THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Challenges of renovating the Gothenburg multi-family building stock

An analysis of comprehensive building-specific information, including energy performance, ownership and affordability

MIKAEL MANGOLD

CHALMERS

Department of Civil and Environmental Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
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MIKAEL MANGOLD
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Department of Civil and Environmental Engineering
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

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Abstract

In Sweden and many European countries, the building stock increased at a rapid pace during the period of 1950-1975. This aging building stock is in need of renovation which is a challenge and an opportunity in reaching the energy performance targets as well as decreasing societal inequities. The contribution of this thesis is to demonstrate how economic, social and resource usage challenges of renovating the building stock can be analyzed and described using comprehensive building-specific data.

In this thesis, building ownership types, area socio-economic characteristics, building energy performance, and investments in renovation, are analyzed for the Gothenburg multi-family dwelling stock. Measured energy usage from the Swedish Energy Performance Certificate was used in the analysis. The data quality of the Energy Performance Certificate was assessed for the purpose of analyzing the building stock. The Energy Performance Certificates were matched with official building information from the Swedish Land Survey and area socio-economic information from Statistics Sweden. Using this dataset, rent increases due to renovations are estimated and compared.

To broaden the analysis, a case study in a renovation project of multi-family dwellings in an economically disadvantaged area is also presented. In the case study renovation, the implemented energy usage reducing measure of volumetric billing of water was found to increase rents. The case study is used to exemplify how energy usage reducing renovation projects, with little consideration for social city development targets, can aggravate economic segregation.

There is positive progress towards the 2020 targets of greenhouse gas emission reduction and improved energy efficiency in the Swedish housing sector; while there is little progress toward the Gothenburg city target to reduce segregation. The Swedish housing sector is rather part of the economic and geographic segregation process in Gothenburg. Renovation will be needed to reduce differences in living standards. The upcoming renovation need is a challenge, for mainly municipally owned companies, in reaching greenhouse gas and energy usage reduction without raising rent and increasing economic segregation.

Keywords: Aging building stock, Energy performance certificate, Energy retrofitting, Equity, GIS, Göteborg, Measured energy usage, Multi-family dwellings, Social sustainability, Tenure

Utmaningen att renovera Göteborgs flerbostadshusbestånd
- En analys av omfattande byggnadsspecifik information,
innefattande energianvändning, byggnadsägande och hyresökningar
MIKAEL MANGOLD
Institutionen Bygg och Miljö
Chalmers Tekniska Högskola

Sammanfattning

I Sverige och många europeiska länder byggdes mycket bostäder mellan 1950 och 1975. Detta åldrande bostadsbestånd behöver renoveras vilket är en utmaning och en möjlighet i att minska energianvändning och minska sociala ojämlikheter. Denna avhandlings bidrag är att visa hur ekonomiska, sociala och miljömässiga utmaningar inom renovering av flerbostadshus kan beskrivas med hjälp av omfattande byggnadsspecifik data.

Byggnadsägande, bostadsområdens socioekonomiska karaktärer, byggnaders energiprestanda och investeringar i renoveringar för flerbostadshusen i Göteborg analyseras i denna avhandling. Uppmätt energianvändning från energideklarationer har använts. En studie om datakvalitet i energideklarationerna för syftet att analysera bostadsbestånd genomfördes. Energideklarationerna matchades med officiell byggnadsinformation från Lantmäteriet och socioekonomisk områdesinformation från Statistiska centralbyrån. Med denna data uppskattades och jämfördes kommande hyresökningar till följd av renoveringar.

För att ta ett bredare perspektiv presenteras även en fallstudie som gjordes vid en energibesparande renovering i ett flerbostadshus i Hammarkullen i Göteborg. I fallstudien studerades hur implementeringen av volymbaserad mätning och debitering av kall- och varmvatten bidrog till ökade månadskostnader. Fallstudien exemplifierar hur renoveringsprojekt, utan hänsyn till Göteborgs Stads mål att minska segregering, kan förvärra ekonomisk segregering.

Utvecklingen för att nå miljömålen till år 2020 är god inom bostadssektorn i Sverige. Utvecklingen för att nå Göteborgs Stads mål att minska geografisk och ekonomisk segregering är däremot negativ. Den svenska bostadssektorn är snarare del av en process som leder till ökad ekonomisk och geografisk segregering. Renoveringar kommer att behövas för att minska skillnader i levnadsstandard. Det växande renoveringsbehovet är en utmaning för framförallt kommunalägda bostadsbolag i att minska energianvändning och höja levnadsstandarder utan att höja hyror och öka ekonomisk segregering.

Sökord: Energibesparande åtgärder, Energideklaration, Flerfamiljshus, GIS, Miljonprogram, Uppmätt energianvändning, Renovering, Social hållbarhet, Upplåtelseform, Åldrande bostadsbestånd

List of publications

Appended articles

I. **Mangold M**, Morrison G, Harder R, Hagbert P, and Rauch S. (2014) "The Transformative Effect of the Introduction of Water Volumetric Billing in a Disadvantaged Housing Area in Sweden." *Water Policy* 16 (5): 973-990. doi:10.2166/wp.2014.105.

II. **Mangold M**, Österbring M, and Wallbaum H. (2015) "Review of Swedish Residential Building Stock Research." *International Journal of Environmental Sustainability*, 11 (2). ISSN: 23251077.

III. **Mangold M**, Österbring M, and 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: 328–36.

IV. **Mangold M**, Österbring M, Wallbaum H, Tuvander L, and Femenias P. (2016) "Socio-Economic Impact of Renovation and Energy Retrofitting of the Gothenburg Building Stock." *Energy and Buildings*. 123: 41-49 doi:10.1016/j.enbuild.2016.04.033

V. **Mangold M**, Österbring M, Wallbaum H, Overland C, and Johansson T. "Building ownership, renovation investments and energy performance - A study of multi-family dwellings in Gothenburg." *Submitted to Energy and Buildings*.

In article I, a case study on the impacts of the common resource usage reducing measure of implementing volumetric billing of water in multi-family dwellings was conducted. Volumetric billing of water is a renovation measure that has been increasingly implemented since 2000 due to decreased costs for metering and billing apartment specific water usage. The exclusion of inhabitant influence on the implementation process is a central part of the conclusions in this work.

In article II, contemporary research connected with the Swedish building stock was reviewed, and basic background data on the development of energy usage in the building stock was summarized in a review article. Measured energy usage in the Swedish Energy Performance Certificate (EPC) was identified as being relevant for describing renovation and energy retrofitting targets.

In article III, the data quality in the EPC was assessed by comparison with measurements of billing data for heating, electricity and water. Ways of deriving the area unit specifically developed for the EPC were analyzed by aligning the EPC data with official records of sellable living space. Methods for mitigating errors for statistical descriptions of building stock were suggested.

In article IV, renovation and energy retrofitting costs of multi-family dwellings in Gothenburg were estimated and compared using data from EPCs. The scientific contribution of this paper was to quantitatively estimate the socio-economic impact of renovation and energy retrofitting of multi-family dwellings.

In article V, the variance in renovation investments and building energy performance between ownership groups is investigated. Municipal real-estate companies are found to make the most extensive renovations, which, on average, result in improved energy performance. Larger renovation projects will be needed in buildings constructed during the Million Homes Program era (1960-1975); in these buildings, economically disadvantaged groups that are sensitive to rent increases are overrepresented.

Related articles

The work conducted in this PhD project relates and has had synergies with the work of other researchers in other of fields of research (see figure i). The following articles are related, but not appended to the thesis. They are referred to using capital letters in the thesis.

A. Hagbert P, **Mangold M**, and Femenías P. (2013) "Paradoxes and Possibilities for a 'Green' Housing Sector: A Swedish Case." *Sustainability* 5: 2018–35.

B. Thuvander L, Österbring M, **Mangold M**, Wallbaum H, and Johnsson F. "Spatial Exploration of the Refurbishment Dynamics of Urban Housing Stocks," CUPUM, Cambridge, 2015.

C. Österbring M, Mata E, Thuvander L, **Mangold M**, Johnsson F, and Wallbaum H. (2016) "A Differentiated Description of Building-Stocks for a Georeferenced Urban Bottom-up Building-Stock Model." *Energy and Buildings.* 120: 78–84.

D. Johansson T, **Mangold M**, and Olofsson T. "A national visualization model to examine future socio-economic and energy renovation challenges in Sweden - Development of a renovation atlas" *Submitted to Energy and Buildings*.

For article A, a qualitative study with building owners and developers was conducted. Hagbert P has applied an array of qualitative methods to describe the sustainable home. The contributions of Mangold M were analyzing the data and writing parts of the article.

Conference paper B focused on visualization and was the first paper in which the authors used value year to identify previous renovations. Mangold M performed value year analyses and tabulation.

Article C is the first article in which the authors compare the measured energy usage in the EPC with calculated energy usage. Mangold M developed the concept with Österbring and wrote part of the article.

In article D, the Gothenburg analyses in this thesis were used to validate an analysis covering all multi-family buildings in Sweden. Mangold M contributed through data acquisition and analysis as well as in the writing of the article.

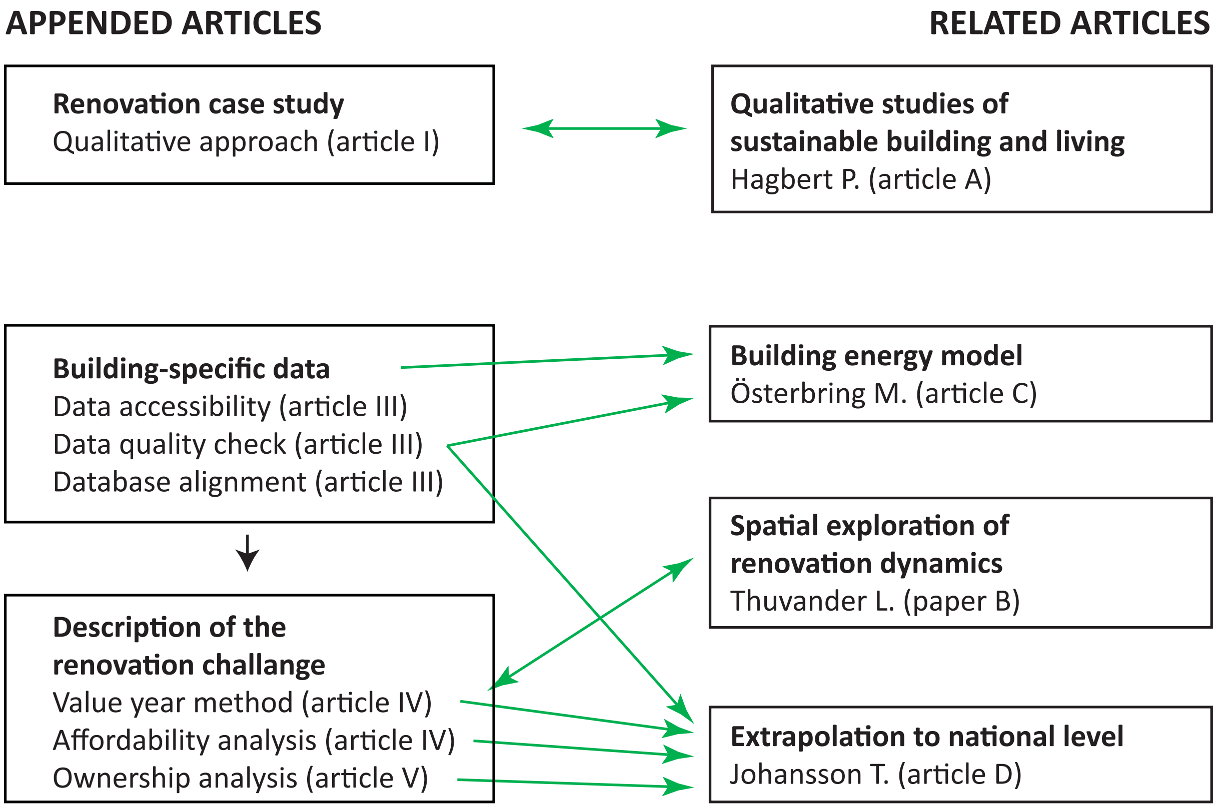

Figure i. Application of developed methods, analyses and data gathered in this thesis related to other researchers and research projects.

