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From Housing Inequalities to an Unjust Energy Transition

Data-driven analyses of socio-technical links in the Swedish multifamily building stock

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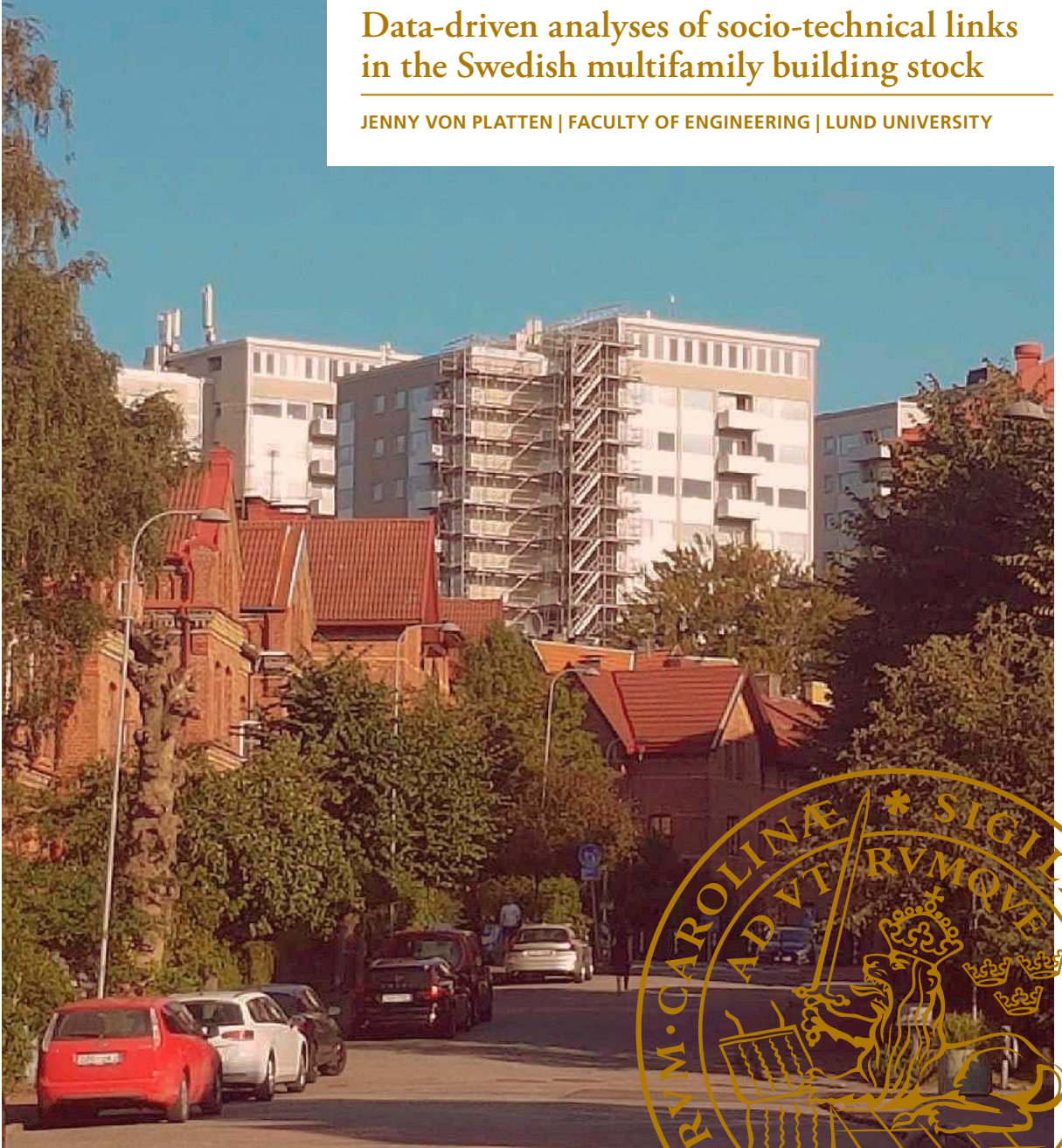
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From Housing Inequalities to an Unjust Energy Transition

Data-driven analyses of socio-technical links
in the Swedish multifamily building stock

