there are still 213 000 apartments in need of major renovation [14].

By European standards, the energy performance of the Swedish housing stock is high and in combination with comparatively low greenhouse-gas emissions due to district heating, the average greenhouse-gas emissions for the residential sector is about a third of that in the EU27 [1]. The average energy use for space heating (SH) and domestic hot-water (DHW) for the 205 million m^2 of heated floor area (HFA) in the Swedish MFB stock has been roughly 27 TWh over the last decade with over 90 % being covered by district heating [15]. The average energy performance in the MFB stock for SH and DHW is 138 kWh/m^2. The energy performance is somewhat lower in older parts of the stock, 147 kWh/m^2 for buildings built before 1961, and 140 kWh/m^2 for buildings built between 1961 and 80 [16]. The yearly rate of renovation has been estimated at around 1 % [17] and as no discernible reductions in total energy use in the stock has occurred in the last decade, it is likely that any energy demand reductions achieved in the existing stock has been at least partly offset by new construction. It has also been noted that the main barrier for increasing the renovation rate is profitability and due to the widespread use of district heating, deep renovation only providing marginal greenhouse-gas reductions [17].

To increase the renovation rate and realise the potential for substantial reductions in energy use, several research and demonstration projects have been carried out on both a European and Swedish level. Over the past decade, there have been several EU funded research projects focusing on energy efficiency measures such as HERB (Holistic energy-efficient retrofitting of residential buildings), E2ReBuild (Industrialised energy efficient retrofitting of resident buildings in cold climates) and RETROKIT (Toolboxes for systemic retrofitting) to name a few. In Sweden, two methods have been developed and applied for deep renovation of residential [18] and commercial [19] buildings respectively. However, while these methods and case studies provide useful tools in assessing the cost-effectiveness of renovation for a specific building, they are not applicable to the building stock as a whole.

Building-stock modelling (BSM) has previously been used to assess the energy demand of the existing stock, prioritize what measures to apply and where they would be most effective. Much work has gone in to develop the energy simulation in BSM but little work has been done taking advantage of the building-specific information that is available. In order to evaluate renovation potential of the existing building stock on an urban level, a space and context specific approach is needed to understand challenges and possibilities associated with renovating the building-stock.

1.1 Aim

The aim of this study is to evaluate the potential for renovation by expanding on the methods used in building-stock modelling in order to account for environmental impact, cost-effectiveness, target a wider range of stakeholders with a particular focus on property owners and to visualize and communicate results using geographic information systems (GIS). In order to do so, the following research questions have been formulated based on the problem description and a literature study. How the research questions relate to the appended papers is shown in figure 1.

- Research question 1

What is the potential for a building-stock description where each building is treated individually?

- Research question 2

How can GIS be used with a building-specific stock description to visualize and communicate results for a wider range of stakeholders, including property owners?

- Research question 3

What are the environmental impacts of current renovation trends in an urban building-stock?

- Research question 4

How can the financial viability of (deep) renovation be assessed across a building portfolio?

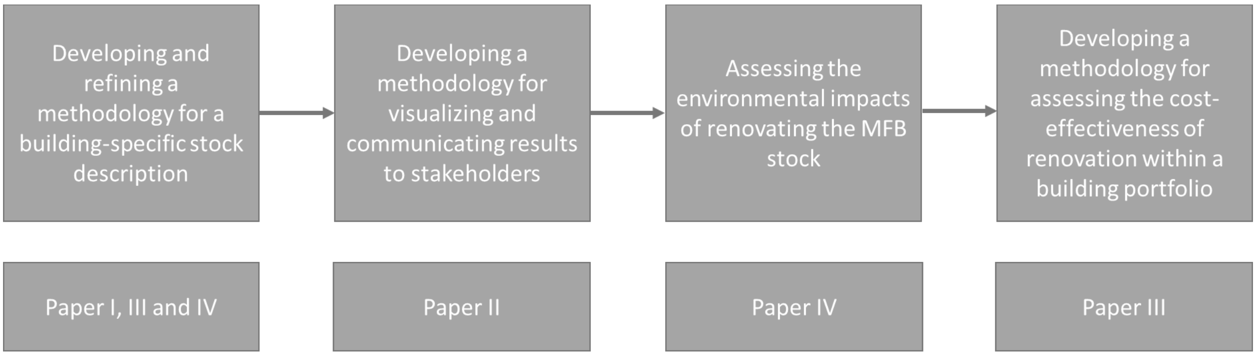

Figure 1 - Research questions and related papers

1.2 Scope

The MFB stock in the City of Gothenburg is used as a case study. The challenge of renovating the urban housing-stock of the City of Gothenburg is evaluated using a building-stock description that enables modelling the effect of renovation activities regarding energy performance, environmental impact and financial viability for each individual building in the stock. As such, the scope of this thesis is limited to MFBs in a Swedish urban context.

1.3 Methodology

The methodology used in this thesis is based on BSM using a building-specific stock description. It consists of the following four steps: (1) data acquisition and processing, (2) developing a building-specific description of the stock, (3) modelling as well as (4) evaluation and visualization. These steps are briefly described below.

Data acquisition and processing

Data has been gathered from national databases such as the property registry, the building registry, the national registry of energy performance certificates and spatially linked to a local 2.5D GIS model of the City of Gothenburg. The building-stock information available in Sweden and how it is processed to describe the characteristics of the MFB stock of Gothenburg is presented in more detail in chapter 3 and in paper I-IV.

Creating a building-stock description

Based on available building-stock information, a description detailing the characteristics of each building in the stock is developed where aspects such as U-values, heating and ventilation system, surface areas and volume are determined. As the available data does not directly cover all aspects needed for modelling, estimations are made based on historic building regulations and architectural history books. A thorough description of the steps involved can be found in chapter 4 as well as in paper I, III and IV.

Modelling

Depending on the research question, different modelling approaches have been used. Generally, modelling the energy use of the building-stock forms the foundation. In this work, two different approaches to modelling the energy performance of building-stocks has been used, ECCABS [20] in paper I and IV and the energy model described in [21] in paper III. In addition, a life-cycle assessment (LCA) has been conducted using SimaPro V8.0.5.13 based on environmental data from Ecoinvent and assessed using ReCIPe [22] V1.12 mid-point categories. Economic modelling has been conducted using equivalent annual cost (EAC) as well as the Swedish tax agency's model for assessing change in building value due to renovation activities. The methodology is expanded on in chapter 4.

Visualization

GIS based visualizations have been used to investigate and showcase spatial patterns or the lack thereof. Visualizations have been done using ArcGIS using different levels of spatial aggregation in a first attempt to tailor results to a wider range of potential stakeholders.

1.4 Structure of the thesis

This thesis consists of a summary compilation and four appended papers. The summary consists of seven chapters containing the following:

- Chapter 1 presents the background for the thesis as well as aim, research questions and a brief methodological overview.
- Chapter 2 contains a comprehensive overview of the research field, further adding to the problem description, as well as a theoretical framework for BSM.

- Chapter 3 accounts for the data sources and attributes used in creating a building-specific stock description for the MFB stock in the City of Gothenburg.
- Chapter 4 details the methodology used to create a building-specific stock description based on available data, how changes to the building stock is implemented and evaluated as well as how visualizations have been done.
- Chapter 5 presents the main results of the work by showing the current state of the MFB stock and summarizes the results of assessing the impact of renovating the existing stock found in the appended papers.
- Chapter 6 contains a discussion and conclusion based on the work presented in the thesis.
- Chapter 7 describes potential future work that has been identified.

2. Building-stock modelling

Building-stock modelling (BSM) has been used over the past decades to model the current state of the building stock and to evaluate possible changes. Over time, the methodologies have become more advanced and the focus has expanded from energy use to a wider range of indicators such as embodied energy, greenhouse-gas emissions and environmental impact. In this chapter, the development of the BSM field is described and development potentials are identified, resulting in a comprehensive framework for bottom-up engineering-based building-stock modelling.

2.1 A brief history of building-stock modelling

BSM has traditionally been used to evaluate energy performance of building-stocks. There are many examples of BSM being used to evaluate the energy demand of the existing building-stock [23]–[28] and several in-depth review papers exists [29]–[32]. BSM typically has three or four distinct methodological steps, depending on whether the current state of the building-stock is to be assessed or if potential changes are to be evaluated. First, a building-stock description is developed to be used as input for modelling. Second, if changes to the building-stock are to be evaluated, a scenario is defined for the future development of the building-stock. Third, relevant parameter(s) are modelled, typically consisting of modelling the energy use and/or energy use reduction potential. Fourth, results are aggregated to a suitable spatial scale, compiled and presented through graphs, tables and map-based visualizations.

In order to model energy use of building-stocks, the overarching approach typically falls within one of two categories, either bottom-up or top-down. The top-down approach treats the building-stock as an energy sink where energy use is impacted due to changes on a macro level. Parameters commonly used are rate of new construction, renovation rate, population growth and costs relating to energy use and construction activities. This also means that energy use for specific end-uses such as SH or DHW is not directly observed as the level of detail is typically limited to the entire stock or housing sector. As such, the approach is not suitable for studying the effects of specific construction or renovation measures. Furthermore, as the variables used are based on historical data, technology development resulting in a shift from common construction practices cannot be accounted for. As the aim of this work is to allow for a more detailed assessment of renovation options, a top-down approach is not suitable.

Bottom-up models can be divided into two sub-groups; statistical models and bottom-up engineering models. Statistical models use aggregated data as input, which through regression methods account for specific end-uses based on the energy consumption of buildings. Bottom-up engineering models use a heat balance model to estimate the energy consumption for individual buildings. The buildings used as input in bottom-up models are defined by building properties such as geometry, U-values, climate data, indoor temperature and use of appliances. Thus, to apply a bottom-up engineering model requires detailed input data. Due to limited data availability and computational time-constraints the building stock is normally represented by sample buildings or archetype buildings, where it is assumed that similar buildings with regard to year of construction, use of the building, type of heating system can be represented by an average building. Sample buildings use detailed data for a selection of buildings (e.g. as obtained from measurements or site inspection of individual buildings) combined with weighting factors for the sample buildings to reflect the entire building stock. Similarly, archetype buildings use representative theoretical buildings, often defined by construction year and the type or use of the building, to represent all buildings with similar characteristics to allow for assessment of the entire stock. These methods of developing a building description have been successfully used to calculate the potential for EEM in existing residential building-stocks on a national scale [33], [34] as well as on an urban scale [35]–[37].

Recent improvements in data availability have allowed greater focus on urban settings in BSM and include a spatial dimension by integrating geo-referenced data using geographical information systems (GIS) [38]–[40]. Using GIS in BSM has several advantages as it enables merging of data from different databases, it enables further analysis and communication by spatially differentiating and visualizing results, and finally it provides a solution for storing and exchanging data through interconnected urban models. The addition of a GIS component to BSM has been carried out to analyse energy policy scenarios in an urban context [41], to assess the urban heat island effect on energy demand [40] as well as to assess environmental impacts of building stocks and potential for EEM [39]. Further developments have been made by incorporating building specific data, most commonly taking advantage of 3D city models based on LIDAR data [42] or by analysing differences in digital terrain models and digital elevation models [43] as well as using building-specific data from EPC to better describe the technical characteristics of individual buildings [44]. This development allows for the possibility of visualizing and communicating results on a building level as well as allowing results to be aggregated arbitrarily to suit communication with different stakeholders.