Other articles by the author

Bratanova B, Morrison M, Fife-Schaw C, Chenoweth J, and **Mangold M**. (2013) "Restoring Drinking Water Acceptance Following a Waterborne Disease Outbreak: The Role of Trust, Risk Perception, and Communication." *Journal of Applied Social Psychology*. 43 (9): 1761-1770.

Harder R, Kalmykova Y, Morrison G, Fen F, **Mangold M**, and Dahlén L. (2014) "Quantification of Goods Purchases and Waste Generation at the Level of Individual Households." *Journal of Industrial Ecology*.

Engström E, Balfors B, Mörtberg U, Thunvik R, Gaily T, and **Mangold M**. (2015) "Prevalence of Microbiological Contaminants in Groundwater Sources and Risk Factor Assessment in Juba, South Sudan." *Science of The Total Environment* 515–16: 181–87. doi:10.1016/j.scitotenv.2015.02.023.

Engström E, Mörtberg U, Karlström A, and **Mangold M**. (2017) "Evaluation of the microbial contamination mechanisms of urban groundwater sources using spatial regression in Juba, South Sudan" *Invited submission sent for special issue in Hydrogeology Journal*.

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Definitions and acronyms

Energy retrofitting (energy renovation, renovation, deep energy retrofitting)

In this thesis it is useful to distinguish between renovation for the purpose of energy efficiency and renovation without energy efficiency purposes. In the European bill 'On the energy performance of buildings' (2002) *energy renovation* is used, however in order to reduce risks of misunderstanding the author will use *energy retrofitting* when referring to projects with the outspoken goals of energy efficiency. *Renovations* may include energy retrofitting but all renovation is used to refer to all projects of investments in building that goes beyond regular maintenance.

Energy usage (Energy consumption)

Energy usage is preferred by the authors since energy is strictly not consumed. Using the term 'energy usage' also makes it easier to speak about re-usage of energy, such as domestic electricity heating the building; or energy used to pump heat to a district heat system.

Renovation (Retrofitting, refurbishment)

These terms are used to describe the same thing, or used as if interchangeable. However, authors do imply different things when using them. In the European bill On the energy performance of buildings (2002) *renovation* is used, and will also be used by the author. Retrofitting is used to signify a provision of something with a component or feature not fitted during manufacture or adding something that it did not have when first constructed Eames et al. (2014) define "sustainable urban retrofitting as the directed alteration of the fabric, form or systems that comprise the built environment to improve energy, water and waste efficiencies." Refurbishment is more often used to signify cleaning, decorating, and re-equipping.

A_{temp} — *Heated floor area* is the floor area to be heated to a temperature above 10 °C; it is limited by the inner side or the envelope. Mandatory indicator in environmental performance certificates.

BOA — Sellable *residential floor area* is the total area of the dwellings, excluding common areas (e.g., staircases) and the area occupied by walls.

BRF	Housing organization (bostadsrättsförening)
CEO	Gothenburg city executive office (Stadsledningskontoret)
CPA	City Planning Authority (Stadsbyggnadskontoret)
EEM	Energy efficiency measure
EM	Ecological modernization
EPC	Environmental performance certificate (Energideklaration)
FNR	National building number (fastighetsnummer)
HUD	Housing and urban development office (Stadsbyggnadskontoret)
HSB	Private real-estate company in Sweden, which also provide service for associations of resident owners
GHG	Greenhouse gas
LOA	Sellable floor area of buildings registered as non-residential
MFD	Multi-family dwelling
SABO	Umbrella organization for municipally or governmentally owned real-estate companies
SFD	Single-family dwelling
SCB	Statistics Sweden (Statistiska centralbyrån)
SWS	Social welfare services (Socialstyrelsen)
SEA	Swedish energy agency (Energimyndigheten)

Contents

1 Introduction

In 2010, buildings accounted for 32% of the total global final energy usage (IPCC, 2014). There are European targets to reduce Green House Gas (GHG) emissions (EU, 2012) by 20% until 2020, partially through renovation of the building stock. IEA (2013) found the energy efficiency gains in Swedish buildings to be larger than the European average. In Sweden, 25% of energy usage and 18% of GHG emissions comes from heating and electricity usage in buildings (Boverket, 2014a; Swedish Energy Agency and Statistics Sweden, 2014)[1]. In Gothenburg 22% of energy usage and less than the national average of GHG emissions come from heating and electricity usage in buildings (Swedish Energy Agency and Statistics Sweden, 2014).

In Sweden and many European countries, the building stock increased at a rapid pace during the period of 1950-1975 (Frits Meijer et al., 2010). This aging building stock needs to be renovated, and there is, amongst other, a possibility of introducing energy efficiency measures in the renovation process (Ball, 2011; Heeren et al., 2013). Renovation of the aging building stock is a challenge and an opportunity in reaching the required energy performance as well as decreasing societal inequities. The Gothenburg housing market is economically, spatially and ethnically segregated (Andersson et al., 2009). According to Gothenburg city (2014a), segregation is also progressing. Similar developments in socio-economic segregation can be found in other Swedish cities, such as Malmö (Malmö Stad, 2013).

The contribution of this thesis is development of methods and analyses that describe challenges and trade-offs between economic, social and resource usage aspects in renovation of the Gothenburg building stock. This is done using comprehensive building-specific data, and in a case study renovation project.

There have been many projects that have addressed the upcoming need for renovation by studying the building stock with sampling methods (Ballarini et al., 2014; Boverket, 2010; Boverket and Swedish Energy Agency, 2013; Kohler and Hassler, 2002, 2012). The increasing accessibility of building-specific data makes it possible to sidestep the sampling and instead generate an overview of the building stock from building-specific data for all buildings (Aksoezen et al., 2015; Heeren et al., 2013; Kholodilin and Michelsen, 2014; Shahrokni et al., 2014). The benefits of this are many: the sampling errors are removed, unexpected patterns can be analyzed without additional sampling, there are a greater number of possibilities to provide client-specific advice, and it makes it possible to further add information to the database. Adding socio-economic data and analyses of the socio-economic impacts

[1] Article II focused on the status of energy usage in the Swedish building stock. It was demonstrated that while total energy usage in the Swedish multi-family dwellings stock is not decreasing, energy efficiency is increasing; additionally, the GHG emissions from the Swedish multi-family dwellings are decreasing on par with the European targets. This is mainly due to the switch to more carbon-neutral heating sources in district heating systems. Boverket (2010) recommended that the implementation of energy efficiency measures beyond economic savings should only be considered if national security interests are taken into account.

of renovation is seldom performed in larger city-scale building energy performance analyses (Pombo et al., 2015).

In Sweden, social sustainability in the renovation of buildings has received increasing attention among researchers in the field of sustainable renovations (Lind and Mjörnell, 2015). However, in the field of building stock analysis and modeling, the social dimensions are underdeveloped (Jensen et al., 2012; Johansson et al., 2016; Pombo et al., 2015). This PhD thesis presents methods of analyzing building stock renovations, including aspects of affordability.

In the licentiate thesis preceding this thesis, focus was on the exploration of sustainable development with special attention to social sustainable development. The Sustainable Integrated Renovation (SIRen) network wrote an anthology on social sustainability with a focus on renovation (Lind and Mjörnell, 2015). In the anthology, Högberg (2015) summarized references to social sustainability in the following groups, as was also done by Barron and Gauntlet (2002), Abbas (2012) and Murphy (2012).

1. Life quality
2. Equity
3. Social cohesion
4. Participation and interconnectedness
5. Diversity and tolerance
6. Democracy and governance

The vagueness and interpretive flexibility of social sustainable development creates a need for using concrete examples (Boström, 2012; Dempsey et al., 2011; Lehtonen, 2004), as well as clearly defining the indicators used when analyzing a building stock. In the building stock analyses presented in this thesis, equity[2] aspects in the renovation of multi-family dwellings are studied. In Gothenburg, social equity has been part of the societal vision with the target to "decrease the differences in life conditions and health" (Gothenburg City, 2014a). Measuring equity in relation to renovations is complicated. In this thesis, rent increases is used as an indicator of decreasing social equity. Rent increases can result in negative impacts on societal economic equity (Bäckman and Nilsson, 2010). There are also renovation examples where residents were disadvantaged (Blomé and Lind, 2011). However, increased standards of living, increased perceptions of safety and other qualities that renovation projects might bring are also needed to increase social equity. There are examples of renovation

[2] Equity is a term used in many fields of research. In epistemic research on sustainable development, equity is placed under social sustainable development and defined as fairness and equality in societies (Kates et al., 2005). Many factors contribute to societal in/equity: legal equity, economic equity, ethnic equality, equal opportunity and spatial segregation (Chiu, 2004; Dempsey et al., 2011). Dempsey et al. (2011) argue for focusing on societal inequities in the urban setting: "In a geographical sense, social exclusion and inequity may manifest itself as areas of deprivation, which may have poorer living environments and reduced access to a range of public services and facilities for residents than other areas". In this thesis, social equity issues of geographical segregation and economic inequality are the foci.

projects which resulted in increased rents, in which inhabitant participation was a strong element with an aim of increasing social cohesion (Blomé, 2010; Pavlovas, 2006).

It is important to note that the Swedish historic housing situation has been slightly different from that of other European countries. Subsidies for housing construction and household allowances have been active policy instruments to ensure quality and equality. However, the prerequisites for this have changed with shifts in housing policy over the past decade (Hagbert et al., 2013; Turner and Whitehead, 2002; Whitehead and Scanlon, 2007). In most other countries, there are programs of social housing and affordable housing. In Sweden, Allmännyttan was created to cover *all* housing need without a special focus on the most disadvantaged (Beer et al., 2007; Gill et al., 2011; Mulliner et al., 2013; Wallbaum et al., 2012). However, in a society that is segregating there is an increasing need for a housing system that focuses on disadvantaged population groups (Törnquist et al., 2012).

These aspects should be considered for decisions regarding renovation measures. There is a need for information in order for authorities and larger building owners to make informed decisions concerning renovation measures and the extent of renovations. Currently, building-specific data is increasingly available. Especially interesting is the possibility of merging measured energy usage from the Swedish Energy Performance Certificate (EPC) database with official building-specific data, for example, ownership, previous renovations and inhabitant socio-economic information.

1.1 Research task descriptions

This thesis is based on four research tasks that have resulted in five journal articles. The connections between articles and research tasks have been illustrated in Figure 1.

- The work behind article I was a case study project on the impacts of the common resource usage reducing measure of implementing volumetric billing of water in multi-family dwellings. The study compared socio-economic impacts with costs and reduced resource usage. From the work conducted for article I, two research gaps were identified: the trade-off between social development targets and energy usage reduction targets in the renovation of the Swedish building stock was not satisfactorily described, and there were few comprehensive building-specific studies on the challenge of renovating the building stock.

- Contemporary research connected with the Swedish building stock was reviewed, and basic background data on the development of energy usage in the building stock was summarized in a review article, article II.