JENNY VON PLATTEN | FACULTY OF ENGINEERING | LUND UNIVERSITY



People reside in buildings. It is therefore not surprising that a significant part of our total end use of energy occurs in the building stock. This makes the buildings we live in important targets for improved energy efficiency – but which buildings should be prioritised? In this dissertation, the energy transition of the Swedish multifamily building stock is analysed and evaluated quantitatively to explore conceptual issues of justice in this transition. The research results tell a story of how initial housing inequalities, where low-income households are overrepresented in energy inefficient buildings, develop into distributive injustices of burdens and accountability in the energy transition. These results raise questions that for a long time have been overlooked: Is it worth to rapidly improve buildings' energy performance at the expense of deepened social inequalities? Is it a sustainable transition if it is achieved through unjust means? And how can alternative energy performance metrics change how we define energy efficient housing – and ultimately who is put at the frontline of the energy transition?



This licentiate dissertation is a product of research conducted by Jenny von Platten as part of a collaboration between Lund University and RISE Research Institutes of Sweden. Since 2019, Jenny holds a master's degree in energy systems engineering from Lund University and dedicates her research to matters of social and distributive justice in the energy transition of the housing stock.

From Housing Inequalities to an Unjust Energy Transition

Data-driven analyses of socio-technical links
in the Swedish multifamily building stock

Jenny von Platten



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LICENTIATE DISSERTATION

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To be defended at V:A, V-huset, John Ericssons väg 1, Lund.

October 2nd, 2020 at 1.15 pm.

Faculty opponent

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Abstract Improving energy performance in the Swedish multifamily building stock is an important undertaking in order to reach national and international targets for energy efficiency. However, growing economic inequalities in Sweden, manifested in the multifamily building stock as housing inequalities that entail segregation, overcrowding, and differences in standard of living, have led to low-income households being overrepresented in buildings with low energy performance. In order to ensure that inequalities are not reproduced in the energy transition of the Swedish multifamily building stock, there is a need for increased recognition of socio-technical challenges and their implications for a just transition. The aim of this licentiate dissertation is to improve the socio-technical understanding of the energy transition in the Swedish multifamily building stock and to explore its implications for distributive justice of benefits and burdens among residents. To do this, a national database including both technical and social data was assembled to enable a data-driven approach to study challenges in this transition. The results from the studies included in this dissertation improve the socio-technical understanding of this transition in primarily three ways. First, it was shown that low-income households have carried the greatest share of the past decade's energy savings in the multifamily building stock. Second, it was shown that low-income households were disproportionately affected by a policy aiming at reducing households' energy use due to their overrepresentation in energy inefficient housing. Finally, it was shown that by analysing per capita energy use instead of area-normalised energy use in buildings, the opposite correlation between income and energy performance was found; per capita energy use was the lowest among low-income households, and the highest among high-income households. The reason for this opposite correlation is the higher residential density that is found in low-income households. These findings have implications for the understanding of distributive justice in the energy transition, as it can be considered an injustice that residents with the lowest per capita energy use are met with the highest demands for energy savings. Above all, these results suggest that one way to promote a socially just and sustainable energy transition of the housing stock could be through an increased recognition of efficient building utilisation as an alternative to high energy performance. This would create a more socioeconomically inclusive definition of sustainable living.		
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*Transition is inevitable.
Justice is not.*

- Quinton Sankofa, 2014

Table of Contents

Abstract	viii
Sammanfattning	ix
List of Publications	x
Acknowledgements	xi
1. Introduction	1
1.1. A Socio-Technical Research Paradigm	1
1.2. The Swedish Context.....	3
1.3. Objectives for Energy Efficiency	5
1.4. Research Focus	6
1.5. Aim and Research Questions	8
1.6. Limitations	9
1.7. Structure of Dissertation	9
2. Research Methodology	11
2.1. Scientific Reasoning and Positioning	11
2.2. Reasons for a Quantitative Approach	12
2.2.1. Studying Energy Performance Improvement.....	12
2.2.2. Studying Distributive Justice	13
2.3. Research Methods.....	14
2.3.1. Research Question 1	14
2.3.2. Research Question 2	16
2.3.3. Research Question 3	18
3. Assembling a Database	21
3.1. Previous Work on Data Assembly	22
3.2. Energy Performance Data	23
3.3. Resident Data	24