2.2 Building-stock description using representative buildings

While the introduction of GIS in BSM has allowed an increase in spatial resolution and enabled focus on urban settings, using a description of the building-stock based on representative buildings has not been adapted to take full advantage of the improved potential for describing each building individually. Using representative buildings to model the stock can be problematic, typically so for older parts of the stock where renovations have been applied to a varying degree which may result in significant differences in the energy performance for the same type of buildings [45], [46]. While the spatial resolution has increased to represent individual buildings and the energy models become more advanced, the building-stock descriptions used as input for these models have seen little development and are still largely based on using representative buildings which are used to scale results to the desired level of output. Such descriptions loose accuracy with increased spatial resolution and commonly results are only presented at aggregate levels for districts or entire cities and not on a building level [31].

As a building stock description based on representative buildings limits accurate results to higher levels of aggregation, stakeholders operating at a planning or policy level are commonly targeted. A few exceptions can be found where other potential stakeholders have been identified. It has been suggested that construction companies can use EPC data to assess the size of the renovation market [47] and [48] points to the possibility to use results for educational purposes. As such, the intended stakeholders for BSM can generally be divided into three broad categories: urban planners, energy planners and governmental bodies needing policy support. However, there is a lack of studies using BSM to target property owners and managers who are essential to the urban transformation process.

To support planners and policy makers, base-line models of the existing stock have been used to assess the current energy performance of cities and districts to highlight areas where interventions should be prioritized on both the energy demand side [49] and the supply side [50]. Similarly, to assess the technical potential of specific technologies, specific measures have been investigated to evaluate the potential to reach environmental targets at an urban level using EEM [51], the potential development of renewables [37] and potential expansion and optimal layout of district heating networks [52]. While these models tend to focus on the technical potential, other models have developed dynamic scenarios to describe the change of the building-stock over time. These scenarios range from assumptions on a fixed rate of technology implementation to agent-based models or other decision models based on economic [53] or socio-economic feasibility [54].

2.3 Building-specific stock description

A building-specific stock description, sometimes referred to as a building-by-building description is what has been developed in this thesis. It treats each building individually rather than relying on using representative buildings and scaling factors. To do so increases the already high demand on data availability as detailed information about each individual building in the stock is needed. However, if issues relating to data availability can be overcome a building-specific stock description has several advantages. First, it provides a potential for a higher degree of accuracy, especially in evaluating potential changes to the existing building-stock. While a representative description can capture the average impact of a renovation measure for a representative building, a building-specific description allows for a fuller picture where the distribution of the impact across the building-stock can be assessed. This will provide better understanding and decision support in cases where a representative description can indicate whether a renovation measure is profitable while the building-specific description will highlight for how many buildings that is the case and what the distribution is. Ideally, this will allow for prioritizing renovation measures for individual buildings within a larger property portfolio. In combination with building-level measured energy use for validation, results can be aggregated arbitrarily where models using representative buildings are typically tied to geographic boundaries and scales where measured energy use is available. As such, it allows for targeting stakeholders such as property owners and managers. Another use of detailed building-by-building stock information is for statistical analysis which has been used to study investments in renovation based on ownership [55], to evaluate the performance gap post renovation [56], [57] and to assess the renovation rate of non-profit housing [58].

2.4 Energy modelling of building stocks

To estimate the energy use of a building, all energy end-uses are typically considered. These end-uses can be broadly divided into SH, hot water use, lighting and appliances as well as auxiliary energy for building operations such as fans and pumps. In addition, there are interdependencies where appliance and interior lighting will affect the heating demand. The energy demand can then be supplied by different energy carriers such as the electricity grid, a district heating system or in-situ generation. Energy modelling of buildings aim to quantify energy demand for different end-uses based on a set of input parameters. The level of detail of input parameters varies depending on purpose, data availability and assumptions made. Depending on the model, the input parameters may be on a macro scale (renovation rate, energy price, inflation) or on a micro scale (U-values, technical systems, building geometry). Quantifying energy use of larger building-stocks and assessing changes to the stock due to renovation and new construction can support decision making regarding energy supply, renovation incentives, the building code and to develop pathways to reach environmental goals.

The energy modelling techniques used to calculate the energy performance of building-stocks have been detailed in several papers [20], [30]–[32]. A wide range of approaches have been used to model the energy demand of building-stocks. Of particular importance is the choice of spatial and temporal resolution of the heat-balance as it impacts computational time. The spatial resolution relates to the number of thermal zones used to model a buildings energy demand. Further complexity can be added if these thermal zones are interconnected. Using a single zone to model the energy demand of a building comes with several limitations. First, using a single thermal zone only allows for using a single temperature set-point which makes it less suitable for buildings with a mixed use. Second, it is not possible to account for a simultaneous heating and cooling load. This is typically problematic for buildings with large solar gains as this may cause a simultaneous heating and cooling load in different parts of the building. In the case of a single-zone model, the heating and cooling load would cancel each other out. Temporal resolution deals with the time-step used in the energy demand calculation, typically using a yearly, monthly, hourly or an adaptive time-step. In addition to impacting the computational time, an increase in temporal resolution also warrants input data with a higher resolution regarding outdoor climate conditions, user-behaviour, solar gains, thermal mass and control schedules. Many urban building energy models focus on domestic buildings as the spatial and temporal resolution of the energy calculation has a lower impact than for commercial buildings with complex heating, ventilation and air-conditioning systems. Engineering-based bottom-up models put high requirements on level of detail and available data regarding the technical aspects of buildings. However, user behaviour has not gathered the same attention. A recent review of user behaviour in urban energy models [59] shows that standardized deterministic space-based occupant behaviour is often used in conjunction with an archetype based description of the stock. The few cases where a more nuanced view on user behaviour is used was observed for single-use districts, either office or residential buildings. Another approach to handle the complexities of user behaviour in urban energy models is the use of synthetic populations [60]. This would allow for dynamic assessment of internal gains and loads resulting in a more detailed energy use profile. This would be beneficial when studying a local energy system to be able to assess interventions in the stock that could help reduce peak loads or to better assess greenhouse-gas emission reductions.

To calibrate and validate urban building energy models, measured energy use on a stock level is often used. This becomes problematic when models are based on a representative description of the building-stock and as it is not possible to separate the validity of the energy modelling from the representative description being used. Similarly, using aggregated measured energy use to calibrate a representative stock description is problematic as the energy use for the different representative buildings is unknown. One of the most commonly cited obstacles for handling uncertainty in BSM is the lack of disaggregated measured energy use data [29], [35], [42], [46], [61].

2.5 Economic modelling of building stocks

In addition to modelling the energy performance of renovation measures for building stocks, the cost and profitability of renovation measures are sometimes evaluated. This has been done by assessing energy saving measures for the Danish housing stock [62], cost and cost-effectiveness of renovating the Swedish residential stock [20], cost of energy conservation and solar systems for existing multi-family buildings in Thessaloniki [37] and economic feasibility of deep renovation of the housing stock in Bologna [63]. The economic impact of EEM has been a subject of study in the past years [64]–[66]. Over the last decade, there have been several large EU funded projects focusing on EEM in the existing stock (see chapter 1). In most cases, these projects focused on assessing the viability and effect of EEM on individual buildings. In addition, there are several papers with a similar aim. The most profitable combination of insulation and glazing have been studied [67] and an optimization mode to define cost-effective measures in order to minimize energy use has been developed [68]. Moreover, several studies evaluated the economic viability and impact of EEM in the housing stock [69], [70], some of which used EPC for their assessments [71]–[74]. In general, economic modelling is typically done by evaluating the total cost of renovation in order to estimate market potential, the cost-effectiveness or profitability of measures to assess the techno-economical potential for renovating the building-stock or to assess the prospect of certain renovation measures. In addition, there are numerous case studies dealing with cost-effectiveness of renovation on a building level and this has been the key focus of many EU funded research projects. Assessment ranges from pay-back time to life-cycle costing methodologies. However, as most assessment is carried out for a specific building or for representative buildings, the distribution of cost-effectiveness for the entire building stock is unknown. There is also potential in using building-stock modelling to investigate policy driven incentives for renovation where a building-specific stock description would facilitate better and nuanced information on the impact of policy instruments or financial incentives. In addition to assessing the cost and cost-effectiveness of renovation, socio-economic costs can be calculated to assess affordability [75].

2.6 Environmental modelling of building stocks

Life-cycle assessment (LCA) is a commonly used tool to evaluate and assess the environmental impact from buildings. The use of LCA in building-stock modelling has recently become more common [76]. LCA has been used in BSM to investigate the impact of end-of-life stage of building stocks [77], to evaluate the environmental performance of façade renovations in an urban setting [78] and to assess the environmental impact of renovation measures on the European residential stock [79]. However, the LCA is often limited in terms of impact categories assessed. Most commonly, global warming potential (GWP) is evaluated [80]–[84]. Additional impact categories differ but often consists of indicators such as abiotic depletion potential (ADP) [43], [77] acidification and eutrophication potential (AP, EP) [43], [77], [85], [86], embodied energy (EE) [78], [87], photochemical ozone creation potential (POCP) [43], [77], [85], [86] and ozone depletion potential (ODP) [43], [77], [85], [86], [88]. In a few cases, more tailored impact categories such as particulate matter formation (PM10) [89] and embodied water [90] have been used. Furthermore, life-cycle stages generally follow those described in relevant standards [91] but differ as to which are included. Impacts relating to the operational phase is often included [39], [80], [82], [85], [89], [92] as well as impacts from manufacturing of components and materials [78], [85], [92]. Some studies have gone further and include environmental impacts from the building phase [84], [85], [92]. A few examples have been found where maintenance [93] as well as end-of-life [77] stages are included.

2.7 Visualization and communication

Results from BSM are commonly visualized on different scales depending on the purpose and stakeholder targeted. In general, visualizations are done on a country [53], regional [50] or city level [94], where models on a city level sometimes highlight a district or neighbourhood [25]. For larger scale visualization for a country or a region, results are commonly visualized in 2D for statistical zones [42] or zones defined by a common urban typology to fit the representative buildings used to describe the stock [95]. On an urban level, results are either visualized in 2D or 3D. 2D visualizations typically represent results for individual buildings or aggregated to areas, where studies of larger cities use areas. 3D, or 2.5D, visualizations of results typically use a district or neighbourhood. If solar energy potential is evaluated, 3D visualizations are done as the higher level of detail is needed [37], [96]. Parameters used in visualizations differ but commonly include energy use or power demand. Other studies use geometric information [42] or typologies [95], [97] in an attempt to draw conclusions by linking such parameters to energy use. To visualize the parametric value, colour coding is often used with a few exceptions where the areas are extruded and the height is used to indicate the parametric value. While many papers mention the ability of these models to provide decision support [98], it is often not explicitly stated which stakeholder the results are aimed at but rather broadly refers to supporting decision making in policy, urban planning and energy planning despite these models targeting specific cities. Furthermore, it is not stated how the spatiotemporal visualization of results are adapted to meet the requirement of the intended stakeholder.