- In article II measured energy usage in the Swedish EPC was identified as relevant for describing building stock renovation status and need. However, the data quality in the EPC has partly been revealed as questionable. The work of studying the data quality and mitigating the data quality for statistical analyses resulted in the methods article, article III.

- Using the EPC data and merging the data with other building-specific databases, two articles were produced. In article IV, renovation and energy retrofitting costs of multi-family dwellings in Gothenburg were estimated and compared using data from EPCs. The scientific contribution of this paper was to quantitatively estimate the socio-economic impact of renovation and energy retrofitting of multi-family dwellings. Article V describes the relationships between building ownership and investment in renovations and building energy performance.

1.2 Purpose & research questions

The overarching purpose of this PhD thesis is to analyze the challenges of renovating and energy retrofitting the Gothenburg multi-family dwellings constructed during the Million Homes Program and to include social dimensions in the analysis.

In order to give structure to this PhD thesis, research questions and sub-questions have been defined. The common research theme for articles II, III, IV and V is the exploration of comprehensive building-specific data to study an entire building stock, RQ1. The common research theme for article I and IV is the exploration of the socio-economic impacts of renovation or implementation of energy usage reducing measures in multi-family dwellings in economically disadvantaged areas in Gothenburg, RQ2. The coverage of the research questions is also illustrated in Figure 1.

RQ1 Can a building stock analysis based on comprehensive accessible building-specific data be used to describe the challenge of renovating the Gothenburg multi-family dwelling stock?

RQ1.1 What building-specific databases can be used to analyze renovation of the Swedish building stock, what are the uncertainties when using these databases, and how can the databases be matched?

RQ1.2 How does ownership matter for renovation investment and energy performance of multi-family dwellings in Gothenburg?

RQ2 What is the economic impact of the renovations and implementation of energy saving measures in socio-economically disadvantaged areas of Gothenburg?

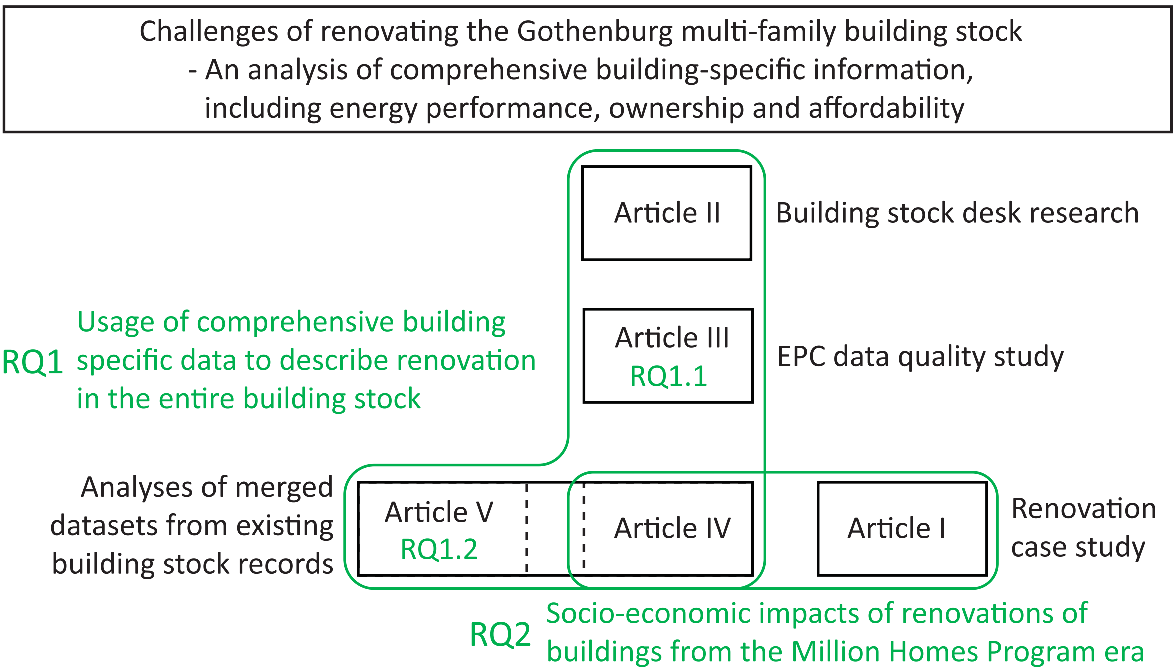

Figure 1. Research structure behind the thesis.

1.3 Methodology

The lion's share of the work behind this thesis has focused on quantitative analyses. However, a mixed-methods approach, including qualitative methods, was used to give a more diverse account of the challenges of renovating and energy retrofitting the buildings built during the Million Homes Program era.

Social dimensions of renovation projects are complex, and when reducing complexity, it is possible to answer research questions without including sufficient perspectives (Flick, 2009). The purpose of this PhD thesis has been to include social dimensions in the analysis of renovation and energy retrofitting of building stock. I found it useful and necessary to include the study in which qualitative methods were applied. The case study project is an implementation of volumetric metering and billing of hot and cold water at an economically disadvantaged area of Gothenburg, Bredfjällsgatan in Hammarkullen (see Figure 2). Volumetric metering and billing of hot water has been in focus as an important element in energy-saving strategies in the buildings constructed during the Million Homes Program era over the last 10 years (Boverket, 2015; Swedish Government, 2014).

Combining a case study with a larger quantitative study provided a more diverse understanding of the challenge of renovating and energy retrofitting the buildings built during the Million Homes Program era. Speaking with residents, members of the Tenants' association and employees of the building owner provided a case of complexity of the decision making in the renovation project. Triangulation of different quantitative and qualitative data was used to provide a diversified perspective on a sometimes opinionated issue (Flick, 2009). Addressing residents' perceptions of the implementation of volumetric billing of water as an energy-saving measure provided a more comprehensive description of the implications of the system's change. Such aspects have also been described by Troy & Randolph (2006) and Keramitsoglou & Tsagarakis (2011). The methods are combined in this thesis by answering Research Question 2 twice: once using the case study in article I, and once using quantitative building stock analyses.

The concrete added value of answering Research Question 2 by using comprehensive building-specific data *and* a case study renovations project is as follows:

- The decision to focus on the indicators rent increase, average base area income and energy usage reduction is supported with the more detailed analysis in article I of rent increase, income, and reduced hot water usage.
- The issue of trade-offs between social and environmental values in renovation projects benefit from being analyzed from several points of view. The building stock analysis describes heterogeneity in the city, and the case study renovation project describes heterogeneity within the buildings.
- The context of the case study is better defined when the description of the building stock is added. For example: one observation in the case study was that inhabitants experienced that the real-estate company did not listen to their opinions about the renovation. When comparing renovation projects of rental apartments across the Gothenburg building stock similar sentiments have been expressed in the renovations of more central areas (Thörn et al., 2016). However, the inhabitants in the more centrally located buildings managed to make their real-estate company change the renovation plans.

Figure 2 Bredfällsgatan, where the 85 apartments in the case study are located (Photo: Frederick Nyandiko).

1.4 Thesis structure

The methods chapter in the thesis includes a more extensive account of the gathering of data for articles I, III, IV and V. This more extensive account of the comprehensive building-specific data gathering answers Research Question 1.1. Descriptions of the methods developed in the articles are not repeated in the introductory part of this compilation thesis.

The results chapter uses the methods described in article IV and V to present results that answer Research Question 1. At the end of the results chapter, Research Question 2 is answered using comprehensive building-specific data and in the case study context presented in article I.

In the discussion chapter, I take the liberty to include a wider perspective on the challenge of renovating and energy retrofitting the Swedish building stock, and I also include some ways of tackling renovation challenges presented by other researchers and stakeholders.

2 Methods

This chapter starts by describing the qualitative methods applied in the work behind article I. Thereafter, the gathering and organizing of building-specific information from official sources is described. Then, the statistical analyses of the gathered data are described, including how information has been used to derive variables used as dependents in the regression analyses. In the end of this chapter, the errors, insufficiencies and limitations encountered during this PhD work are described.

2.1 Qualitative methods applied in article I

Because there were diverse opinions amongst the stakeholders on the renovation project studied in article I, triangulation was used to describe the steps in the decision making process of implementing volumetric billing of water, using both quantitative and qualitative methods. Flick stated that "the different methodological perspectives complement each other in the study of an issue and this is conceived as the complementary compensation of the weakness and blind spots of each single method" (2009 p. 26-27).

For the triangulation, informant interviews were carried out separately with the water company, Social Welfare Services, the residents' association, and the real-estate owner and manager to map the various interests. Field notes were taken and used to describe the case study and reflect the stakeholders' positions. Furthermore, an economic summary of the system's change provided insight into the incentives of each stakeholder group. Triangulation using qualitative methods helped to avoid overlooking parts of an opinionated and complex issue. A general weakness in triangulation is the lack of assured comprehensiveness.

In the study (article I), semi-standardized interviews were conducted in 85 households to reveal residents' experiences and opinions. The interviewees were asked one initial question: "What do you think about the new system for water payments?" This question was chosen to answer a direct research question, as suggested by Flick (2009). Thereafter, confrontational questions were asked to affirm the interviewee's position, and the interviews continued until the interviewee was content with the answers given. Interviews were recorded with a handheld device. These interviews were used qualitatively to provide insight into the respective interests of residents and actors. After completion, the interviewees' statements were grouped thematically, and characteristic quotes were translated into English (2012).

Furthermore, unstructured and informal meetings occurred without recording. These informal meetings included seven occasions when I was invited for dinner or coffee for longer periods of time. During these times, issues other than the water system were discussed, but an understanding of life in the area was created.

A bias was the language barrier that sometimes existed in communication with native Kurdish, Vietnamese, and Arabic speakers. Interviews were conducted in Swedish, English, German, Spanish and Persian. Flick (2009) mentions interpretation as a shortcoming of semi-standardized interviews. The selection of quotes and the translation are connected biases. The selection of quotes is addressed first with a comprehensive account of statements by the research question directly corresponding to the initial question asked and the affirming confrontational questions, and, second by a subjective measure of exhausting the thematic groups. The translation was addressed by cross confirmation with fellow researchers.

2.2 Building stock data accessibility

As part of answering RQ1.1, building-specific data for the purpose of analyzing renovation of the building stock was gathered and matched in the methods article, article III. In Table 1, databases containing building-specific information with national coverage are listed that have been assessed in the work done for this thesis.

Table 1. Building-specific national databases relevant for the analyses of renovation in building stock. Records that were not used in this thesis are in grey.

Database/Data owner	Aggregation level	Information relevant for analyzes of renovation in building stock	Used in article:
Statistics Sweden (SCB)	Person*	Inhabitant socio-economic data: income, employment status, education level, ethnicity, etc.	I, II, IV, V
The real-estate registry (Fastighetsregistret)** / Swedish Land Survey	Various, apartment being the most disaggregated level	Information categories: real- estate, districts, property owner, property taxation, buildings, legal status, spatial planning, community association and address. Value year is the most complete in 43S	IV, V
Gripen/Boverket	EPC	Resource usage: water, electricity, heat. Heating systems Building energy performance Recommended energy saving measures Culturally sensitive buildings.	II, III, IV, V
Swedish Tax Authority	Real-estate number.	Construction year, value year and renovation year.	IV, V
Tenants' Association (Hyresgästföreningen)	Building*	Current rent level Installed apartment amenities	IV
Retriever business/ University of Lund	Business organization number	Property sales Real-estate company establishment data	V

*This data is sensitive but accessible if aggregated to base area levels (the smallest demographical statistics area in Sweden, which contain 50 to 4000 residents) or squares of 250m*250m developed by SCB.
**The Swedish real-estate registry is managed by the Swedish Land Survey but contain information from several authorities including the Swedish Tax Authorities. This register became free for Swedish research institutions to use in 2016.