3.4.	Property Data	25
3.5.	A Comprehensive National Database	26
3.5.1.	Limitations in Data.....	28
4.	Results	29
4.1.	A Gap Between Actual Progress and Targets	30
4.2.	Social Risks of Closing the Gap	33
4.3.	New Metrics Reveal Injustice and can Reduce Risks	34
5.	Discussion	39
5.1.	Interpretation and Reach of Results	39
5.1.1.	Interpretation of Research Results.....	39
5.1.2.	Should Energy Savings in Low-Income Housing be Opposed?.....	40
5.1.3.	Further Aspects of Sustainability in Transitions	41
5.1.4.	Beyond the Available Data.....	42
5.2.	Contribution of Research Findings	44
5.2.1.	Academic Contributions	44
5.2.2.	Contributions for Approach to the Swedish Energy Transition	45
5.2.3.	Contribution of Assembled Database.....	46
6.	Conclusions	47
6.1.	Addressing the Research Questions	47
6.2.	Concluding Remarks	48
6.3.	Future Research	49
	References	51

Abstract

Improving energy performance in the Swedish multifamily building stock is an important undertaking in order to reach national and international targets for energy efficiency. However, growing economic inequalities in Sweden, manifested in the multifamily building stock as housing inequalities that entail segregation, overcrowding, and differences in standard of living, have led to low-income households being overrepresented in buildings with low energy performance. In order to ensure that inequalities are not reproduced in the energy transition of the Swedish multifamily building stock, there is a need for increased recognition of socio-technical challenges and their implications for a just transition.

The aim of this licentiate dissertation is to improve the socio-technical understanding of the energy transition in the Swedish multifamily building stock and to explore its implications for distributive justice of benefits and burdens among residents. To do this, a national database including both technical and social data was assembled to enable a data-driven approach to study challenges in this transition.

The results from the studies included in this dissertation improve the socio-technical understanding of this transition in primarily three ways. First, it was shown that low-income households have carried the greatest share of the past decade's energy savings in the multifamily building stock. Second, it was shown that low-income households were disproportionately affected by a policy aiming at reducing households' energy use due to their overrepresentation in energy inefficient housing. Finally, it was shown that by analysing per capita energy use instead of area-normalised energy use in buildings, the opposite correlation between income and energy performance was found; per capita energy use was the lowest among low-income households, and the highest among high-income households. The reason for this opposite correlation is the higher residential density that is found in low-income households.

These findings have implications for the understanding of distributive justice in the energy transition, as it can be considered an injustice that residents with the lowest per capita energy use are met with the highest demands for energy savings. Above all, these results suggest that one way to promote a socially just and sustainable energy transition of the housing stock could be through an increased recognition of efficient building utilisation as an alternative to high energy performance. This would create a more socioeconomically inclusive definition of sustainable living.

Sammanfattning

Förbättrad energiprestanda i det svenska flerbostadshusbeståndet är en viktig del i att nå nationella och internationella mål för energieffektivisering. Ökad ekonomisk ojämlikhet i Sverige, som manifesteras som segregation, trångboddhet och skillnader i boendestandard i flerbostadshusbeståndet, har dock lett till att låginkomsthushåll idag är överrepresenterade i byggnader med låg energiprestanda. För att undvika att ojämlikheter reproduceras i energiomställningen av Sveriges flerbostadshusbestånd finns därför ett behov av ökat erkännande av socio-tekniska utmaningar och deras innebörd för rättvisa i energiomställningen.

Syftet med denna licentiatavhandling är att öka förståelsen för socio-tekniska korrelationer i energiomställningen av det svenska flerbostadshusbeståndet, och att utforska hur dessa korrelationer påverkar fördelningsrättvisa mellan boende i denna omställning. För detta syfte har en nationell databas innehållandes både tekniska och sociala data sammanställts som möjliggör datadrivna analyser av dessa socio-tekniska utmaningar.

Resultaten från de studier som ingår i denna avhandling bidrar till en ökad förståelse för socio-tekniska korrelationer i energiomställningen på framförallt tre sätt. För det första visade resultaten att låginkomsthushåll har burit den största andelen av de senaste decenniernas energibesparingar i flerbostadshusbeståndet. För det andra framkom det att låginkomsthushåll, på grund av deras överrepresentation i byggnader med låg energiprestanda, blev disproportionerligt påverkade av en reglering med syfte att minska hushålls energianvändning. Slutligen visade resultaten att en analys av energianvändning per capita istället för energianvändning per kvadratmeter gav en motsatt korrelation mellan inkomst och energiprestanda; energianvändning per capita var som lägst bland låginkomsthushåll och som högst bland höginkomsthushåll. Anledningen till denna motsatta korrelation är att boendetätheten generellt är högre bland låginkomsthushåll.