2.8 Towards comprehensive building-stock modelling

Current frameworks or classifications for building-stock modelling are based on using representative buildings to model the energy performance of the stock. As data availability increases, the need for representative building descriptions is reduced. A shift from energy use to other indicators for assessing the current and future state of the stock is warranted as energy use in and of itself is rarely of interest. Rather, the environmental impact and especially the greenhouse-gas emissions from the building-stock should be the focal point moving forward in conjunction with economic modelling to assess the cost-effectiveness of renovation. As such, a wider framework for building-stock modelling is needed. In figure 1, a framework for a more comprehensive building-stock modelling is suggested relating to the spatial scale, the scope, the temporal scale and the assessment. The spatial scale indicates the geographic boundaries and is of importance as modelling the building-stock for an urban area or a country will impose different methodological choices. The scope relates to what part of the stock is being investigated. As has been previously mentioned, modelling requirements are vastly different for residential and non-residential buildings and the object of study will again dictate methodological choices. The temporal scale indicates whether the model considers the current state of the stock, a future state based on fixed trends or a future state based on dynamic evolution of the stock. The assessment defines what is to be studied, divided into environmental, economic and social aspects. The assessment stage also includes presenting and visualizing results appropriate for the intended stakeholders. Energy is not considered as a separate aspect of study, but rather as a prerequisite for a wider assessment. It should be noted that the ability of a building-stock model to account for social aspects is limited. However, there are aspects of affordability and movement patterns relating to renovation that can be studied. In the work presented in this thesis, an urban spatial scale is used to assess the environmental and economic impact of renovation measures applied to the MFB stock in the City of Gothenburg using static and dynamic scenarios. The intended stakeholder is the City of Gothenburg and the municipal housing company.

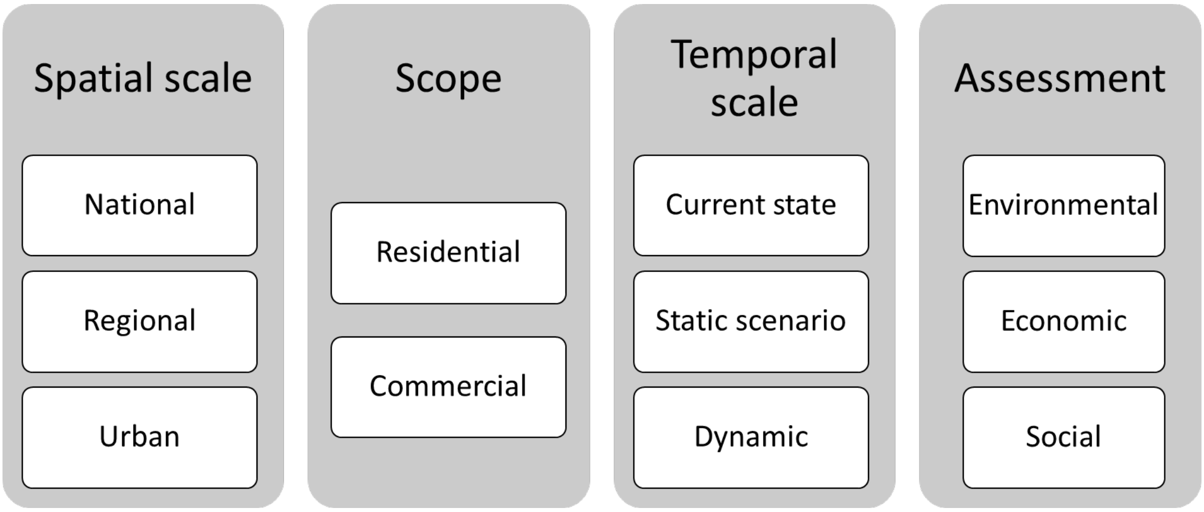

Figure 2 - Framework for comprehensive building-stock modelling.

3. Building-stock information

For this thesis, data were retrieved from the Swedish Mapping, Cadastral and Land Registration Authority, the Swedish Tax Agency, the National Board of Building, Housing and Planning and the City planning office of Gothenburg.

3.1 Data sources

Table 1 shows the building specific databases available for the City of Gothenburg, at what level of aggregation they are available, identifiers used and the information they contain most relevant for this work.

Table 1 - Building specific databases relevant for analysing the building stock, their level of aggregation and the identifier used to match them.

Database/Data owner	Aggregation level	N	Relevant information	Identifier
The property register (50A)	Building	153 000	Building type, construction year, value year and renovation year	Building ID, Property ID, mid-point coordinates
(42P)/Swedish Mapping, Cadastral and Land Registration Authority	Property	114 000	Property owner, % owned, income	Property ID
Gripen/National Board of Building, Housing and Planning	Building	6320	Energy use, HVAC systems, energy performance, heated floor area, number of stories, number of apartments	Building ID
Cadastral maps/City planning office	Building	178 000	2D, 3D (roofs)	Coordinates
Swedish Tax Agency	Taxation area	55	Taxation data	Coordinates

The Swedish Mapping, Cadastral and Land Registration Authority supplied parts of the property register for the City of Gothenburg. Specifically, they provided the building register (Table 50A) and the register of property owners (Table 42P). The building register contains information on building type, year of construction, year of renovation and value year. The value year is of particular interest as it serves several functions. It is calculated based on the year of construction, year of renovation and the economic extent of previous renovation measures and represents a calculated current state of the building. Hence, it can be used to assess the remaining lifetime of a building and to assess the cost of previous renovation activities. In addition, it is used to calculate the taxation value of a building. Table 2 and Equation 1 describes how the Swedish Tax Office requires a renovation to be registered as a change in value year depending on the cost of the renovation in comparison with new building cost [99]. The Swedish Tax Agency also provided taxation information relating to the location of buildings where the City of Gothenburg is divided into 55 value areas, which is used together with the value year and the rental income to calculate the taxation value of a building.

Table 2 - Calculation of value year based on renovation cost according to the Swedish Tax Office

Renovation cost	Calculation of value year
Less than 20 % of new building cost	No change in value year
20-70 % of new building cost	The value year is set based on Equation 1
More than 70 % of new building cost	The value year is set to the year of renovation

$$\frac{(Value\ year - Construction\ year)}{Renovation\ year - construction\ year} = \frac{Renovation\ cost}{New\ construction\ cost} \qquad (1)$$

The National Board of Housing, Building and Planning supplied all EPC for the City of Gothenburg. The Swedish EPC are unique since they not only contain valuable information on characteristics of the buildings such as heating, ventilation and cooling (HVAC) system but also measured energy use for SH, DHW and auxiliary electricity use. However, the Swedish EPC also suffers from some drawbacks. While the energy performance is given separately for SH, DHW and auxiliary electricity use, it is rarely measured as such but rather subdivided by the energy expert issuing the certificate. Similarly, HFA is rarely measured but rather derived based on the living area. In addition, updates are infrequent as the EPC is valid for 10 years unless major changes to the building are done. More information on the Swedish EPC and suggestions on how to overcome issues of deriving the HFA on a stock level have been done in previous work, see Paper I and [100].

From the City planning office, GIS shape files in 2D were provided for the footprints of the buildings, property boundaries as well as outlines of two different levels of areas, so-called base areas which are the lowest level statistical information is presented on and primary areas which are used for administrative purposes. Primary areas typically consist of a dozen base areas.

3.2 Combining datasets

The datasets are combined based on the identifiers as follows. The EPC are connected to the property register using the building ID (50A) and the register of property owners is connected to the building register using the property ID. Coordinates is then used to connect these datasets to each individual footprint in the 2D-map of Gothenburg. As not all EPC contain the correct identifier, 5901 of the 6320 EPC are spatially linked to footprints. Similar work has been carried out on a national level using the address to spatially link the databases [101].

4. Building-specific stock description and modelling framework

To allow for modelling and assessing energy performance, environmental impact and cost-effectiveness of renovating the building-stock, available building-stock information presented in Table 2 is condensed to a description of the building-stock where the technical parameters are characterized. Since all information necessary for energy, environmental and economic modelling are not known directly from the information available, assumptions are made using secondary sources in conjunction with the available information. Further information on the methodology and assumptions made can be found in Paper I, III and IV. In Table 3, the reduced set of data used to describe the building stock of the City of Gothenburg is shown.

Table 3 - Reduced set of data used to describe the MFB stock of Gothenburg

Database	Source	Information
EPC	National board of building, housing and planning	HVAC systems, number of stories, attachment to other buildings, measured energy use, number of staircases
2D-map of Gothenburg	City planning office	Footprint, length and orientation of external walls
Building register	Swedish mapping, cadastral and land registration authority	Year of construction, year of renovation, value year, owner, rental income

4.1 Determining the U-value

To estimate a likely U-value, historic building regulations and architectural history books are used. The classification follows the most common method of dividing buildings into different age-type categories. Using an architectural history book [102] containing 32 different MFB types spanning a period of 120 years (1880-2000) together with historic building regulations, average and component specific U-values for an age-type classification have been developed. As not all of the 32 building types listed in the book are unique considering the type but rather construction methods or other architectural features, they are grouped to form overarching categories. In total they are divided into seven different categories and 27 time periods. As all building types do not exist for all time periods the total number is reduced. Furthermore, for several building types the U-value does not change significantly, or at all, over several time periods. In Paper I, average U-values were applied while paper III and IV uses component specific U-values. In paper III, U-values are part of the calibration to better capture the current state of the stock for older buildings were components likely have been replaced.

U-values for the age-type classification are derived from structural drawings provided in [102]. For time periods where there is no knowledge on the structural composition, the U-value is instead taken from the building regulations. National building regulations for Sweden have existed since 1946 with demands connected to the U-value of a building. Due to different climate conditions, regulations have been differentiated by climate zones. All values given in this section refers the City of Gothenburg. From 1946 to 1988, demands on U-values were set at a component level and differentiated between light and heavy constructions, see Table 5. From 1989 to 2006 demand on U-values was instead given as an average U-value for the entire building and from 2007 and onward the regulations have been based on an average U-value in combination with measured energy use, see table 4. The building code demands an energy performance of a building based on SH, DHW and auxiliary electricity use. As the way demands are set has changed, it is difficult to make a comparison between buildings built before 1989 and those built later as the shape factor, adjacency to other buildings and window to wall area ratio would impact the results.

Table 4 - Demands on average U-value and measured energy use for space heating, domestic hot water and non-domestic electricity use.

Building code	Valid	Average U-value [W/m²,k]	Measured energy use (for buildings with electric heating) [kWh/m²,y]
NR*	1989-1994	$0.18 + 0.95 * Aw/Aenv$	
BBR* 1-8	1995-2002	$0.18 + 0.95 * Aw/Aenv$	
BBR 9-11	2003-2006	$0.18 + 0.95 * Aw/Aenv$	
BBR 12-15	2007-2008	0.5	110 (75)
BBR 16-18	2009-2011	0.5	110 (55)
BBR 19-21	2012-2014	0.4	90 (55)

* NR stands for Nybyggnadsregler and BBR stands for Boverkets byggregler, English translation: New construction rules and the national board of building, housing and planning's construction rules. Aw denotes window area and Aenv denotes envelope area.