Graphical building information exists in various databases with different methods of access. Official 2D georeferenced data is managed by the Swedish Land Survey for buildings and base areas. The Swedish Land Survey is developing a 2.5D model of Sweden. Agency 9 is selling 2.5D models based on aerial surveys and 2D building footprints. Additionally, 3D models are available: on Google Earth, Agency9 city planner and at local city planning authorities. Street views from the Google Car also cover many of the larger cities in Sweden. Analyses of street views and 3D models would make it possible to access useful information for building energy performance models such as window sizes, balconies, renovations types and façade types.

2.3 Matching and aggregating building information

When matching different databases with information about buildings, it is necessary to aggregate data to a common aggregation level and to use a key for matching the data. In Table 2, aggregation levels used in the analyses in this thesis have been summarized.

Table 2. Levels of aggregation and keys in databases used in this thesis in increasing levels of aggregation.

Key / index / aggregation level	Exists in databases	Comment
Address	EPC, National Land Survey, Retriever Business	Addresses contain errors of data entry. One address may also have many entrances if there are multiple staircases.
Registerbyggnad, ByggnadsID	National Land Survey, EPC	List is not complete in the EPC database.
EPC index	EPC	Only used in the EPC, the aggregation level was developed for energy-performance calculations.
Real-estate index (Fastighetsbetäckning)	EPC, National Land Survey	Properties may contain many EPC. Can be used with property building number to disaggregate further.
FNR	EPC, National Land Survey	May contain many separated buildings. FNR was used to match EPC and National Land Survey data in articles IV and IV.
Building owner	EPC, National Land Survey, Retriever Business	Buildings are owned by companies, private persons, foundations, authorities or residents. This is registered by the Swedish Tax Authorities.
Real-estate owner	Retriever Business	Buildings owned by companies are often owned or shared between other companies, persons and foundations.
250x250 m squares	SCB	
Base area	National Land Survey, SCB	

An EPC-related aggregation problem studied in article III is that water, heat and electricity usage are sometimes metered in a manner that includes energy that should not be included in the EPC or energy that is used in another building. Then, the certified energy expert must distribute the resource usage according to assumptions. The distribution error is mitigated to some extent when the data is aggregated to FNR and building owner levels.

Another issue when merging databases is that different building types are used in different databases (see Table 3). One building can also contain many types of activities. For example, there are many multi-family dwellings with commercial segments on the bottom floors. Some parts of multi-family dwellings are also used as shared spaces. In the EPC, this is addressed using the description of activities as a percentage. In the register of the Swedish Land Survey buildings are only separated as domestic and non-domestic areas (BOA or LOA). The official 3D separation of building ownership is not common and has only been used since 2009.

Varying aggregation levels and differences in time between data recording may cause differences in registered building type. The official type code is registered in both the EPC and Swedish real-estate registry, but there are also more separations in different building types (see Table 3). Row houses and chain houses should be placed in a separate building type, but this is not always the case in Gothenburg.

Table 3. Building types registered in the databases.

Type name	Database	Comment
Building category	EPC	Multi-family dwelling/ Single- or double-family dwelling/ Commercial building/Other
Type code simple	Swedish Land Survey	Dwelling/Industry/Societal function/Business/Belonging/Other
Type code	EPC, Swedish Land Survey	Described by the Swedish Land Survey (2015) under 50A.
Judicial ownership form	Swedish authorities	Found in the Swedish Land Survey (2015) 42P. This categorization was used to separate buildings in ownership groups in article V.

2.4 Creation of building groups

From the official records, buildings were divided into ownership groups. In the Swedish Land Survey, the categories on the left-hand side in Figure 3 are registered together with the name of the owner. The subdivisions of final ownership groups are listed on the right in Figure 3.

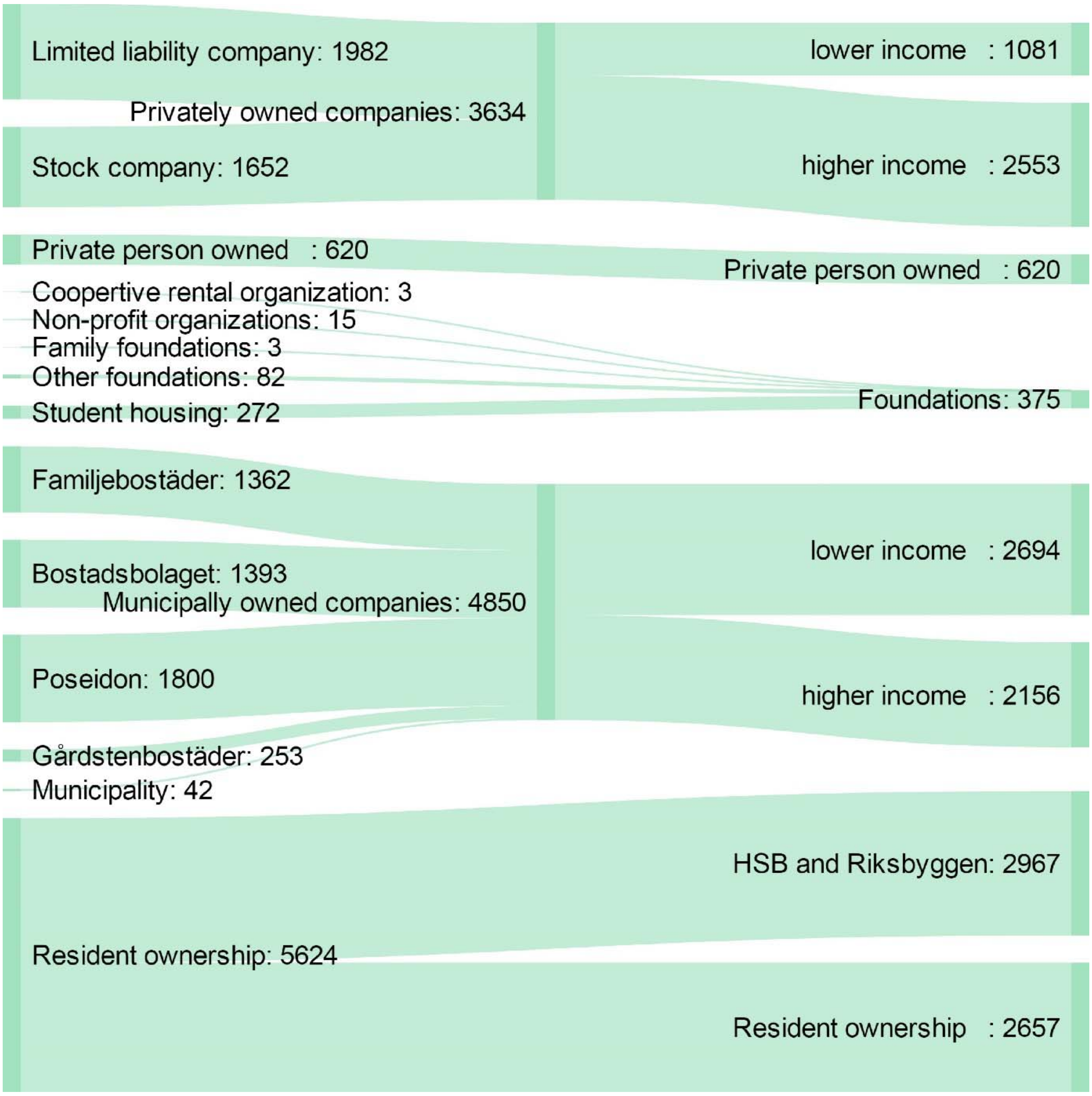

Figure 3 Creation of ownership groups from official ownership records [10^3 m^2 BOA].

These groups were used in article V. The multi-family dwellings were also divided into age groups as described in article IV and article V, and one separation according to heating system type was made for the statistical analysis in article V.

2.5 Statistical analyses

In articles III, IV and V, regressions were used to study correlations and to develop equation 1 and 2. Analyses were made in SPSS. Regressions were in part stepwise regressions adding variables with a confidence interval of <0.05, and in part linear regressions including all variable groups. An outlier criterion of 2.5 standard deviations was used for the dependent variables if nothing else is specified. In this chapter, the dependents are described first, followed by a deeper analysis of the independents.

Heated floor area, A_{temp}

In article III, data quality issues in the EPC were assessed for the intended usage of describing building stock. The building area unit was found to be the most critical issue. Heated floor area, A_{temp}, is defined as the heated floor area, including shared spaces, basements and footprints of walls but not including garages.

In articles IV and V, EPC data was used to describe the Gothenburg building stock. In these articles, different building groups were created than the one presented in article III. In Table 4 and Table 5, the errors that were made when the heated floor areas were derived from BOA and LOA in the different building groups in articles IV and V are presented. These errors have been estimated in the new groups by comparing heated floor area, A_{temp}, with BOA+LOA in the EPCs where the heated floor area have been measured.

Table 4. Estimated error from conversion of BOA+LOA to A_{temp} for building ownership groups.

Ownership group	A_{temp}/BOA+LOA ratio	Number of EPC with measured Heated floor area	Mean group error of building heated floor area
Municipally owned, higher income	1.359	9	+15%
Municipally owned, lower income	1.298	2	+9%
Private company owned, lower income	1.317	21	+9%
Private company owned, higher income	1.338	127	+10%
Private person owned	1.413	45	+14%
Resident owned	1.329	178	+7%
HSB and Riksbyggen	1.359	158	+12%
Foundation owned	1.455	106	+4%

Table 5. Estimated error from conversion of BOA+LOA to A_{temp} for building construction periods.

Construction period	A_{temp}/BOA+LOA ration	Number of EPCs with measured heated floor area	Mean group error of building heated floor area
Built before 1931	1.348	103	+9%
1931-1945	1.364	146	+11%
1946-1960	1.418	152	+17%
1961-1975	1.337	140	+11%
1976-1990	1.255	67	+4%
1991-2005	1.374	60	+11%
Built after 2005	1.311	22	+2%

Energy Performance

In article V, building energy performance is used as dependent for regression analyses. The distribution of buildings with varying energy performance can be seen in Figure 4. The Energy Performance in the EPC is derived through equation 1 in which the heating energy is adjusted using energy index with the purpose of making energy usage measurements comparable between different years and locations (BBR, 2015; Heincke et al., 2011). It is notable that Q for domestic electricity usage is not included. In article III, the exclusion of Q for external building electricity usage, such as streetlights, was mentioned as an uncertainty because this exclusion is made manually. Analyses of domestic electricity during the work for article V did however not reveal any correlations with other parameters.