Dessa resultat bidrar till förståelsen av fördelningsrättvisa i energiomställningen då det kan anses vara orättvist att de boende med lägst energianvändning per capita får motta de högsta kraven på energibesparingar. Framförallt föreslår dessa resultat att ett sätt att främja en socialt rättvis och hållbar energiomställning i bostadsbeståndet kan vara genom ett ökat erkännande av effektivt nyttjande av byggnader som ett alternativ till hög energiprestanda. Ett sådant erkännande skulle bidra till en mer socioekonomiskt inkluderande definition av hållbart boende.

List of Publications

This licentiate dissertation is based on the following papers, which will be referred to by their roman numerals in the text. The papers are appended at the end of the dissertation.

- I *The renewing of Energy Performance Certificates—Reaching comparability between decade-apart energy records*
J. von Platten, C. Holmberg, M. Mangold, T. Johansson and K. Mjörnell
Applied Energy, 255, 113902 (2019)
- II *Using machine learning to enrich building databases: Methods for tailored energy retrofits*
J. von Platten, C. Sandels, K. Jörgensson, V. Karlsson, M. Mangold and K. Mjörnell
Energies, 13(10), 2574 (2020)
- III *Energy inequality as a risk in socio-technical energy transitions: The Swedish case of individual metering and billing of energy for heating*
J. von Platten, M. Mangold and K. Mjörnell
IOP Conference Series: Earth and Environmental Science, accepted for publication (2020)
- IV *A matter of metrics? How analysing per capita energy use changes the face of energy efficient housing in Sweden and reveals injustices in the energy transition*
J. von Platten, M. Mangold and K. Mjörnell
Submitted (2nd review round) to Energy Research & Social Science

Other related publications by the author:

Sharing indoor space: stakeholders' perspectives and energy metrics
N. Francart, M. Höjer, K. Mjörnell, A. Sargon Orahim, J. von Platten and T. Malmqvist
Buildings and Cities, 1(1), 70-85 (2020)

Impact of high residential density on the building technology, HVAC systems, and indoor environment in Swedish apartments
A. Abdul Hamid, J. von Platten, K. Mjörnell, D. Johansson and H. Bagge
E3S Web Conf., 172, 09003, (2020)

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Och till Mattias: tack för att du ger mig en trygg plats att falla i bitar på, och kärlek som likt superlim lyckas lappa, laga och stärka mig igen.

Jenny

Gothenburg, August 24th 2020

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1. Introduction

A building and its installations require energy to elevate from simply being a static crust to becoming a dynamic system that can provide an adequate indoor environment for decent living conditions. It is thus not unexpected that a significant share of the world's end use of energy is used in buildings where people work, spend time and reside. Buildings' energy use is therefore not energy used by buildings *per se*, but energy used by people receiving the variety of services provided by buildings worldwide [1].

Ever since the oil crises in the 1970's, energy efficiency has been an important aspect when constructing new buildings and when refurbishing the already existing building stock [2]. In time, awareness of environmental and climate impacts from energy use as well as issues of energy security and sovereignty have continued to put emphasis on energy efficiency in buildings. Along with an acceleration of international mobilisation against climate change in the 21st century, the conversion towards a more sustainable energy system has climbed up on the political agenda, directly affecting national energy systems as well as energy systems in individual buildings. The ongoing transformation of energy systems for this cause is often referred to as an "energy transition". The current energy transition of building stocks in colder climates includes two major objectives: (i) reduced greenhouse gas emissions from buildings' energy use, most often achieved by replacing fossil fuels with renewable energy sources, and (ii) improved energy efficiency in buildings [3]. The focus of this dissertation is how the imposition of the latter is distributed among residents.

1.1. A Socio-Technical Research Paradigm

For a long time after the oil crises in the 1970s, research on the energy transition was centred around technological and economic perspectives on energy use [4]. It was suggested already in 1986 that analyses of energy use needed an increased integration of social sciences in general, and behavioural science in particular, in order to fully understand all dimensions of energy use [5]. Since then, the request for enhanced interdisciplinarity between energy research and social sciences has continued to grow [6, 7], resulting in the establishment of a new journal for this cause in 2014, *Energy Research & Social Science* [8]. The emergence of this new field of research has

contributed to an improved socio-technical understanding of the energy transition by acknowledging the significant impact of humans on energy systems, and vice versa.