Table 5 - Demands on U-value for building components in the Swedish building code from 1946-1988

Building code (unit)	Valid	Heavy brick construction	Light brick construction	Other stone material	Wood	Heavy roof construction	Wooden roof construction	Floo
BABS* 46 (kcal/m², ch)	1946-1950	1.0	0.9	0.8	0.6	0.6	0.5	0.4
BABS 50 (kcal/m², ch)	1951-1960	1.05	0.95	0.85	0.65	0.55	0.45	0.45
BABS 60 (kcal/m², ch)	1961-1967	1.0	1.0	0.8	0.5	0.5	0.4	0.4
SBN* 67 (kcal/m², ch)	1968-1975	1.1	1.1	0.8	0.5	0.5	0.4	0.4
SBN 75 (W/m²,k)	1976-1981	0.3	0.3	0.3	0.3	0.2	0.2	0.3
SBN 80 (W/m²,k)	1982-1988	0.3	0.3	0.3	0.3	0.2	0.2	0.2

* BABS stands for Byggnadsstadgan and SBN stands for Svensk byggnorm, English translation: Building code and

4.2 Modelling of energy use, environmental impact and cost-effectiveness

The building-stock description is used to model the energy performance (Paper I, III and IV), the environmental impact of renovation measures (Paper IV) and the cost-effectiveness of deep renovation (Paper III). In paper I and IV, the existing building-stock energy model ECCABS [20] have been adapted to incorporate spatial information. The model is dynamic, using an adaptive time-step method and treats each building as a single zone. In paper III, an existing building-stock energy models including calibration routine has been used [21]. The model uses a single-zone monthly steady-state method to calculate the energy demand for space heating. For more information on the calibration routine used, see paper III and [21]. On a stock level, both energy models achieve a similar level of accuracy using the same building-stock description while the calibration in the steady-state model provide more accurate results on a building level. The accuracy of the ECCABS model on an urban scale is similar to previous studies on a national scale [34].

The LCA is carried out using the software SimaPro V8.0.5.13 and the database Ecoinvent V3.1. Global data is used in cases where European data is not available. 15 of the ReCIPe [22] V1.12 mid-point categories is used to evaluate the environmental impact of all construction related impact while interior measures for energy efficient lightning and appliances are omitted due to lack of available data. The material use for construction measures is based on a library of common renovation measures on the Swedish market [103], [104]. Several options are considered for measures relating to façade insulation and windows. Emissions from energy use is based on average values for the local energy company for district heating and the Swedish market mix for electricity [105]. Using consequential data is not considered as it is not relevant with regards to local targets being evaluated. The assessment is carried out in accordance with relevant standards [91], [106], using life-cycle stages A1-A3 and B6 with the functional unit being the 5901 MFB used in the assessment.

In order to assess the cost-effectiveness of deep renovation, EAC is used. EAC is calculated for each component and summed up for each building (Eq. 2). The minimum technical lifetime of the component is used as the lifetime of the investment and a discount rate of 4% is used. The EAC does not factor in a change in maintenance cost following renovation.

$$EAC_i = C_i \frac{r}{1-(1+r)^{-t_i}} \text{ (Eq. 2)}$$

EAC: *Equivalent annual costs for a component in [EUR/y]*
C_i: *Investment costs of EEM for a component in [EUR]*
r: *Discount rate*
t_i: *lifetime of component i [y]*

4.3 Assessing changes to the building-stock

To assess changes to the building-stock, three different methods have been used. In paper III, a step change was used in order to evaluate a deep renovation package for the municipal housing company. In paper II, a static scenario was used to assess the implications of current levels of EEM coupled with rate of new construction based on planning documents in order to evaluate the change in energy demand until 2035. In paper IV, two dynamic scenarios were used based on cost-effectiveness of renovation. The two dynamic scenarios have different driving forces as well as two levels of limitations regarding yearly investment cost and maximum share of the stock to be renovated [107]. Scenario 1 assumes building components will be updated at the end of their lifetime, regardless of the cost-effectiveness of the ESM. Scenario 2 considers that ESMs are implemented if they are cost-effective, with the renovation taking place at the end of the lifetime of the building component. The technical lifetime of components is based on EN 15459. Cost-effectiveness of individual measures is evaluated using EAC based on the method described in [108]. Furthermore, renovation packages are prioritized if both individual renovation measure and package is cost-effective. The two scenarios are further divided based on limiting factors based on maximum yearly total HFA being renovated (m^2_{HFA}/year) and as yearly maximum annual investment capacity per HFA [€/($m^2_{HFA,}$ year)]. The limitations are not applied on a building level but based on groups of property owners; the municipal housing company, private housing cooperatives and private property owners. Two levels of limiting factors are used. Limitation A is based on average investments in energy efficiency measures by the municipality housing company (7.5€/m^2 HFA) [109] and on the national average renovation rate of roughly 1% [17]. Limitation B uses a higher investment capacity of 10.0€/m^2 HFA and allows for 2.5 % of HFA to be renovated yearly.

The renovation measures applied for assessing deep renovation in the municipal housing stock and evaluating the environmental impact of continuing current renovation practices for the MFB stock are described in detail in paper III and IV respectively.

4.4 Spatial visualisation

Throughout this work, several different spatial visualizations have been used depending on the stakeholder and parameters being evaluated. Yearly energy use has been spatially visualized using different spatial resolutions and units. Results have been presented aggregated to administrative districts such as base areas (935 in Gothenburg) or primary areas (96 in Gothenburg) as well as shown on a building level. Cost-effectiveness have been aggregated to value areas (55 in Gothenburg) or shown on a building level. Environmental impact has not been shown spatially as the aim, and to a certain extent the accuracy, does not warrant such visualizations.

5. Results

This chapter starts by presenting results at different levels of aggregation based on the building-stock information that has previously been presented followed by assessing the impact of renovating the building-stock considering energy use, environmental impact and cost-effectiveness. This section contains information related to the entire MFB stock as well as more in-depth information and results related to the municipal housing stock. The effects of renovating the existing stock is a summary based on results in paper II-IV.

5.1 Current state of the stock

The City of Gothenburg was founded in 1621 and is the second largest city in Sweden with about 550 000 inhabitants. The urban housing stock of MFB grew outwards until mid-1970s before densification started. The MFB-stock and its spatial distribution is shown in figure 3.

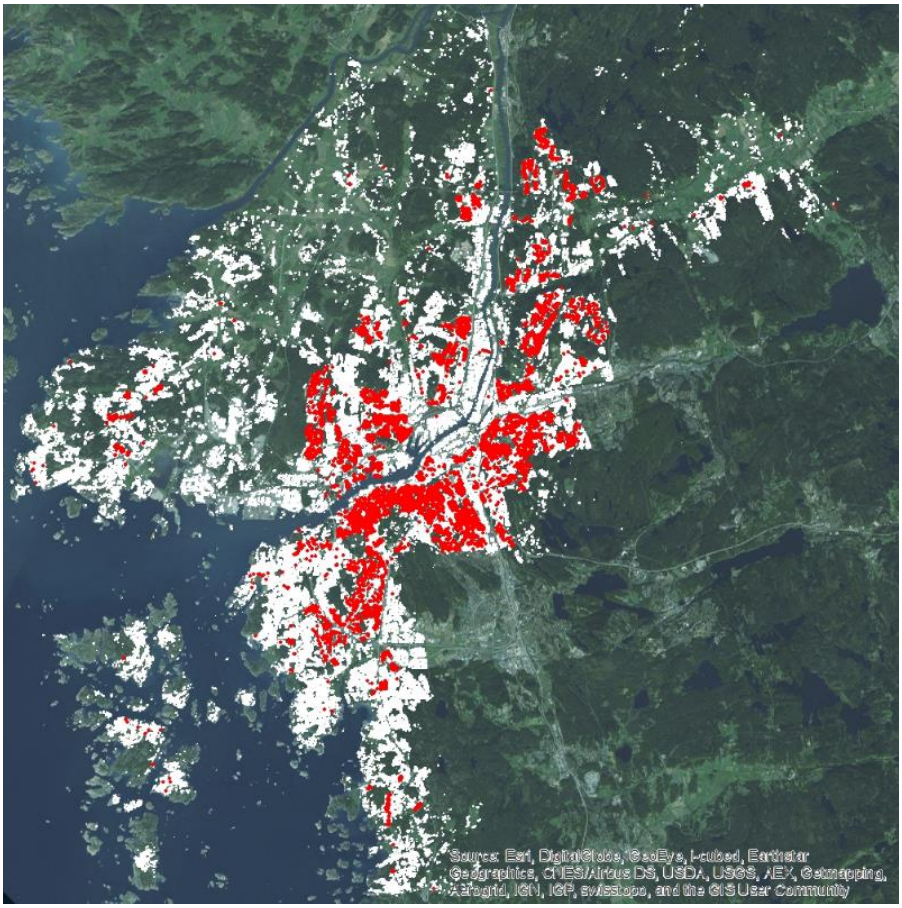
Source: Esri, DigitalGlobe, GeoEye, i-cubed, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Figure 3 - Spatial distribution of multi-family buildings in the City of Gothenburg shown in red.

Figure 4 shows the distribution of HFA in the MFB stock divided by property owner or owner type. The municipality housing company owns about a third (36%) of the stock with another third (33%) being private housing cooperatives. The last third of the stock is owned by private owners, individuals, foundations and others where the last category includes estates and non-profit organisations.

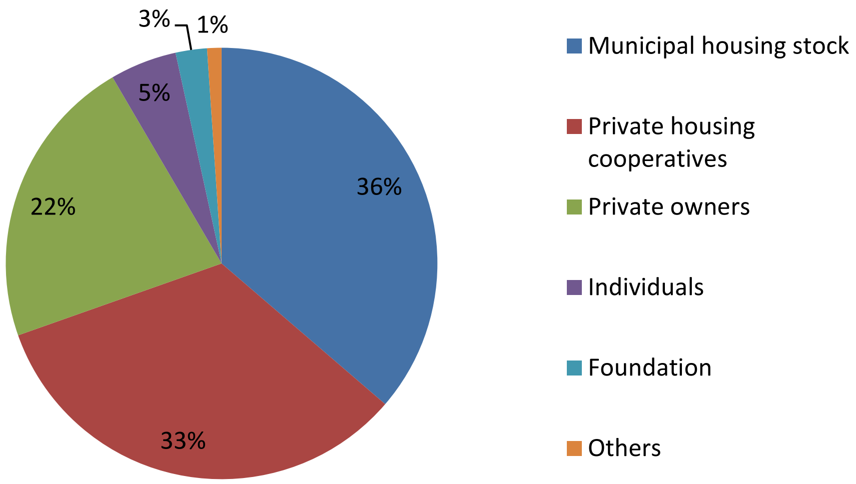

Figure 4 - Percentage of total m² of HFA in the stock divided by property owner and owner type.

The technical characteristics for the building-stock of the municipal housing company is shown in Figure 5-9 where the U-value for different components as well as the ventilation system is described. Buildings are grouped per decade and U-vales are given in ranges. The U-values are based on the calibrated building-stock description used in paper III while the ventilation systems are based on data from the EPC. As can be seen, the distribution of U-values of walls and windows within the different age categories is large, especially so for older parts of the building stock which has gone through renovations to varying degree. This supports the view that year of construction is not an ideal indicator of energy performance. The distribution of U-values for the roof follow a similar pattern, although the gap between buildings with well insulated roofs and those without is smaller. This is even more pronounced regarding U-values for the floor, as the relative difference becomes smaller. This is partly due to the insulating effect of the ground. It is also interesting to note that natural ventilation is more or less absent in the stock from the 1960s and onwards and that a central exhaust system is the dominant ventilation system used. The widespread use of a central exhaust system limits the renovation options as a central supply- and exhaust-air system with heat-recovery will require considerable changes to the buildings.