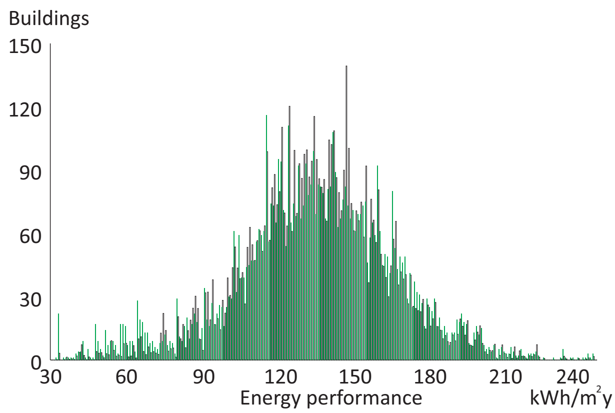

Figure 4. Distribution of buildings in regard to EPC registered building energy performance. The heated floor area weighted distribution is in grey.

$$Energy\ performance = \frac{f_{energy\ index}\,(Q_{Heating} + Q_{Building\ electricity}) + Q_{Domestic\ hot\ water\ heating}}{A_{temp}} \qquad \text{Equation 1.}$$

However, it was found that energy performance excluding water usage more accurately describes variations in building energy performance. Variations in the average heating used for domestic hot water between the ownership groups are substantial, as demonstrated in figure 1 in article V. After the removal of energy for heating water, the average building energy performance is uniform between the groups. Resident owned buildings have a lower average energy performance that is explained by the overrepresentation of heat pumps as a heating source (in the EPC, energy supplied to the heat pump is registered, not the energy supplied by the heat pump to the building).

The removal of heating for domestic hot water was conducted because only a minor share of this heat remains in the buildings; most of the heat exits the building in the waste water (McNabola and Shields, 2013). On the building stock aggregation level, variations in hot water usage are most strongly predicted by the number of inhabitants (Pullinger et al., 2013). This offers an indication of in which ownership groups the buildings are more crowded. Kontokosta and Jain (2015) used building-specific data and measured water usage to predict water usage in larger areas. One possibility would be to estimate crowdedness by using EPC recorded water usage as a predictor. Using analyses, as in article I, on yearly water usage in buildings would make it possible to estimate the number of inhabitants from the EPC. This would add internal loads in building energy models and would make it possible to express energy usage per person rather than energy usage per heated floor area.

In article III, the inaccuracies in the energy performance of buildings with heat pumps is not described. The energy supplied to the heat pump is registered in the EPC without a record of the performance coefficient. This results in 'buildings with heat pumps' being a strong negative predictor of energy performance, but the varying performance coefficient introduces an additional uncertainty for this group of buildings. In article C, this uncertainty was further investigated.

Renovation extent

Renovation groups and renovation extent used as a dependent in article V were derived from value year and renovation year as described in article V. In Table 6, the four groups in the ordinal regression are the staples 0%, 10%, summed 20-70% and 90%. The distribution of renovation extent in Figure 5 is not even. There are couple of reasons for this: all buildings that are renovated to more than 70% of the new building cost are given the value year of the renovation year, making any differences in renovation extent in this group inseparable. Furthermore, deductions on the real-estate tax can be made for buildings that have been renovated to more than 70% of the new building cost (Swedish Tax Agency, 2015).

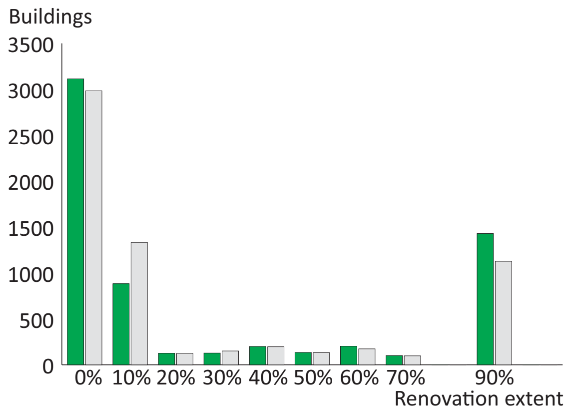

Figure 5 Distribution of buildings in regard to renovation extent. The heated floor area weighted distribution is in grey.

For articles IV and V, previous renovation costs were estimated based on calculations from value years. The records of value year and reconstruction year have data quality issues, of which some can be mitigated. Reconstruction years were not recorded before 1988. When the registers were digitalized, buildings without a reconstruction year but with a changed value year were given the reconstruction year 1988. This error was mitigated by changing the reconstruction year 1988 for buildings that have a renovation degree of 70-99% (which the buildings cannot have because those buildings would have been in group 1 in table 5 in article IV) to a reconstruction year that instead would give a renovation degree of 100%.

The changes in value years and construction years are registered by the Swedish Tax Authorities and sent on an annual basis to the Swedish Land Survey where previous value years and renovation years are overwritten. The Swedish Land Survey has the mandate to provide research institutes with information, but the Swedish Tax Authorities do not. If cooperation with the Swedish Tax Authorities could be initiated, then more accurate descriptions of particularly older renovation projects could be generated.

Independents

The independent variables used in the regressions in article V are described more in depth in Table 6 and Table 7. Table 6 contains ordinal variables and ventilation. The EPC separates an additional three types of ventilations: exhaust, balanced, and natural ventilation. Ventilation systems with heat recovery were grouped into one group for the regressions.

Table 6 Description of independent ordinal variables in regression analyses

Variables	0 / No	1 / Yes	2
Mechanical ventilation heat recovery	5730	589	
Other ventilation heat recovery	6100	219	
Number of walls shared with other buildings	4429	621	1269
Heated basements	1937	4257	125

As can be seen in Table 7, the number of staircases varies greatly in the EPCs. This variation is consistent with the variations in total heated floor area between the EPCs. To ensure that this variation has been taken into account, the regression analyses were always repeated when weighted for heated floor area, as seen in Figure 4 and Figure 5. The collinearity criteria of 2.5 did not exclude the variable number of staircases but number of apartments was removed due to collinearity with heated floor area.

In Table 7, it can also be observed that most multi-family dwellings do not have a garage. Garages are not included in a building's heated floor area and heating in this space should also not be included. A garage will certainly impact the total energy performance of a building, the variable was thus modified to indicate the relationship between the garage area and the heated floor area. Garages larger that than the total heated floor area were removed as outliers.

Table 7 Description of independent scalar variables in regression analyses

Variable	N	Average	Standard deviation
Number of floors	6318	4.21	2.24
Number of stair cases	6319	3.62	3.93
Garage size in comparison with heated floor area [%]	6320	0.861	4.38
Base area share of people with a university degree [%]	6100	43.6	19.4
Base area average income [KSEK*/year]	6054	239	65.4

*1€ = 9.27SEK, 2016-05-25

The groups of the nominal variable ownership was already described in the beginning of this chapter. Building types have not been part of the analyses presented in this thesis. In article III and C, building types (slab block (lamellhus), enclosed block (sluten kvartersbebyggelse), point block (punkthus), slab block (skivhus) and gallery access (loftgångshus)) are derived primarily from the building age registered in the EPCs. The nominal age groups used in articles IV and V are rather based on the construction periods themselves, which were defined as typical in article B. For the regression analyses, the groups after 1946 were treated as nominal building groups (see Figure 6).

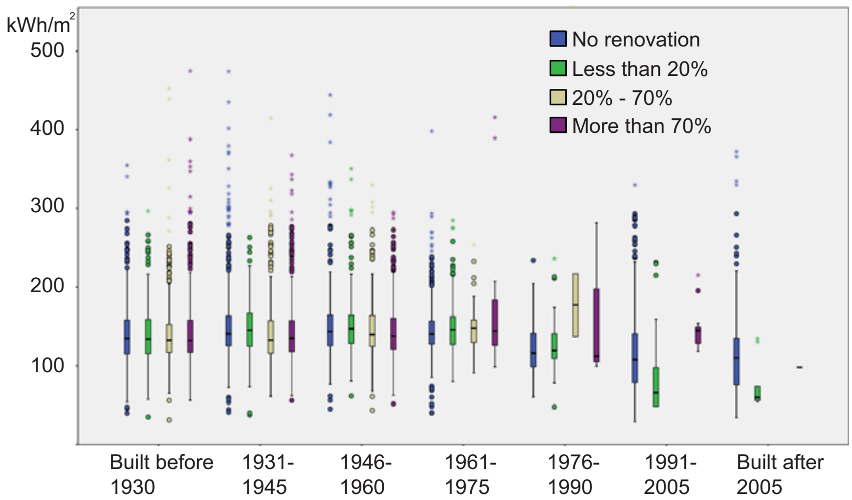

Figure 6. Distributions of energy performance divided into construction periods and renovation cost groups.

Heating system is another nominal variable that was merged into groups, as seen in Table 8 in article V. Building stock heating system distributions is context specific; in Gothenburg, the district heating network provides heating to most multi-family dwellings, making it the optimal group to use as reference in the regression analyses to avoid multi-collinearity. Other reference groups that were kept outside of regressions to avoid multi-collinearity were the private company owned in the ownership groups, and the buildings built before 1945 in the age groups.

The energy efficiency measures and the potential energy savings recommended by the certified energy experts in the EPC were other independent variables that were omitted in the regression analyses. As can be seen in the number of EPCs that have a measured heated floor area in Table 4, there is a difference in the manner in which the EPCs are made between the building owners. The municipal real-estate companies are large enough to have certified energy experts in their staff, and they have a comparatively uniform method of making the EPC, such as deriving heated floor area, A_{temp}, from BOA+LOA. Another way this can be seen is that fewer energy saving measures are made for this ownership group. In communication with energy experts during the work behind article III, it was also understood that the energy experts employed by building owners may have been selective in the types of recommendations that are given so as not to include costly energy-saving recommendations.

There is information about ethnicity in the data from Statistics Sweden. Correlations were found for ethnicity and building energy performance; however, I am not comfortable with presenting statistical correlations with ethnicity without a much deeper analysis. Important to note is that the other Statistics Sweden variables of ethnicity, average income and average educational level should not be interpreted as behavioral variables that impact energy usage, because domestic electricity usage and domestic hot water usage are removed from the heat supplied to the building; rather, they should be interpreted as indicators of how base areas are segregated (Gothenburg City, 2014a). These base area variables were recoded from the number of residents with completed university educations into a share of the population with a university degree, by percentage. Unemployment was also not included due to a strong covariance with the base area average income.

Two additional datasets that would add to the understanding of variations in energy usage in the Swedish building stock are: the building-specific records from the tenants' association on fixed household amenities, such as fridges, stoves etc.; and apartment sizes of all of Sweden in Table 55B organized by the Swedish Land Survey, this data is only accessible by a few state organizations.

2.6 Errors, limitations and insufficiencies

One error in this thesis is equation 1 in article III. The coefficients found for BOA and LOA are close to the Boverket recommended factors used to derive heated floor area, A_{temp}, from BOA and LOA. In article III, it was mistakenly argued that this indicated an agreement between methods. When the EPC data was used in articles IV and V it was concluded that some energy experts had used the Boverket method but mistakenly registered that heated floor area, A_{temp}, was derived through measurements. This resulted in the reproduction of the Boverket factors in the regression, which produced equation 1 in article III. When the regression analysis was repeated with a filter applied for EPCs in which the relationships between heated floor area, A_{temp}, and BOA+LOA equaled the Boverket recommended factors then the regression instead produced equation 2 below (N=683, Adjusted R^2=.969, all coefficients are significant at the 0.001 level).

$$\text{Heated floor area} = -99.9 + 1.0194(\text{BOA+LOA}) + 42.1\text{Floors} + 50.1\text{Staircases} + 11.1\text{Apartments} \quad \text{Equation 2.}$$

For the final results presented in articles IV and IV, heated floor area, A_{temp}, was used without any adjustment. The rationale behind this is that article IV and IV present analyses that produce results that are disaggregated to building levels. The utilization of equation 2 would produce results that would increase the error made for certain buildings without the possibility of identifying which buildings these would be. Table 4 and Table 5 present error factors for the ownership and age groups used in this thesis derived from measured heated floor area without the mistakenly registered calculated heated floor area. One general problem with using comprehensive building-specific data is that the data has been gathered by many unknown people, making it impossible to completely assure data quality. During the data quality assessment for article III it was found that the geographic component of the data is useful in identifying and understanding errors by comparison with publicly available building footage.