In the field of energy use in buildings, many researchers have studied how human behaviour and occupancy influence buildings' energy performance [9, 10]. Similarly, it has been studied how housing choices, such as housing size and housing type, affect residential energy use [11, 12]. Studies have also analysed the effect of energy conservation measures on indoor environment and on the health and perceived comfort among residents [13, 14]. However, little has been said about how the energy transition of the building stock affects residents on a more general level, especially regarding the proportionality between residents' energy use and the demands for energy savings they are faced with simply due to the energy performance of the building they live in.

This can be analysed as an issue of social injustice in general, and in light of distributive injustice in particular. The housing market embodies and manifests inequalities, and fundamental economic inequalities between social groups are displayed as residential segregation (spatial separation) and housing market segmentation (separation in terms of tenure) [15]. Exaggerated by the continued undermining of housing rights brought on by global interests in real estate [16], unequal starting points in society thus play a significant role in the correlation between residents' income and buildings' energy performance. This can be seen as a form of "energy performance segregation" where low-income residents are overrepresented in buildings with low energy performance [17-19]. The fact that residents with low income – despite the arguably unchosen energy performance of the building they live in – are put at the frontline of the energy transition can be viewed as a particularly deep inequality, according to Rawls definition thereof [20]:

“The intuitive notion here is that [...] men born into different positions have different expectations of life determined, in part, by the political system as well as by economic and social circumstances. In this way the institutions of society favor certain starting places over others. These are especially deep inequalities. Not only are they pervasive, but they affect men's initial chances in life; yet they cannot possibly be justified by an appeal to the notions of merit or desert. It is these inequalities, presumably inevitable in the basic structure of any society, to which the principles of social justice must in the first instance apply.” (see [20], p. 7)

Despite significant progress in the field of energy justice over the past decade [21-25], there is still a lack of studies exploring the distribution of benefits and burdens among residents in the energy transition of building stocks. Similar to underlying concepts in environmental justice theory that oppose disproportionate environmental impact in disadvantaged communities [26], energy transition studies should support the principle that disadvantaged residents should not be subject to disproportionate burdens and costs in this transition [27, 28]. Although a smaller body of research has investigated distributive justice of costs associated with changes in national and local

energy systems [29, 30] as well as people's perception of this distributive justice [31], few have considered the building stock as a (physical and spatial) structure where inequalities can be reproduced in the energy transition [32, 33]. Given the embedded inequalities manifested in building stocks, distributive justice in the energy transition of the building stock presents an overlooked area of research [34]. It is the objective of this dissertation to contribute to the progression of such analyses in particular, while also contributing to increased integration of social perspectives in energy research in general.

1.2. The Swedish Context

The Swedish building stock has since the 1970's undergone a successful transition from fossil fuels to more sustainable energy sources [35]. Significant development of district heating has been one contributing factor [36], along with an increased use of electric heat pumps [35]. Since the 1990's, heat pumps have gained substantial recognition, especially in single-family houses, which in combination with other measures for improved energy efficiency have contributed to improved energy performance of buildings [37]. The total end use of energy in the sector has however only decreased slightly since the 1970's [38], as measures for energy efficiency to some extent have been offset by expansion of the building stock and increases in residential area per capita [39].

The focus of this dissertation is on the multifamily building stock, which is home to 42% of the Swedish population [40]. Like in many European countries, the Swedish building stock expanded during the decades following World War II. Although increased rates of construction started in 1945, the peak in construction of new multifamily buildings in Sweden came in the 1960's, reaching an all-time high between 1965 and 1975 during the so called Million Homes Programme [41]. This was a response to the severe shortage of housing and lack of adequate housing standards that prevailed [42], and the government implemented the Million Homes Programme with the goal of constructing 100 000 dwellings per year. At the end of the programme, the housing shortage had been replaced by a housing surplus [41], and the standard of living in Sweden had come to exceed that of many European countries. The extensive construction of buildings in general and of multifamily buildings in particular between 1945 and 1975 has made a significant imprint on the characteristics of the current multifamily building stock.