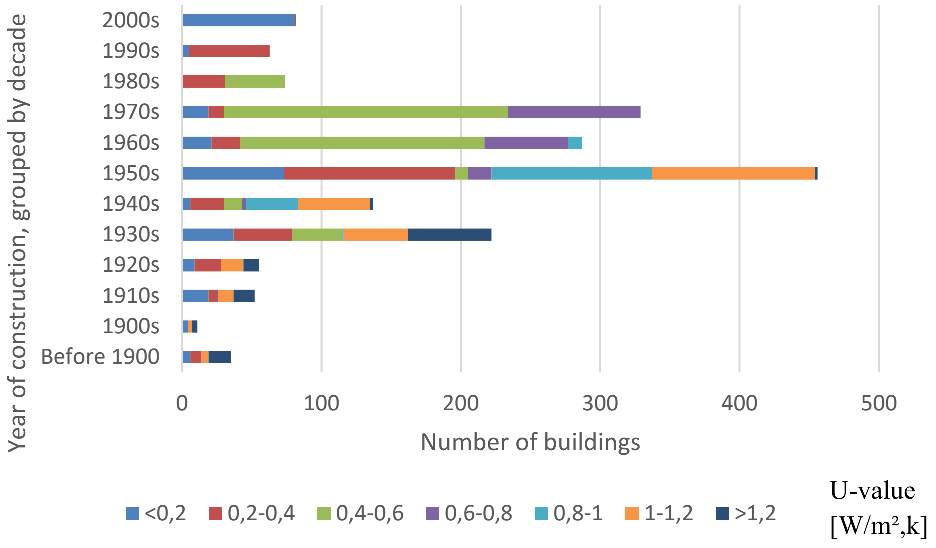

Figure 5 - Distribution of U-value of walls for buildings in the municipal housing stock grouped by year of construction.

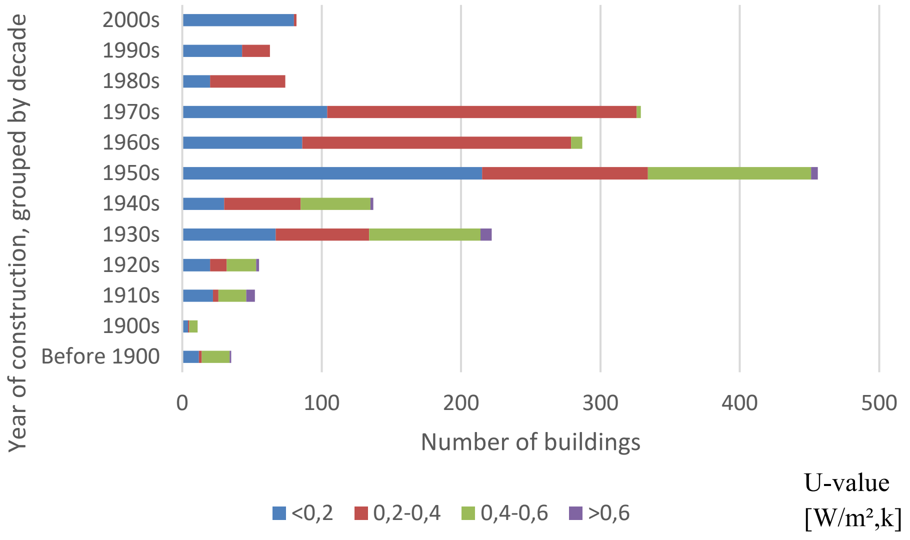

Figure 6 - Distribution of U-value of roofs for buildings in the municipal housing stock grouped by year of construction.

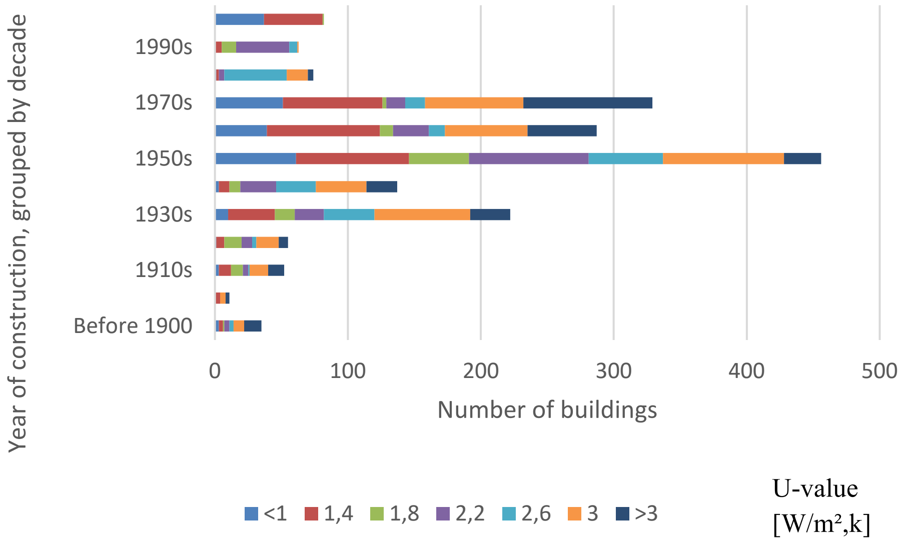

Figure 7 - Distribution of U-value of windows for buildings in the municipal housing stock grouped by year of construction.

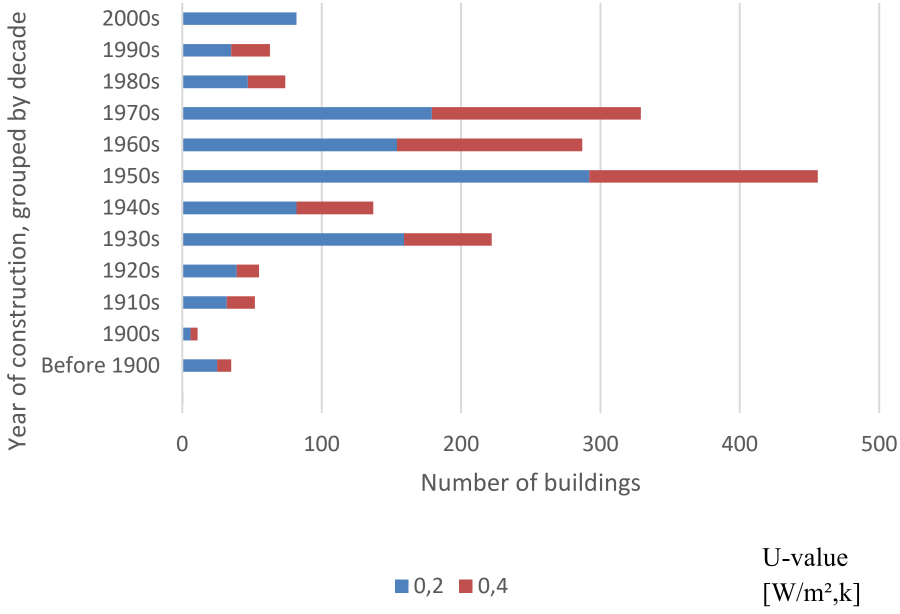

Figure 8 - Distribution of U-value of floors for buildings in the municipal housing stock grouped by year of construction.

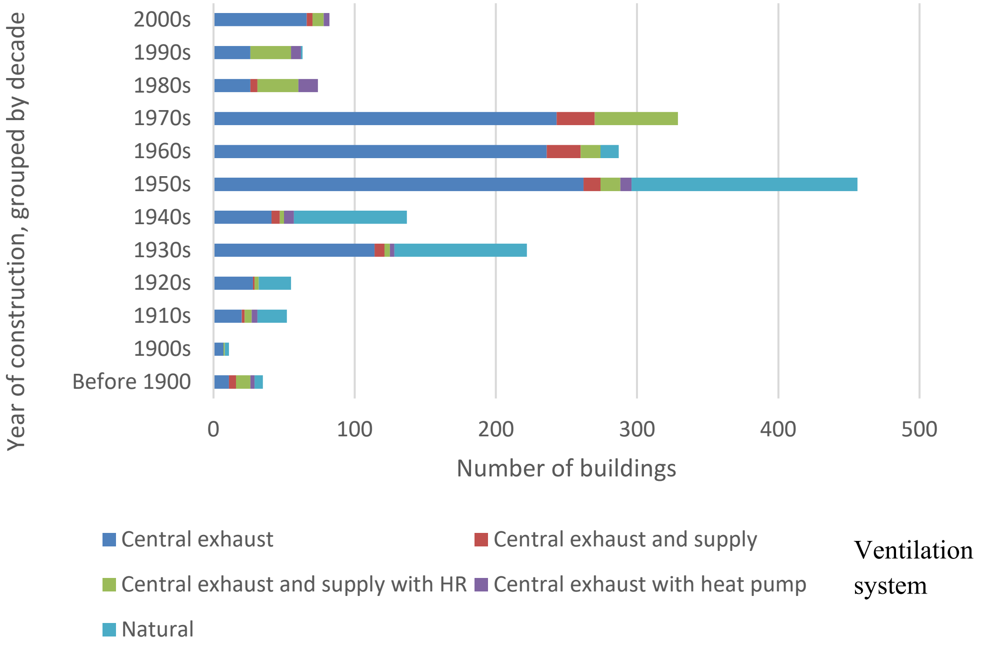

Figure 9 - Distribution of ventilation systems for buildings in the municipal housing stock grouped by year of construction.

Figure 10 shows the measured energy use for SH, DHW and auxiliary electricity use for the MFB stock in Gothenburg. It is divided into age-groups with their associated share of the total HFA. As can be seen, the energy performance is quite even for the stock up until 1980. The sharp decline in energy use in the building-stock occurring during the 1980s can be explained by more stringent demands on U-values being introduced in 1975 as shown in chapter 4. Buildings from 1960-1975 are of particular importance as they consititute the largest part of the stock (42 % of all HFA) and have the highest average energy use (146 kWh/m²,y). Unlike buildings from earlier time-periods, these buildings have to a large extent never been renovated and are nearing the end of their service-life, requiring renovation in the coming decade. If substantial reductions in energy demand is to be achieved, EEM needs to be implemented in this part of the stock.