In article IV, 50 years of building service life and renovations costs according to the example renovations in Table 7 in article IV are assumed. These two assumptions are the limitations used for article IV and when producing Figure 7, Figure 8 and Table 8 in this thesis. The assumption of 50 years of building service life results in a sharp peak in renovation costs. As mentioned in article IV, it is neither likely nor advisable that renovation investments are made in such a manner. The assumed renovations costs described in Table 7 in article IV are high. To frame the assumption, reference costs based on assumptions of SABO (2009) are presented in Table 8. An error sensitivity analysis could have been presented, but it was decided that the work of estimating variations in both service life and renovation extents would be a task large enough to require a new research task. Collaborations with the purpose of estimate work force and material needs due to renovations has been initiated, in which methods and databases developed in this thesis will be used. Variations in renovation extents and service lives should be an integral part of this task.

In article B, building types are used for the assumption of building envelope energy performance characteristics such as heat conductivity of walls, windows, doors etc. These building types have not been included in the analyses in articles III and IV because an additional layer of inaccuracies would have been added. Specifically for the regressions in article V, assumptions of building types could increase the understanding of building energy performance. For this thesis the limitation has been made to focus on building-specific information, without making assumptions of building types.

A problem in the combination of article I and the other articles is that the renovation project studied does not include any improvement of apartment or building qualities. It is strictly an energy/water saving project with few benefits for inhabitants. This renovation project does not cover the complexity of a trade-off between improved living standards and increased rent.

3 Results

This chapter discusses the main findings of the appended articles. The results of the combination of methods from the articles are also presented to answer the research questions.

3.1 Renovation challenges in different ownership groups

Article V focused on the differences in renovation status and need between ownership groups, RQ1.2. Two central findings in article V are that resident owned multi-family dwellings built by HSB and Riksbyggen have been reporting relatively few renovation projects and that specifically municipal real-estate companies will indeed need to spend more resources if energy usage targets and building living standard targets are to be met (Figure 7). Figure 7 is developed using value year, renovation year, the renovation extent assumption and the 50-year service life assumption described in article IV, but for the ownership groups separated in article V.

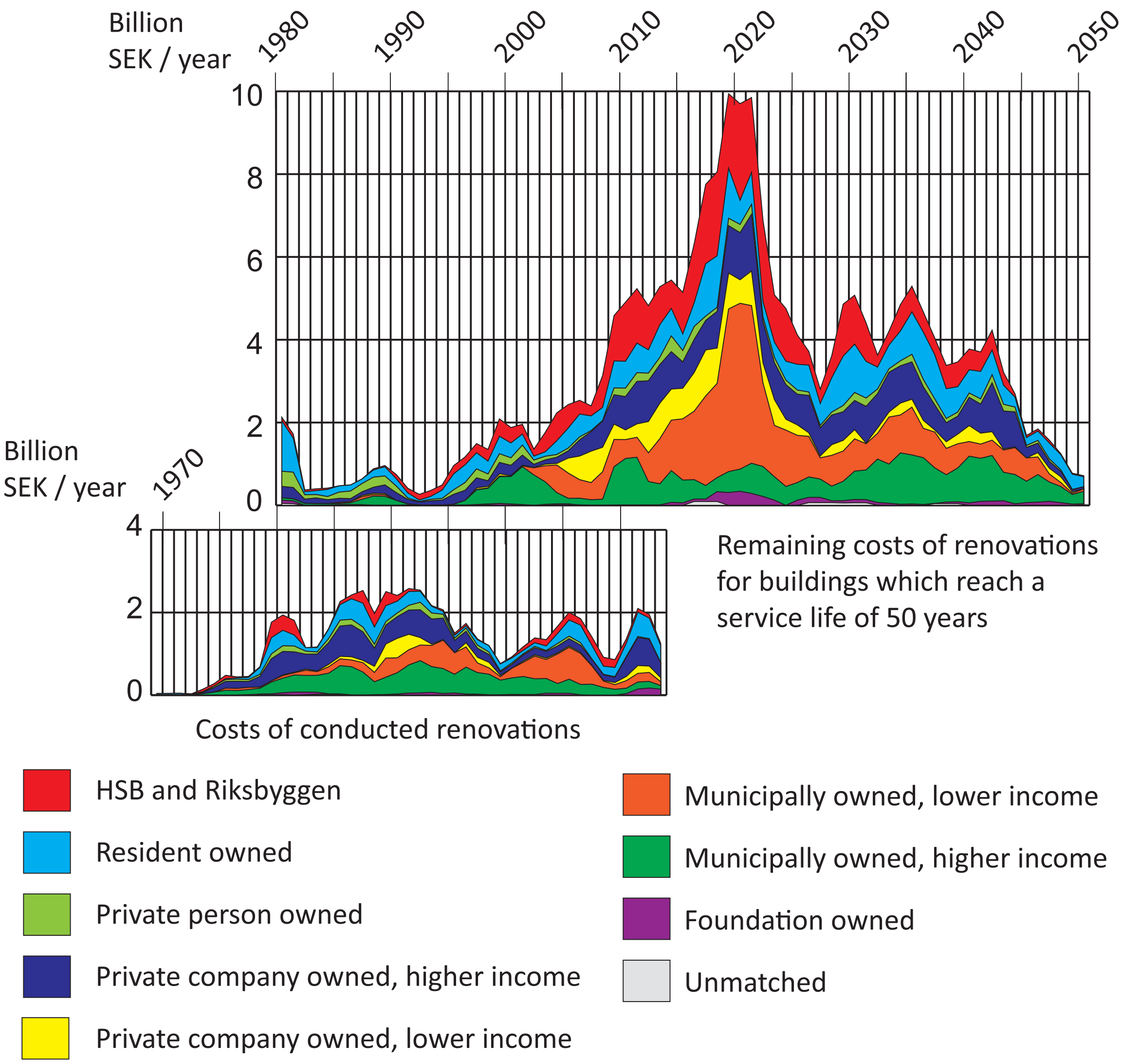

Figure 7. Costs of conducted renovations and coming renovation cost estimates for ownership groups. (1€ = 9.27SEK, 2016-05-25)

As can be seen in Figure 7, the building ownership groups that will have especially high increasing renovation costs “HSB and Riksbyggen” and “Municipally owned, low income”. This was also the conclusion of Boverket and Swedish Energy Agency (2013) in their study on strategies for energy efficient renovations. The renovation cost estimates behind Figure 7 are described in article IV. The average renovation cost is set at 12 600 SEK/m^2 + energy retrofitting costs, which is an estimate comparable with the higher costs presented by SABO (2009). The SABO study is commonly referenced when estimates of renovation costs of building stock are presented. In the SABO study, costs are calculated by the multiplication of a range of renovation costs per square meter with the not yet renovated building stock of SABO. This provided the estimate of 50-275 BSEK for the renovation of 300 000 apartments. This cost range is large, and for a specific part of the building stock. A contribution of this PhD thesis is a more detailed estimate of the amount of apartments that are approaching a 50-year service life and the addition of energy retrofitting costs, see Table 8. The corresponding energy usage reduction is estimated to be 711 and 11 800 GWh/year for Gothenburg and Sweden. In 2013, the total energy usage in Swedish multi-family dwellings was 29 500 GWh/year (Swedish Energy Agency and Statistics Sweden, 2014).

Figure 8 demonstrate the importance of using building-specific information when analyzing building stock. Even though a statistically significant correlation can be found in conducted renovations and future renovation need in the Gothenburg building stock, building groups such as ownership groups or construction period groups will be heterogeneous.

Another contribution of the work behind article III was the advice provided to Boverket for their internal report on reworking the EPC for 2017 when the EPC should be reissued. In addition to what can be found in article III, it was recommended to include the number of inhabitants in the next version of the EPC. This would make it possible to estimate more accurate demand curves for water and electricity usage and to calculate energy usage per person, which is of interest for analyses of life-styles that contribute less GHG emissions than that allowed by international targets and analyses of fairness in GHG emission policies (Büchs and Schnepf, 2013).

Table 8 Estimation of renovation costs for apartments that will have reached a service life of 50 years during the next ten years, in ownership groups. Comparisons with national data have been added from article D.

	Share of building stock that remains to be renovated	Number of apartments to be renovated	Heated floor area to be renovated	Share of renovations that cost less than 20% of new building cost since 1990	Renovation cost estimate according to SABO (2009)		Renovation cost estimate using the method developed in article IV		Renovation cost estimate for only buildings from 1960-1975 using the method developed in article IV	
			[10^3 A_{temp}]		Mini 2000 SEK/m² [BSEK]	Maxi 12 000 SEK/m² [BSEK]	Excluding energy retrofitting [BSEK]	Including energy retrofitting [BSEK]	Excluding energy retrofitting [BSEK]	Including energy retrofitting [BSEK]
Municipally owned, higher income	44%	16 014	1170	37%	3	16	15	18	3	4
Municipally owned, lower income	70%	28 825	2320	39%	5	32	29	34	23	27
Private company owned, lower income	78%	10 711	900	39%	2	12	11	14	8	10
Private company owned, higher income	56%	16 473	1530	45%	4	21	19	22	10	11
Private person owned	74%	6004	528	20%	1	7	7	8	2	2
Resident owned	51%	15 963	1560	57%	4	21	20	23	6	7
HSB and Riksbyggen	71%	25 285	2090	36%	5	28	26	31	16	19
Foundation owned	44%	3250	179	17%	0.4	2	2	3	2	2
Unmatched	15%	260	32	0%	0.1	0.4	0.4	0.5	0.2	0.3
Grand Total Gothenburg (excl. suburbs)	60%	122 785	10 300	40%	23	140	130	152	70	82
Grand Total Malmö (excl. suburbs)	70%	85 635	7650	39%	17	104	96	113	42	49
Grand Total Stockholm (excl. suburbs)	60%	235 537	23 600	37%	48	286	265	310	61	72
Grand Total Sweden	60%	1549 546	127 000	38%	288	1728	1600	1873	824	965