Over the past decades, several parallel processes have progressed in the Swedish multifamily building stock. First, the energy transition is proceeding with increasing demands for energy efficiency. The greatest hindrance for increased energy retrofitting of multifamily buildings is currently a general lack of profitability as well as difficulties to assess profitability [43, 44], and the pace of energy performance improvement is

consequently not on par with national ambitions [45]. Second, the needs for refurbishment of buildings from the Million Homes Programme have continued to increase and registered renovations in these buildings have been on a constant upsurge since the early 2000's. Yet, there is still a pent-up need for refurbishment in the buildings from this era, and in the multifamily building stock in general [46]. Third, increases in residential segregation, overcrowding, and illegal sublease of apartments have been observed during the past decades in certain parts of the multifamily building stock [47-49], which are likely to partly be consequences of the distinctive increase in economic inequality that have distressed Sweden since the early 1990's [50, 51] and a general lack of affordable housing. Given the known negative effects of economic crises on income inequality and residential segregation [52], these issues are likely to be sustained, if not amplified, in the aftermath of the Coronavirus [53].

Together, these processes have led to a situation that requires a comprehensive socio-technical understanding of the energy transition of the Swedish multifamily building stock. With an overrepresentation of low-income households in multifamily buildings from the Million Homes Programme, these processes have led up to a situation where low-income households are overrepresented in multifamily buildings that are in need of refurbishment and that are seen as the nation's untapped source of energy savings [54]. This will here be analysed as a case of distributive injustice in the energy transition.

The challenge to accomplish extensive refurbishment and significant improvements in energy efficiency while also limiting rent increases is gaining more and more interest; unsurprisingly among affected residents, but also among housing companies [55-57], interest organisations [58] and in the scientific community [59, 60]. Much of this interest has been fuelled by incidents of injustice where renovation-induced rent increases have put residents at economic distress or forced them to move due to the increased rent, sometimes referred to as "renoviction" (eviction due to renovation) [61].

An official response to this challenge came in 2016, when the Swedish government implemented a subsidy for refurbishment and energy efficiency "in some residential areas" [62]. It was a two-part subsidy where the first part of the financial support was intended for refurbishment and reduction of rent increases, and the second part was intended for energy conservation measures. Property owners of rental multifamily buildings in areas with low purchasing power were eligible to apply for the subsidy [62]. However, deficiencies in policy-design and other administrative issues contributed to a low interest in the subsidy among property owners [63]. The Swedish National Audit Office (Riksrevisionen) came to review the subsidy and concluded that one of the reasons behind the setback was lack of sufficient information and analysis before implementation [63].

This example highlights the need to be able to quantify the technical and social effects of different measures in order to account for and carefully balance multiple objectives in decision-making processes. Such a task calls for comprehensive data, and data-driven research can be an effective approach to deepen the knowledge on how the multifaceted energy transition of the multifamily building stock is proceeding.

With this backdrop, the work in this dissertation uses a unique national building-specific database where information about the buildings and their energy use have been combined with socioeconomic information about the residents. The development of this database has followed from the research conducted by Mangold [17] and Johansson [64] and provides an unprecedented opportunity for quantitative socio-technical analyses of the energy transition of the Swedish multifamily building stock.

Eventually, the database assembled in this dissertation was used by the Swedish National Audit Office for their review of the subsidy. They concluded that had analyses similar to those carried out by them during the review been undertaken before implementing the subsidy, a more appropriate policy-design could have been created [65]. The subsidy was cancelled in 2019, but the need to acknowledge residents and ensuring justice in the energy transition remains. A practical contribution of this dissertation is thus to provide a data-driven knowledgebase that lays the ground for more successful policies, and to increase the integration of distributive justice in the creation of such policies.

1.3. Objectives for Energy Efficiency

National and international strategies and policies for improving the energy efficiency of building stocks often aim to do this in the most cost-efficient manner. In most cases, this means that measures for energy efficiency are targeted towards buildings with particularly low energy performance, and in some cases towards buildings that are to undergo refurbishment due to technical deficiencies. As many of the multifamily buildings from the post-war construction era have undergone or are soon to undergo refurbishment, improving energy performance during this refurbishment have been and continue to be a high priority for energy policy. In the European Union (EU), this is regulated in directive 2010/31/EU on the energy performance of buildings (EPBD) [66].