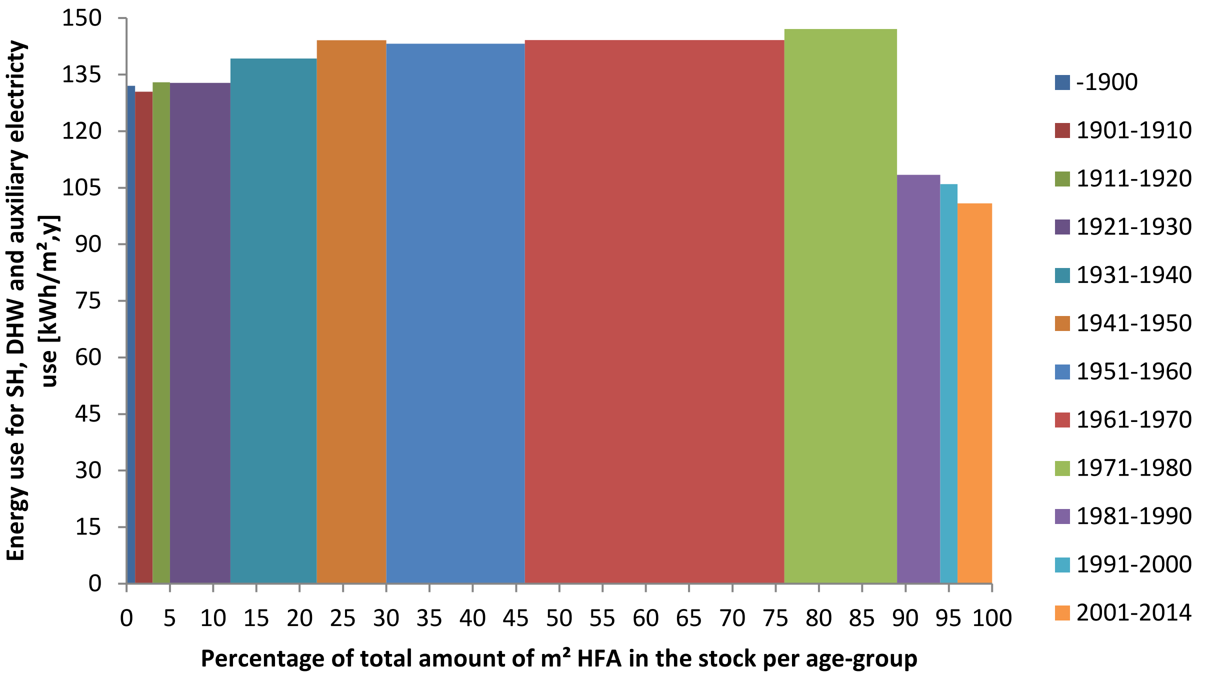

Figure 10 - Measured energy performance for different age-groups of the Gothenburg MFB stock and their respective share of the total stock.

5.2 Renovating the existing stock

This section details the impact of renovating the MFB stock relating to energy use, environmental impact and cost-effectiveness. Environmental impact is assessed for the entire stock while cost-effectiveness is evaluated for the municipal housing stock. Energy use reductions are assessed for both the stock in its entirety as well as the municipal housing stock. The results summarize the findings in paper II-IV.

Energy use

In Figure 11, energy use reductions for the MFB stock until 2050 are shown for two scenarios and two levels of limiting factors. Scenarios are differentiated based on the renovation logic while limiting factors use two different levels for yearly investment capacity and maximum yearly floor area possible to renovate. For a thorough description of the renovation logic for the scenarios as well as the limiting factors this is provided in chapter 4 and paper IV. Energy use includes SH, DHW and all electricity use (including household electricity use). The total energy use is 3009 GWh/year for the current state of the stock. Changes in energy use over time are small apart from for scenario 1B where a 23 % reduction in yearly energy use by 2050 is achieved. Measures regarding energy efficient lighting and appliances reduce electricity use whilst increasing SH demand. As such, there is a shift from electricity use to district heating, particularly for scenario 2 where energy savings to a large extent is a result of reduced electricity use. As such, while the total yearly energy use is decreased by 0.7 % for scenario 2B and 4.1 % for scenario 2B, the yearly energy use for district heating increases compared to current levels.

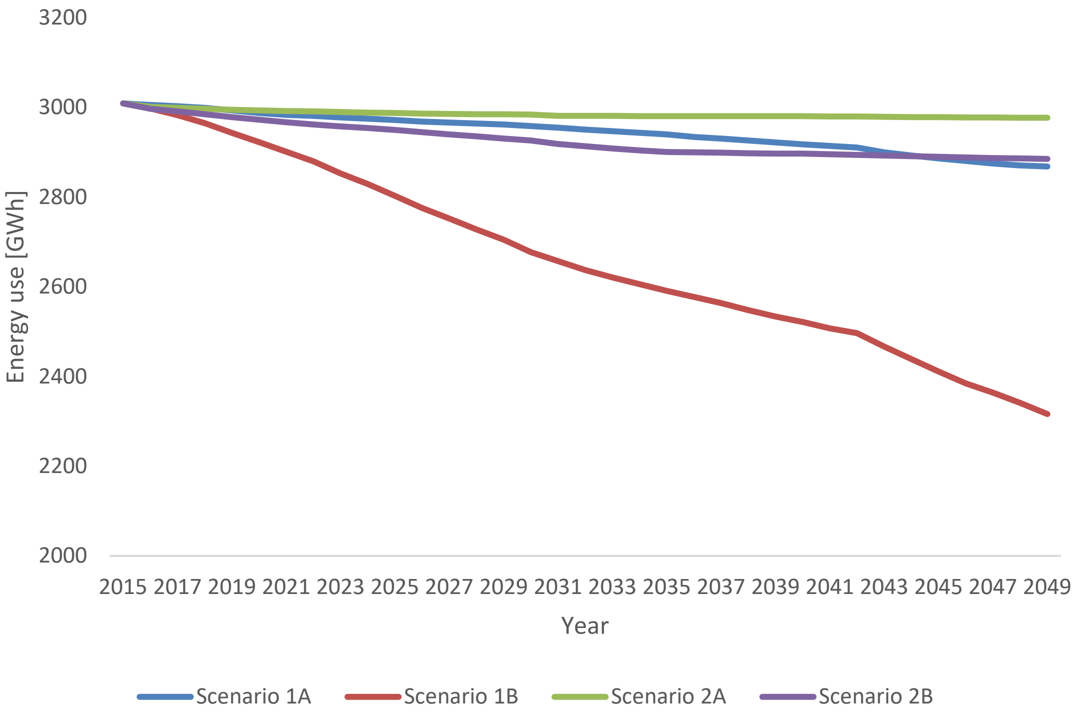

Figure 11 - Yearly energy use in the MFB stock until 2050 under different scenarios and limiting factors.

Figure 12 shows the energy use for SH and DHW until 2035 for the entire MFB stock based on current implementation rate of EEM as well as accounting for planned new construction. As can be seen, any energy use reduction achieved by renovating the existing stock is offset by increased energy use in new construction. This indicates that current efforts to reduce greenhouse-gas emissions in the existing MFB stock will not be sufficient to reach targets set by the municipality. Hence, to reach local climate goals, substantial improvements on the energy supply side to reduce emissions are needed based on the assumed development scenario.

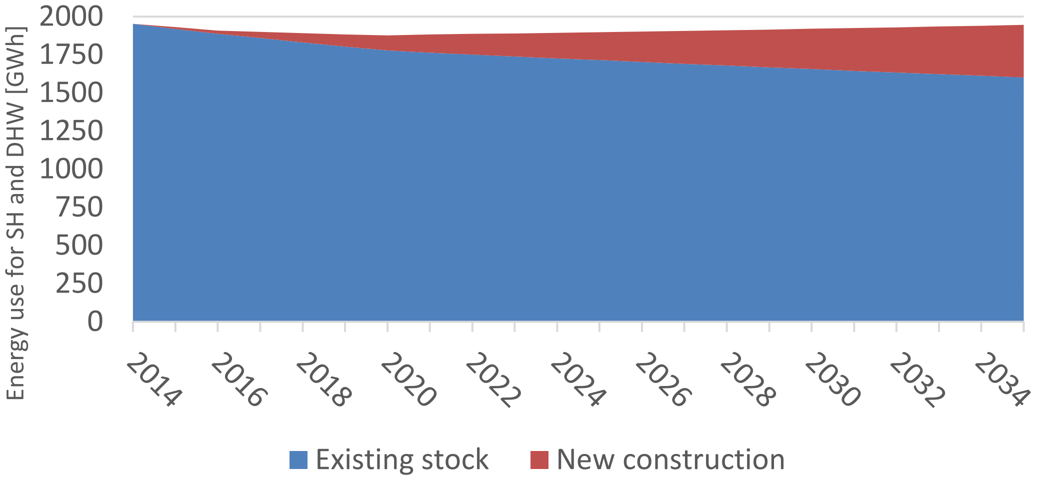

Figure 12 – Yearly energy use for SH and DHW in the current and future MFB stock.

Figure 13 shows the final energy use for the stock of the municipal housing company after deep renovation grouped by year of construction. The deep renovation applied results in average final energy use reduction by 51%, to 55 kWh/m^2 year by applying the renovation measure to all buildings. The difference in final energy use after deep renovation does not vary considerably between the different age groups.

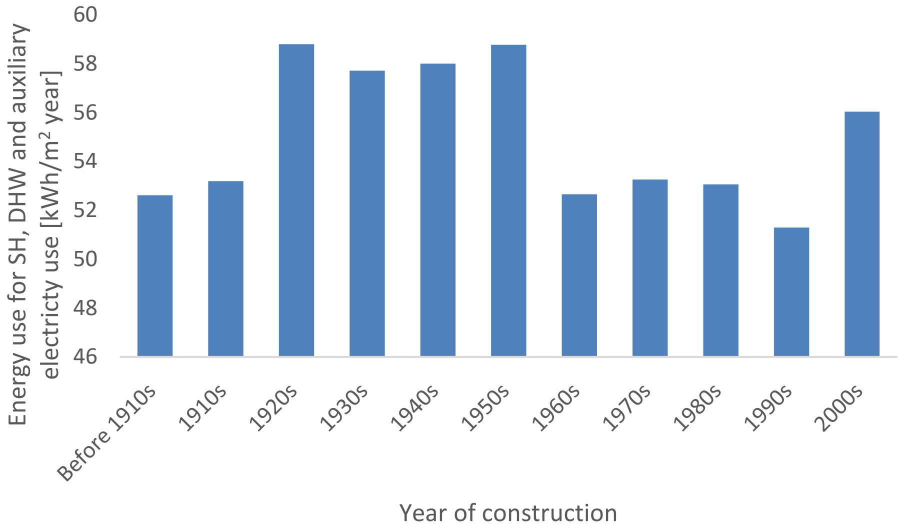

Figure 13 – Average final energy use grouped by year of construction for the stock of the municipal housing company after deep renovation.

Environmental impact

In figure 14, the yearly greenhouse-gas emissions based on energy use reduction in Figure 12 are shown for the MFB stock. Current yearly greenhouse-gas emissions from the MFB stock is 204 ktonCO$_2$eq/year. The reduction in yearly emissions follow the same pattern as energy use, but with a larger total reduction. This is due to the shift from electricity use to district heating. This can be exemplified by scenario 1B where the reduction in yearly energy use is 23% while reductions in yearly greenhouse-gas emissions increases to 31% until 2050. It should be noted that no changes to current emission levels are assumed in order to indicate to what extent renovating the building-stock can help meet local climate goals.