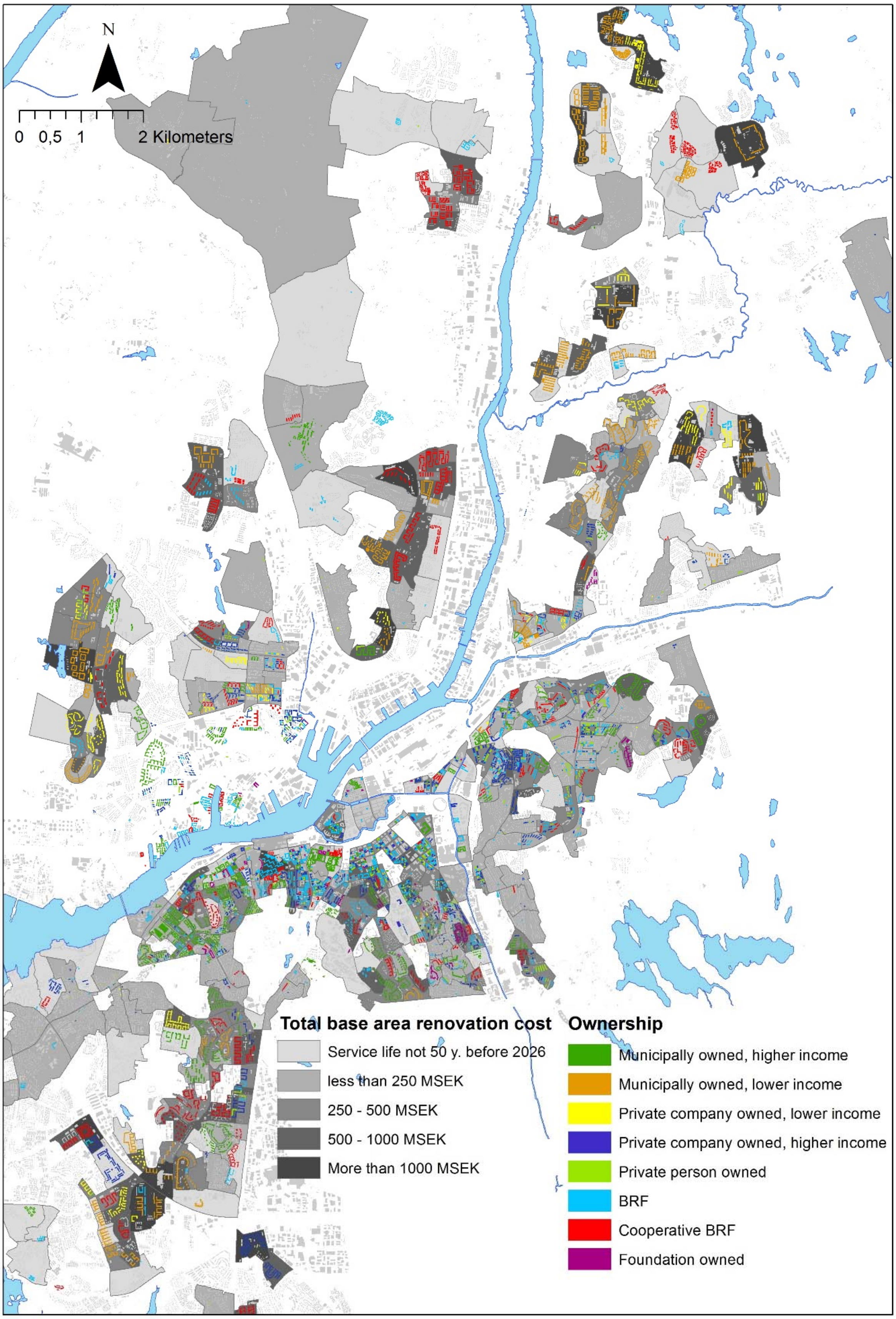

Figure 8. Map of Gothenburg with multi-family dwellings color-coded according to ownership groups and base areas grey scale-coded according to estimated total area remaining costs of renovation.

One finding in article V was that municipally owned buildings are especially overrepresented in larger renovations (costing more than 70% of the new building cost). Larger renovation projects can reduce inequities in society by improving living standards; however, concerns have been raised that large investment by real-estate companies will lead to increasing rents that force the most economically disadvantaged to move (Thörn et al., 2016).

In article V, a negative correlation was found between the energy performance of buildings and base area average income. If heating for water usage is included in the total building energy performance, then economically disadvantaged areas appear to contain buildings with even worse energy performance, as can be seen in figure 1 in article V. Social dimensions and rent increases should be included when suggesting that buildings from the Million Homes Program era in economically disadvantaged areas should be energy retrofitted. Three reasons for this are presented in this thesis: It is more difficult for inhabitants in economically disadvantaged areas to have an impact on renovation decision making (Rojas et al., 2014; Tahvilzadeh, 2015); if energy usage per person is considered instead of energy usage per heated floor area, then building performance would be relatively better in the economically disadvantaged areas; and rent increases for the more economically disadvantaged groups in Gothenburg is not in line with the Gothenburg city (2014a) targets to reduce segregation.

3.2 Socio-economic impacts of renovation of multi-family dwellings

RQ2 was in the focus of articles I and IV. Article IV presented an estimate of rent increases due to renovation and energy retrofitting that found the highest rent increases in economically disadvantaged areas. It was found that 30 600 inhabitants earning less than 60% of the median income live in buildings that will reach a service life of 50 years in the coming decade. These residents are further disadvantaged because they more often move several times after being forced to move, as demonstrated by Boverket (2014b).

Article I was based on a case study of hot- and cold-water usage reducing renovations in an economically disadvantaged area and found that rents had been increased by the private company real-estate owner with the intention of making profit from the renovation project with a few years of return on invest. The conclusions from these studies is that there are risks of increasing societal inequities from the renovation need for several reasons:

- A larger share of the buildings in economically disadvantaged areas will reach a service life of 50 years in the coming decade (article IV).
- Inhabitants in socio-economically disadvantaged areas often experience that they have little influence on building maintenance or renovation decisions (article I).
- Energy usage per heated floor area and energy-saving potential is higher in socio-economically disadvantaged areas, but the common method of individual metering and billing does not allow the most economically disadvantaged inhabitants to participate in the cost savings from reduced resource usage (article I).
- In the case study, maintenance needs are higher because more people live in the area than the official inhabitant statistics (article I).

As was demonstrated by Rojas (2016) the inhabitants of economically disadvantaged areas built during the Million Homes Program era is a heterogeneous group. Many inhabitants could well afford rent increases, and many people would welcome a renovation project that improves living standards (Högberg, 2014).

In the Bredfjällsgatan case, it was found that water and heat saving was used as a way of motivating rent increases that followed the implementation of volumetric billing of water. This was part of the initial cost estimate made by the real-estate company as can be seen in Figure 9 from my licentiate thesis. All costs in Figure 9 were known to the real-estate owner before the implementation of volumetric billing of water. This reduced the financial risk of the investment.

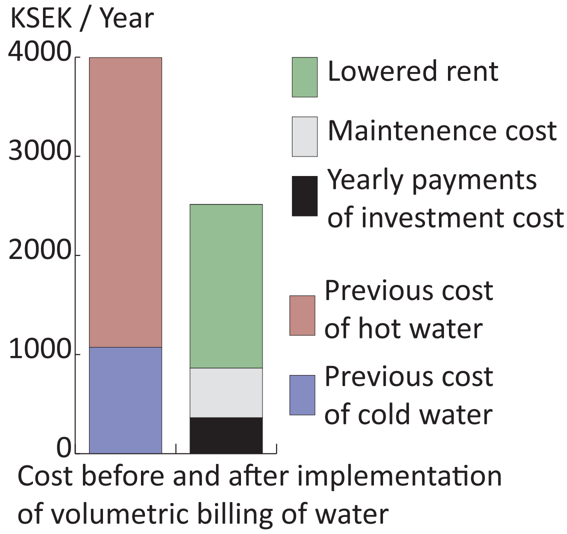

Figure 9. Real-estate-company cost estimates in the implementation of volumetric billing of water at Bredfjällsgatan.

Social Welfare Services is mandated to provide protection for marginalized inhabitants. Social Welfare Services is administered locally as a part of the municipality. Building on Murphy's (2012) social/environmental framework, it is possible to conclude that one, Social Welfare Services is subsidizing energy usage, and two, Social Welfare Services is protecting marginalized groups from fiscal policy designed to mitigate climate change. The system deficits are that Social Welfare Services has no mandate to reduce energy usage and has non-utilized knowledge of residents' socio-economic status that could be used to design an improved tariff structure. There is no formal cooperation between real-estate owners and Social Welfare Services. Social Welfare Services paid 25% of the monthly revenues of the real-estate owner in the study area, motivating formal contacts. Social Welfare Services representatives expressed suspicion against the real-estate owners' intentions to require funding for building upgrades, instead of taking a clear stance for marginalized groups.

4 Discussion

Building regulations, construction prerequisites, climate and inhabitant preferences vary between contexts. This make it relevant to study and compare separate building stocks. There is an increasing amount of studies that use comprehensive building-specific data to describe building stock. Hsu (2014) used building-specific energy usage and engineering audits to describe variations in energy usage in New York and found that variance in energy performance of buildings is not sufficiently explained by building and heating system characteristics. Adding ownership information and renovations investments increases the capacity to explain energy usage patterns. Michelsen et al. (2015) also used measured energy usage from EPC data for a German building stock and used statistical methods to demonstrate that larger real-estate outperform smaller companies in terms of extensive renovations, but that smaller companies can be better at continuous maintenance. Aksoezen et al. (2015) studied a GIS containing building gas usage using statistical methods, and were able to show that there is a strong inter-dependence between energy usage, compactness, and building age. Aksoezen et al. (2015) specify that buildings in Basel constructed between 1947 and 1979 constitute the largest share of stock and use the most energy for heating. Curtis et al. (2015) used EPC data matched with census data for the Irish building stock and found patterns of inequity using building energy performance and inhabitant socio-economic backgrounds. Heeren et al. (2013) used building-specific data to create extrapolations for development scenarios for the 2000-watt society in the city of Zurich. In this thesis, the Gothenburg building stock has been studied using comprehensive building-specific data, with the addition of socio-economic data and building ownership. Social dimensions of renovations were further explored by the addition of a case study renovation project set in an economically disadvantaged area.

Over the past three decades, the main driver of energy usage reduction in the Swedish building sector has been energy price. The reduction in GHG emissions from the building sector is rather due to a change in the energy-mix (Nässén et al., 2008). Similar observations have been made in the Norwegian building stock (Sandberg et al., 2011). As indicated in article II, the 2020 GHG emission targets for the Swedish building sector can be presented as achievable. The Swedish housing market has grown economically over the last 20 years, and the average living standard and lowest living standard in the Swedish dwelling stock is high in comparison with international levels (OECD, 2016). Deregulations of the rental market, conversion of rentals to resident ownership, tax reduction under the RUT program and tax reduction for interests of dwelling loans has contributed to an economic growth that has made possible renovations of large parts of the building stock. Sustaining the economic growth, including more buildings in the group of buildings that can be profitably renovated by resident owners, decreasing household debts and preventing a housing crisis are societal challenges in relation to renovation of the building stock (Sørensen, 2013). However, the Swedish housing market has been described as a contributor to physical, social and economic segregation over the last 20 years (Andersson et al., 2009; Hedin et al., 2012; Sven Bergenstråhle and Peder Palmstierna, 2012). One contribution of this thesis has been to connect building stock research in the field of building technology with research on building ownership and economic equity.

Using the comprehensive building-specific data of Gothenburg it is possible to show that there is an increasing renovation need, especially for municipally owned multi-family dwellings in more economically disadvantaged areas. The renovation cost estimates for the Gothenburg building stock presented in Figure 7 and Figure 8 correspond to the average renovation costs from the pilot renovation projects from Table 7 in article III. As presented by SABO (2009) and in Table 8, actual renovation costs can vary greatly. Priorities for all renovations will not be set based on the commonly used 50 years of service life, nor will all renovation be as costly as the pilot renovations. This thesis is pointing at the issue of increasing needs of renovation and it is providing tools for an early quantitative assessment of the renovation challenge.

With comprehensive building-specific data on the building stock, it is possible to identify which buildings and areas that are especially suitable for, or sensitive to, renovation projects. This information could be useful for the tenants' association and groups working with organizing tenants, to identify areas that need support; for building owners, to compare their buildings with buildings with other owners; and for policy makers, in the work to decrease segregation.

Seventy-one percent of the building stock in economically disadvantaged areas is municipally owned. In these areas, Social Welfare Services pays the rent of the most disadvantaged group. In the case study area of article I, Social Welfare Services paid the rent for 25% of the households, which made it relevant for the real-estate company to know which renovation projects that Social Welfare Services would support. Information sharing and negotiation between Social Welfare Services and housing companies could be beneficial for planning of renovation projects to avoid subsequent rent increases that would further aggravate societal inequities.