One of the most extensive requirements in EPBD is the system with Energy Performance Certificates (EPCs). EPCs are issued for individual buildings and entails information regarding the building's installations, heating systems, and energy performance, among other things. The purpose of the EPC is to facilitate the communication of buildings' energy performance, and ultimately to increase the demand for buildings with high energy performance. Owners of single-family houses are required to provide a valid EPC when selling their property, whereas owners of multifamily buildings are obligated to always have a valid EPC, meaning that the EPC must be renewed every 10 years. As the regulation was first enforced at the end of 2008 in Sweden, many owners of multifamily buildings have now issued, or are soon to issue, a second EPC for their building(s) [67].

Another central requirement in the EPBD is the long-term renovation strategy, which requires all member states to develop a strategy to support the transformation of the existing building stock into a highly energy efficient and decarbonised building stock by 2050. This should be achieved by facilitating renovations that transform existing buildings into nearly zero-energy buildings.

Apart from the EU targets, Sweden has an overarching objective to achieve 50% more efficient use of energy 2030 compared to 2005. Although it is not explicitly stated, this objective can be interpreted as a 50% improvement in energy performance of buildings over the same period of time.

It is against this background of high ambitions for improved energy performance along with increasing social inequalities in the multifamily building stock that perspectives of justice in the energy transition comes to a head. In his doctoral thesis from 2016, Mangold combined building-specific data from EPCs and residential data from Statistics Sweden to study the social challenges of renovating the multifamily building stock in Gothenburg, Sweden [17]. The aim of this dissertation is to build on the research conducted by Mangold in three main ways: (i) by widening the analyses to a national perspective, (ii) by enriching the database with more building-specific information, and (iii) by continuing to explore issues of distributive justice in the energy transition of the multifamily building stock.

1.4. Research Focus

In the following chapters, a national database is assembled and utilised to answer to three current research possibilities in the energy transition of the Swedish multifamily building stock. The first two possibilities relate to enriching the database to make it a strong foundation for analysis, whereas the third possibility relates to socio-technical analysis of the multifamily building stock.

The first research possibility is the newly arrived opportunity to study building-specific energy performance development over time, as owners of multifamily buildings now are renewing their EPCs 10 years after the initial EPC requirement. Enabling such analyses within the assembled database allows for unprecedented evaluations of correlations between energy performance improvement and variables such as energy conservation measures, renovation, and socioeconomic characteristics. This is addressed in Paper I.

The second possibility concerns the requirement from the European Union (EU) for member states to develop national long-term renovation strategies with focus on energy performance of buildings. The developed database is used to generate new knowledge about the multifamily building stock that can help improve estimations of the national energy savings potential, which is important for the Swedish long-term renovation strategy. This is addressed in Paper II.

The third, and most central, possibility is to study distributive justice in the energy transition of the multifamily building stock. The database is used to analyse to what extent residents in different income groups are faced with burdens in the energy transition. This is addressed in Paper III. This analysis is then complemented by comparing per capita energy use between different income groups and relating that to their respective imposed requirements for energy savings. This is addressed in Paper IV.

By attending to these research needs and possibilities, the aim of this dissertation is to paint an overarching picture of how this energy transition is proceeding and which main challenges it contains. Figure 1.1 shows how the appended papers relate to different processes in the energy transition. Ultimately, the unique national database with technical and social data presents a critical opportunity to raise questions of justice on a higher level than previously done in the discourse on this transition. Seizing this opportunity is the main objective of this dissertation.