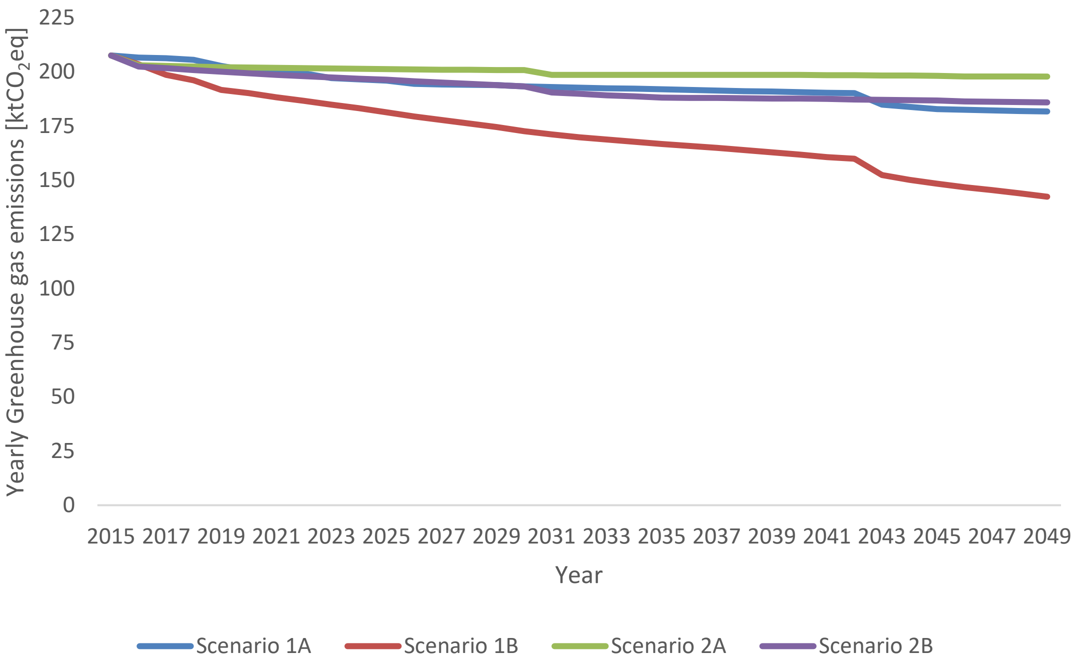

Figure 14 - Yearly greenhouse-gas emissions in the MFB stock until 2050 under different scenarios and limiting factors.

In figure 15, the environmental impact of all construction related measures for scenario 2 until 2050 is given using 15 of the ReCIPe mid-point categories. To indicate trade-offs, impact categories have been normalised to show the relative impact of individual measures. As results are based on the total uptake of measures across the MFB stock until 2050 it can be used to compare total relative impact but cannot be used to compare individual measures. As opposed to figure 11 and 14, results are only given for scenario 2A as scenario 1 contains a high degree of interior measures relating to lighting and appliances not accounted for in the LCA and there is little difference in the relative impact between scenario 2A and 2B. Installation of PV panels dominates most impact categories , accounting for more than 50% of the environmental impact for nine out of 15 impact categories. Due to the use of package solutions, measures affecting the U-value are more comparable. Replacement of windows has the largest relative environmental impact followed by insulation of facades. Roof insulation has a consistently low environmental impact around 3-5% while insulation of floor or basement has an environmental impact ranging from 3-10% with the exception for marine eutrophication where it is responsible for 64% of the environmental impact for scenario 2A. Upgrade of ventilation system with heat recovery have a relatively low environmental impact across all categories, peaking at 10% for metal depletion in scenario 2B.

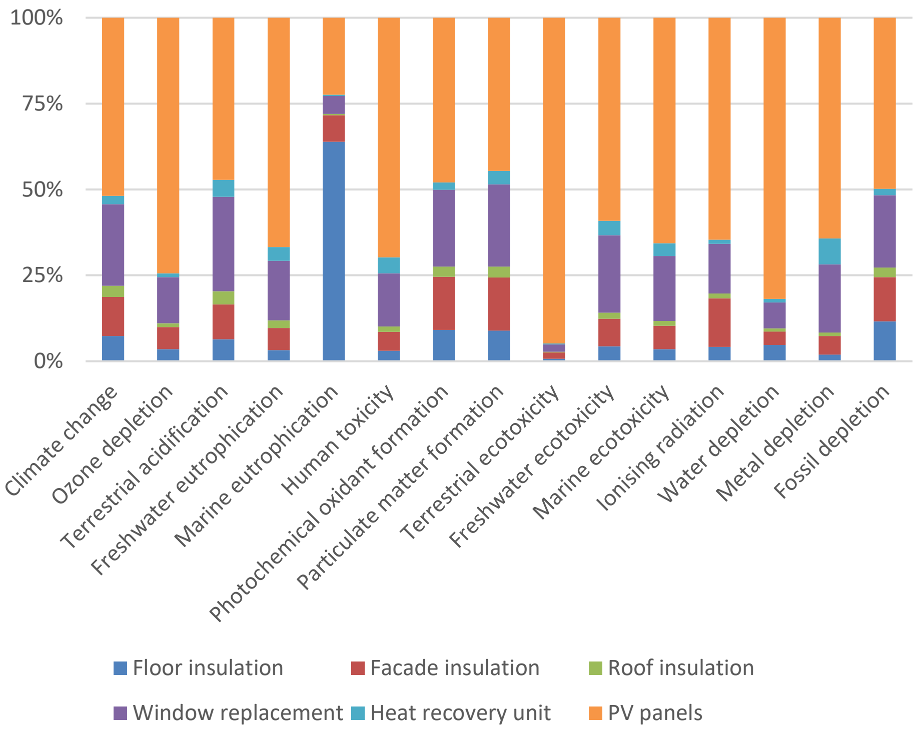

Figure 15 - Relative environmental impact of construction related renovation measures implemented until 2050 for 15 mid-point coordinates under scenario 2A.

In figure 16, the cumulative greenhouse-gas emission savings until 2050 for scenario 2A and 2B accounting for changes in energy use and embodied impacts from material use is shown as ktCO$_2$eq. As the main difference between the two limiting factors are the total uptake of measures rather than what measures are applied, it serves as an indication of to what extent renovation is beneficial. In both cases, a decreased climate impact is observed with greenhouse-gas emissions saved corresponding to one years' worth of current emission levels. However, the increased number of buildings being renovated in scenario 2B only marginally increases greenhouse-gas emissions saved, from 201 to 211 ktCO$_2$eq. Hence, increasing the renovation rate and implementing similar renovation measures for more buildings will have a marginal climate impact and trade-offs relating to other impact categories should be considered.

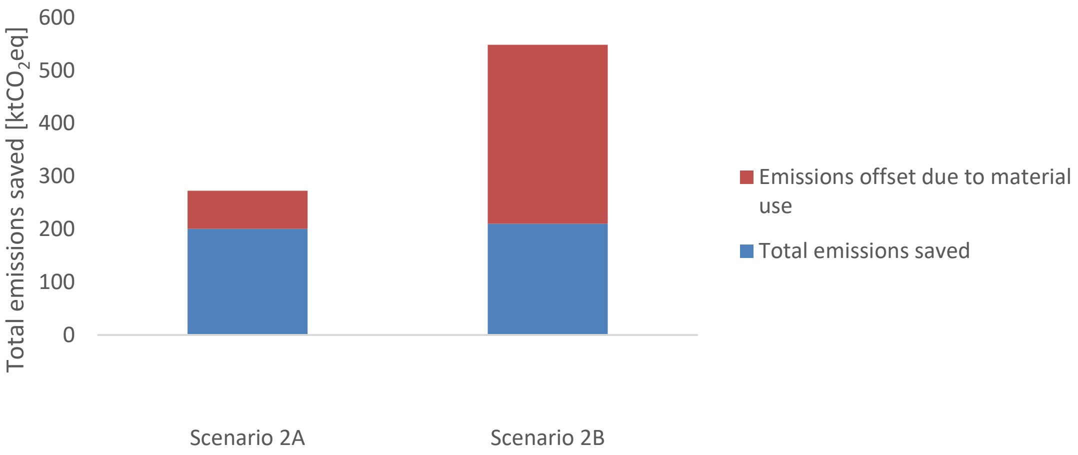

Figure 16 – Cumulative climate impact due to energy savings until 2050 and material use for the EEM for scenario 2.

Cost-effectiveness

In Figure 17, cost-effectiveness is evaluated by showing yearly energy cost savings achieved by deep renovation of the municipal housing stock as a share of EAC. As previously shown, the distribution in U-values is large within the portfolio and as such, cost-effectiveness of deep renovation varies greatly. In addition to a difference in technical characteristics, the compactness plays a major role as well as the fact that certain reinstatement costs scale with number of apartments rather than building size. Annual cost savings account for 21 % of EAC across the municipal housing stock while individual buildings show annual energy cost savings offsetting over 50 % of the annualised cost of deep renovation. As the deep renovation package used is not profitable for any building, additional gains are needed through adapting the renovation measures for individual buildings, achieving lower maintenance cost after renovation or by increasing rent levels.

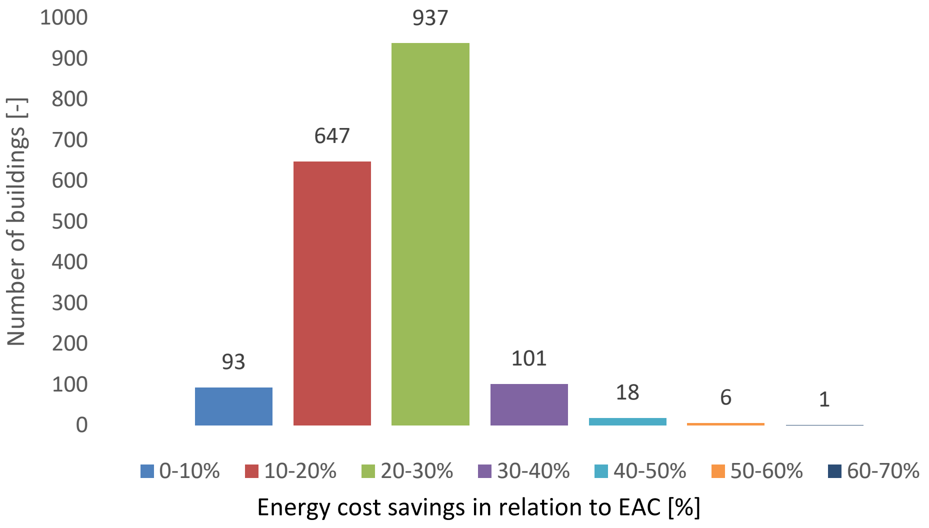

Figure 17 – Number of buildings grouped by yearly energy cost savings in relation to equivalent annual cost [%].

Figure 18, yearly energy cost savings as a share of EAC is spatially visualized for a specific value area. Results are presented for both the value area as indicated by the background colour as well as for individual buildings. As can be seen, the cost-effectiveness of deep renovation of individual buildings within the area varies greatly. This highlights one of the pitfalls of aggregating results to areas or zones as the distribution in results for individual buildings can be large.