There is a risk of discrepancies between phrased targets (Gothenburg City, 2014a) and actual outcomes if policy does not take into consideration that implementing agents are guided by short term economic profits. This was also found in the case study of article A, in which real-estate developers were required to have high environmental ambition, but were not given economic incentives, and thus, competition between developers resulted in minimum investments towards the sustainable development targets of the municipality.

The Swedish stock of dwellings was said to be in shortage already in 2014 (Boverket, 2016a). During 2014 and 2015, 244 000 refugees came to Sweden and has joined the Swedish economy mostly as low-income households (Migration Agency, 2016). A "new" Million Homes Program has been called for at a time when the building constructed during the "old" Million Homes Program era are in need of renovation. During the work for article I, it was found that actual crowdedness of apartments was higher than that listed in official records. With an increased number of low-income households and increasing housing need, crowdedness in multi-family dwellings in the suburbs of larger cities will increase[3]. Insecure tenure and lack of ownership of the dwelling also further increases the maintenance need (2008).

The free/open housing market is seen as a solver of problems and regulations as the tool to set the direction of development. However, little regulation has been implemented that successfully solved the problems of segregation. It has also been claimed that the very nature of a free housing market is to be flexible/unstable and that regulations only make the housing market more volatile (Lind, 2015a). If we take a step back and look at the renovation of multi-family dwellings of different tenure types, these processes have resulted in housing segregation:

- Owners of apartments make a profit from renovating their apartments, while rental apartment tenants fight not to have their apartments renovated (Lind, 2015b; Markusian and Azizi, 2015).
- Working with social equity challenges in renovation projects is problematic because the societal economic segregation is outside of the scope of analyses. Yet, the housing market itself is responsible for the segregation in economic savings that has been occurring in Sweden over the past 20 years (Hedin et al., 2012; Sven Bergenstråhle and Peder Palmstierna, 2012).

4.1 Ways to address the challenges of renovating the building stock

This chapter does not present a comprehensive nor exhaustive account of ways to address renovation challenges. This thesis has focused on analyzing and describing, rather than solving challenges. This chapter is a collection of studies and strategies which have been brought forward by other researchers, professionals and stakeholders as ways of tackling the challenges of energy retrofitting and renovating the building stock.

In the Swedish budget proposition for 2016–2019, 1 BSEK is provided yearly for energy saving renovations (Swedish Government, 2015). In Table 8, the cost of energy retrofitting the multi-

[3] While writing this thesis, the author was involved in several projects with the goals of improving possibilities for refugees to join the housing and work market. The arrival of more inhabitants during 2014 and 2015 made a significant impact on the housing market, specifically raising the price for the cheaper segments of larger inhabitable buildings that are far from larger cities. As integration work is initiated and people move to cities, where it is more common to find work (Riksrevisionen, 2015), the demand for low-income housing and crowdedness will increase.

In 2015 and 2016, the European system of refugee management came under increasing stress. Some called it a systems collapse, while some called it a restriction of refugee rights, illegal under international law (MSF, 2016). In refugee crises there are three groups of response types: maintaining the existing system, creating new systems, or protecting the system from additional stress. The Swedish housing market has also come under increasing stress. For the Swedish housing market, response in these three categories could be: increased production of dwellings funded according to market principles and increased crowdedness in the existing buildings in economically disadvantaged areas, development of some type of social housing system, or reducing the number of people that require housing in cities.

family dwelling stock built during the period 1960-1975, over the next 10 years was estimated to be 141 BSEK. It is not specified how these resources will be cost effective and benefit those who are most in need. Boverket and Swedish Energy Agency (2015) studied governmental loans and credit guaranties concluding that a principal problem is renovation profitability. The possibility of increasing rents to finance energy efficiency renovations, motivated by increased comfort is sometimes mentioned (ClueE, 2013). Legal aspects of the landlord responsibility to comply with comfort specified in building regulations (BBR, 2015; Socialstyrelsen, 2005) and social equity aspects should be considered for such energy retrofitting projects.

The challenge of reducing energy usage by renovating multi-family buildings in economically disadvantaged areas is complex. One approach could be not to install energy usage reducing measures that cannot be financed through reduced energy costs. As was demonstrated in article II, energy usage has decreased over time in existing buildings due to renovations that did not have an energy usage reduction focus (Swedish Energy Agency, 2013). Ott and Bolliger (2015) studied energy renovation strategies by comparing them with an "anyway" renovation. It could be argued that the "anyway" renovation also reduces energy usage simply because old building elements are replaced with new building elements that meet new and tougher minimum requirements.

There are many renovation projects that are lifted up as successful renovations from various perspectives (Lind and Mjörnell, 2015; Thörn et al., 2016). The renovation of Gårdsten, in Gothenburg, included energy saving measures, improved status and attractivity of the area and involvement of the inhabitants in the renovation process; however, the most disadvantaged inhabitants moved away from Gårdsten in the process (Hagblom, 2014). The renovation of Lagerberg in Eskilstuna included an energy-saving target of 50%, inhabitants were mostly satisfied with the results, and rent increases were kept low through an assumed pay-off time of 40 years (BeBo, 2015). In the renovation project called Fittja People's Palace, efforts were made to include residents' opinions during the renovation project and some energy-saving measures were implemented (Eklund, 2016; Nordic Innovation, 2015). The municipal housing company in Malmö, MKB, strove to take an inclusive and responsible role as landlord of the more economically disadvantaged areas in Malmö (Kijewska, 2011).

As identified by Rojas et al. (2014), the inhabitants of disadvantaged Million Homes Program areas often perceive building owners or authorities as careless. Citizen dialogues (medborgardialoger/invånardialoger) as a way of including the tenants' perspectives were studied by Tahvilzadeh (2015) and Lindholm et al. (2015), who also found that the active concern of the authorities is a key component. MKB project leaders stressed the need of spending time with inhabitants (Kijewska, 2011).

In Gothenburg, there are a couple of examples of organized tenants working to change renovation plans of private real-estate companies (Pennygången and Vita Björn). Thörn et al. (2016) have summarized lessons learned from these organizational and legal processes. One way forward is to strengthen community organizations in areas where people have less influence on the development of the society. Social and ethnical segregation are also factors that contribute to final rent increases set after renovation projects. One conclusion from the case study at Bredfjällsgatan is that inhabitants had difficulty making their opinions heard. The tenants' association and Social Welfare Systems did not support the residents that did not want increased rent. The tenants' association and Social Welfare Services have the formal responsibility for representing and caring of socio-economically disadvantaged areas, but there are also plenty of civil society movements that could be part of organizing and strengthening community interests (Kings, 2011).

One increasingly practiced way forward has been to vary the level of renovation extent within multi-family dwellings. This was studied by Lind et al. (2014) in a suburb of Stockholm where a municipal real-estate company allowed inhabitants to choose between mini-, midi- and maxi-renovation alternatives with rent increases of 820, 1790 and 1900 SEK/month, respectively. Rojas (2016) stresses that inhabitants in the Swedish economically disadvantaged multi-family dwelling areas are heterogeneous in terms of income. Some inhabitants want a renovation and subsequent rent increase, while others cannot afford a rent increase. Varying apartment renovation levels is a way of taking differences in economic situations among inhabitants into account, but how the cost of renovations should be split between inhabitants, building owners and authorities is complex. It is also possible that the investments in renovations will not increase. The current housing shortage (Boverket, 2016a) make it profitable for developers to build new buildings. The result of stagnant or reduced investments in renovation could further increase differences in livings standards.

The Swedish housing demand (Boverket, 2016a) has led to increasing real-estate value (Boverket, 2016b) yet the municipality of Gothenburg has set a required return of invest for municipal real-estate companies to comply with possible EU competition regulation (Boverket, 2016c). In the most economically challenged areas of Gothenburg, the municipality owns 71% of the building stock. Motivating a requirement of profitability for municipal housing companies that mainly compete with themselves is insincere. The requirement of profitability is a way of prioritizing. In the Lagerberg case, the pay-off period of the renovation cost was increased to 40 years to decrease the rent increase (BeBo, 2015). The average pay-off time was 24 years for the pilot renovation cases presented in Table 7 in article IV.

Other economic policy tools suggested by the tenants' association are: ROT tax reduction also for rental apartments, tax exempt maintenance funds, and reduced real-estate tax also for rental apartments. MKB began integrating social clauses in the municipal procurement of renovation projects of multi-family dwellings from 2015 (Swedish translation: social upphandling). Thus far, this social clause implies the integration of inhabitants between 18 and 29 in the renovation work force.

In Sweden, social housing has been perceived as part of a segregated housing system. This is not the case in other European countries. In recent years, there has been an increasing interest in adopting some type of social housing system in Sweden, partly due to increasing geographical and economical segregation (Scanlon et al., 2015; Törnquist et al., 2012; Whitehead and Scanlon, 2007). If municipally owned companies (SABO/Allmänyttan) could be seen as social housing, under EU law, then it might be possible to focus public funding on the renovation and energy retrofitting of the municipally owned buildings.

One way forward that has been practiced is to convert municipally owned rental apartments into resident ownership, or private companies, and use the acquired funds to finance renovations. Consequences of such a strategy would be decreasing the influence of authorities and increasing the number of actors in the real-estate market; however, no impact on segregation from applying this method was found by Boverket (2009). In article V, it was found that fewer large renovation projects are conducted in resident owned buildings.

5 Conclusion

The overarching purpose of this thesis has been to analyze the challenges of renovating and energy retrofitting the Gothenburg multi-family dwellings constructed during the Million Homes Program, including equity aspects of geographic and economic segregation. By assembling a database containing building-specific data on energy performance, ownership and socio-economic information, economic challenges were estimated on area levels for building owners, authorities and inhabitants.

Building ownership is in itself not easily used to statistically predict building energy performance. However, for investment in renovations, municipal housing companies carry out the most costly renovation projects, which on average resulted in decreased energy usage. Larger renovation projects will be needed in buildings constructed during the Million Homes Program era (1960-1975); in these buildings, economically disadvantaged groups that are sensitive to rent increases are overrepresented. The lowest number of renovations is reported from privately owned multi-family dwellings. This ownership group has less means and no official mandate to decrease housing inequities.

Renovations and energy retrofitting in the more economically disadvantaged areas have been set up as societal targets, but subsequent rent increases risks aggravating economic inequities. In fact, 30 600 people earning less than 60% of the median income live in buildings that will reach a service life of 50 year in the coming decade. It is recommended that renovation projects in these buildings include social perspectives.

5.1 Future research

As mentioned in chapter *2.2 Building stock data accessibility,* building-specific data is increasingly accessible. Article D is the first step in a national comparison of renovation needs between cities in a GIS. A comprehensive Swedish national building-specific database on energy performance, renovation investments, ownership, and area socio-economic statuses could be used to identify buildings and areas that are especially suitable or sensitive for renovation projects.

The work of comparing building-specific measured energy performance with calculated energy performance is initiated in article B. However, in article B, the sample size is not comprehensive. A comprehensive analysis of the entire building stock would make it possible to analyze renovation scenarios. For article B, building types derived from the EPCs were used to assume building envelope energy performance characteristics, needed for the calculated building energy performance. The possibilities to predict *measured* building energy performance by assumed building types has not yet been sufficiently investigated.

High renovation needs and high housing demand for newly built dwellings, may create work force shortages in the Swedish housing industry. Collaborations with Boverket have been initiated to address this need of future research on the estimation of work force and material needs. In this study it will be necessary to include plans for new construction. For Gothenburg city, the calculations behind the Gothenburg development plan until 2035 (Gothenburg City, 2014b) should be used for this task. This was done by Sweco (2016) using older assumptions of minimal renovations of summed building stock totals, which resulted in lower total renovation costs.

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