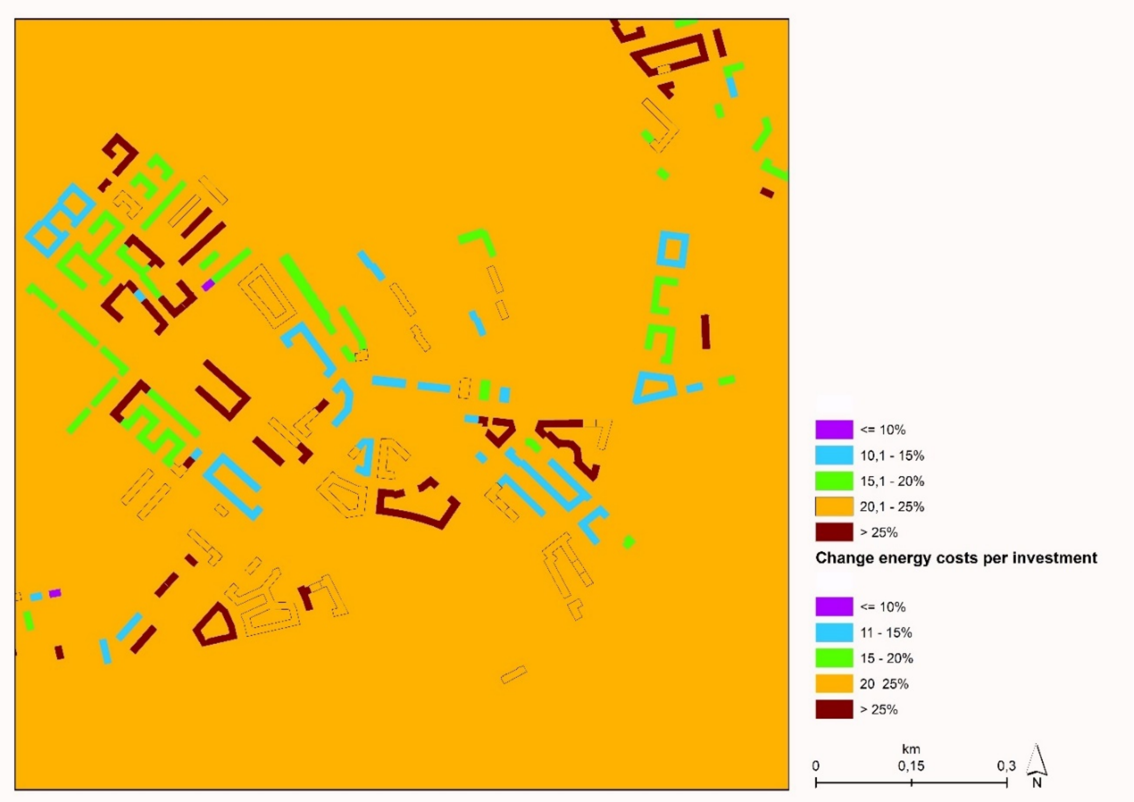

Figure 18 - Yearly energy cost savings in relation to equivalent annual cost. Background colour shows average yearly energy cost savings in relation to equivalent annual cost for the value area.

6. Discussion and conclusions

The aim of this thesis has been to evaluate the renovation potential of the existing building-stock on an urban level by expanding on methods used in building-stock modelling to enable assessment of environmental impact and cost-effectiveness, to explore the potential for visualizing and communicating results using GIS and in particular to target property owners. In doing so, a methodology for describing building-stocks on a building-by-building basis has been developed and used in assessing environmental impacts of renovating the MFB stock in the City of Gothenburg as well as the cost-effectiveness of deep renovation of the municipal housing stock. The building-specific description in combination with the possibility to validate results on a building level using measured energy use from the EPC allows for results to be presented and communicated at any level of spatial aggregation. This has enabled exploration of possible ways to visualize and communicate results to different stakeholders involved in urban transformation. As such, the research questions posed have been answered and the findings are summarized below.

RQ1 – What is the potential for a building-stock description where each building is treated individually?

As shown in paper I, III and IV it is possible to create a building-stock description where each building is treated individually. The methodology has expanded from paper I where average U-values for buildings was used to a component level differentiation in paper IV which was needed in order to assess renovation options. In paper III, the issue of calibrating the description on a building level was dealt with, resulting in increased accuracy on a building level. By creating a building-specific stock description, a wider range of stakeholders could be targeted and a more nuanced understanding of the current state of the building stock achieved as well as a differentiated view on the impact of renovation measures.

RQ2 – How can GIS be used with a building-specific stock description to visualize and communicate results for a wider range of stakeholders, including property owners?

In paper II, different spatiotemporal resolutions were explored in visualizing results to communicate the information regarding the current state and possible future development of the MFB stock to specific stakeholders. In paper III and IV, spatial visualizations and aggregation of results where done with specific stakeholders in mind. Information relating to energy use, environmental performance and cost-effectiveness have been visualized using several scales and metrics to target specific stakeholders. The visualizations used here should be seen as a first step and further work is needed in assessing what metrics and level of aggregation is suitable depending on the intended stakeholder. Additionally, for many stakeholders the housing stock is only of partial interest as part of a larger system.

RQ3 – How can the financial viability of (deep) renovation be assessed across a building portfolio?

As shown in paper III, assessing and differentiating cost-effectiveness of deep renovation within a building portfolio using EAC and change in assessed building value is possible. Deep renovation is certainly not suitable for all buildings in the portfolio, neither from an energy nor cost-effectiveness point of view. Rather, the results serve as a first step to prioritize buildings and areas or neighbourhoods to differentiate where deep renovation is suitable within a large building portfolio. Further detailed assessment of buildings suitable for deep renovation is needed as well as tailoring of the renovation measures to each building. Ideally, the financial viability should be assessed using the yield by incorporating maintenance costs.

RQ4 – What are the environmental impacts of current renovation trends in an urban building-stock?

In paper IV, the environmental impact of renovating the existing MFB stock in the City of Gothenburg until 2050 using business-as-usual scenarios has been done. The use of business-as-usual scenarios highlights the limited impact current renovation rate and measures will have and acts as a counterbalance to estimations of technical potential. As the measures used are conservative, a more aggressive renovation strategy could be investigated as the marginal costs are likely to be small. However, renovation measures with a larger energy reduction potential may prove to be inefficient or detrimental in reducing greenhouse-gas emissions due to the relatively low emissions from district heating while negatively affecting other environmental impact categories. In addition, the possibility of including further life-cycle stages in the LCA as well as assessing local impacts using national data could be investigated. Depending on the intended stakeholder, using select end-point indicators or tailored weightings should be considered.

This thesis with appended papers has shown that available data sources can be used to describe the characteristics of the stock on a building level while considering the location and context. Building attributes such as year of construction, value year and owner from the Swedish Property register, spatial data provided by the City planning office of Gothenburg as well as EPC from the national board of housing, building and planning can provide detailed and valuable information to policy makers, urban planners and property owners. Being able to target property owners is especially important as this is something that has been largely missing from previous research. In this work, the potential for renovating the MFB stock in the City of Gothenburg has been assessed. The need for renovation provides an opportunity for achieving considerable reductions in energy demand and associated emissions of green-house gases. This work gives an overview of the existing situation and provides a thorough assessment of the potentials and impacts associated with renovating the existing MFB stock. However, the issue of profitability in renovation persists and the potential reduction in greenhouse-gases is limited.

Limitations

There are still limitations regarding understanding the current state of the stock. Information regarding past renovation activities is limited and the level of maintenance is unknown. Furthermore, the databases used can be updated, especially the EPC as many of them are a decade old. The use of a 3D-model of the City of Gothenburg could be used to better assess the geometry of buildings. In addition to technical characteristics, the user-behavior is simplified and in order to improve the accuracy of calculated energy use, load curves can be used.

The main drawback of a building-specific bottom-up model is the extensive need for granular data. As such, applying such a description on a national or European level is difficult. As an alternative to using representative buildings for national or pan-national stock models, a hybrid approach can be used. These approaches can achieve a similar level of detail as a building-specific stock description at the cost of spatial granularity. By creating artificial distributions from representative buildings, a synthetic stock description can be used [21]. Another example of a hybrid method is the Canadian hybrid residential end-use energy and greenhouse gas Emissions model [110] using a large sample of buildings coupled with a neural network.

Visualization and communication with stakeholders

The spatial visualization of renovation activities related to individual buildings can be used to support communication with urban planners, policy makers and property owners regarding coming renovation needs in an urban context. It is also clear from this work that while the renovation need will be large in the near future, information at aggregate levels need to be used with care when suggesting areas where measures are to be prioritized. Further work is needed to assess what information different stakeholders involved in the transformation of the urban building stock needs and how it should be presented and visualized.

While information relating to the building stock constitutes partial information to individual stakeholders, it opens the possibility to facilitate communication and joint understanding between the different stakeholders. While spatial representation is an important tool in promoting joint understanding, it is not always relevant to all stakeholders. For property owners, spatially visualizing energy related information only make sense for portfolios of sufficient size. However, to spatially visualize results with this level of detail is not always needed and the spatial aspect may not always be warranted. GIS may still be used for practical reasons regarding data acquisition, merging and analysis. One of the main benefits of a bottom-up modelling approach is the ability to aggregate results to different scales depending on the use case. Care should be taken not to visually represent data at a scale at which the methods used to derive it is not accurate. As such, the practice of visualizing results on a building level when distributing aggregated data or when results are based on archetypes should be avoided.

A building-specific description for a heterogenous building stock

The effect of renovation on energy use, environmental impact and cost-effectiveness varies greatly within the stock. While the average effect of renovation based on current practices provide marginal energy use reductions and associated reductions in greenhouse-gas emissions are small, individual buildings can be identified within the stock where the potential is larger. Similarly, the cost-effectiveness of deep renovation shows a wide distribution across the municipal housing portfolio. As such, going forward it is suggested that key buildings within the building stock suitable for large scale renovation are identified. All buildings are unique which is why a building-specific approach in describing the building stock is required. While there are technical similarities between some buildings, aspects such as current state, location, owner and tenants ensures that each building deserves to be treated individually when assessing potential renovation measures.

In the Swedish context, the approach towards renovation have shifted in the past years. In the past, deep renovation was argued for and several methodologies were developed to support such endeavours. Recently, the pendulum has swung and property owners such as the municipal housing company in Gothenburg now argues for "gentle renovation". The results of this thesis show that there is a need for a more differentiated view on renovation. Applying a building-specific stock description that can capture the distribution within the stock is thus warranted.

7. Future research

The methodology used in this thesis to develop and apply a building-specific stock description can be further developed. With digitalization, more information is bound to become accessible which would allow for creating a digital twin [111], [112] of a city that can be used to in detail describe the current state and evaluate changes in the built environment.

To better assess the impact of renovating the stock, methodological advancements are necessary. While steps have been taken in this work to better describe the current state of the stock, there are still room for improvement. By incorporating maintenance plans and inspection reports, the current state of the stock would be better understood. On the modelling side, energy modelling should better capture the user behaviour in order to allow for better understanding of load curves and what measures and interventions affect them. This becomes increasingly important as greenhouse-gas emissions are tied to peak demand. Similarly, to be able to better assess the environmental impact of renovation measures, local datasets should be developed for LCA and local environmental impacts estimated and spatially visualized. This is especially important in developed countries where renovation measures may end up moving local emissions to a global scale. Such trade-offs should be highlighted to better support policy makers. In parallel to increased spatial resolution of environmental impacts, the temporal resolution should be increased as emissions from energy use vary over the year and time of day. Furthermore, evaluating cost-effectiveness of renovation measures should also include maintenance costs [113] to allow for evaluating the yield to better align with common decision practices for property owners. For many of the stakeholders targeted, the MFB stock is only of partial interest. To better assess the building-stock as a whole, describing and modelling the energy use of non-residential buildings needs further attention. Lastly, the use of a detailed description for a bottom-up engineering model for evaluating policy measures and subsidies regarding renovation should be investigated.

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