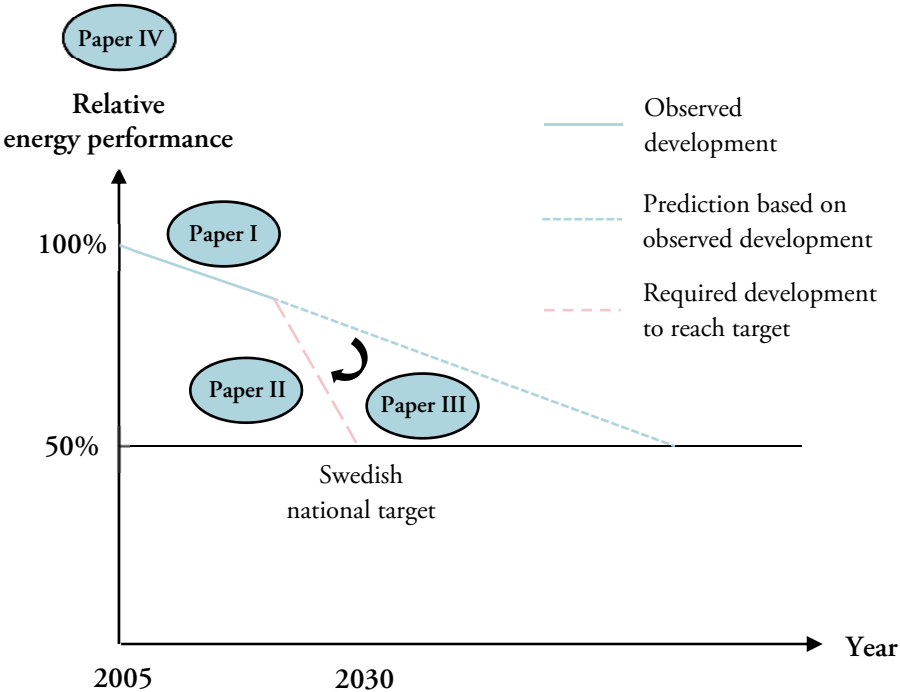


Figure 1.1 A conceptual figure showing how the appended papers correlating to overarching processes in the energy transition of the Swedish multifamily building stock.

1.5. Aim and Research Questions

Aim The aim of this licentiate dissertation is to use data-driven research for an improved socio-technical understanding of the energy transition in the Swedish multifamily building stock and its implications on distributive justice of benefits and burdens among residents.

The first two research questions (RQ1 and RQ2) concern database enrichment:

RQ1 How can a building database be enriched with renewed EPCs and enable quantitative and longitudinal studies of the energy transition?

RQ2 How can machine learning methods be used to enrich national building databases with new information relevant for studying the energy transition?

The last research question (RQ3) concerns socio-technical analysis of the energy transition:

RQ3 How can social and technical data be combined to reveal new knowledge about distributive justice regarding the imposition of the energy transition among residents?

In Figure 1.2, an illustration of the correlation between the research questions, the appended papers, and the two major themes of this dissertation, database enrichment and socio-technical analysis, is shown.

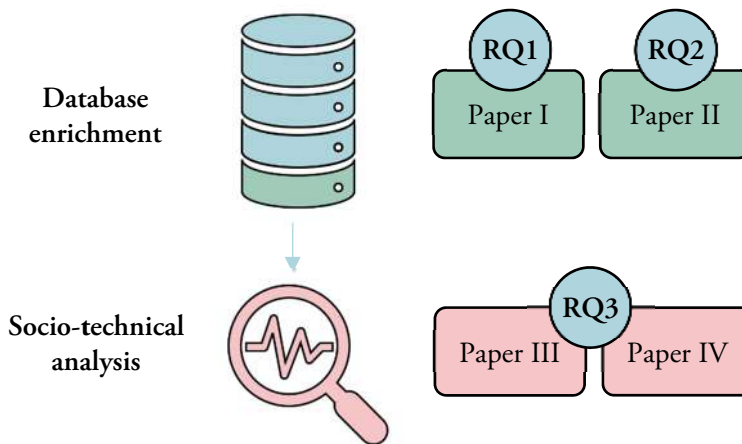


Figure 1.2 An illustration of the correlation between the research questions, the appended papers, and the two major themes of this dissertation – database enrichment and socio-technical analysis.

1.6. Limitations

The main limitations of this dissertation concern the data availability and the quality of data. In order to fully understand the distributive justice of burdens in the energy transition, the inclusion of costs for residents in terms of rent increases would be necessary. However, it is difficult to untangle causality between low energy performance, renovation investments and rent increases, and especially to pin-point how different interventions – such as energy conservation measures and other measures that help finance a renovation – end up contributing to rent increases. As efforts to untangle such relationships were out of the scope of this dissertation, the conducted analyses must be understood as having more conceptual implications for distributive justice rather than providing concrete verdicts of how costs are being distributed. Limitations caused by the character and quality of data are described in section 3.5.1.

1.7. Structure of Dissertation

Following this introductory chapter, Chapter 2 describes the research methodology starting from scientific positioning and narrowing down to specific methods used in the research. In Chapter 3, the data and the data registers that have been used to assemble the comprehensive national database are described along with the strengths and limitations of the database. Chapter 4 summarises the main findings in relation to the aim of the dissertation, and is followed by a discussion of these findings and an outlook of their implications in Chapter 5. Finally, Chapter 6 offers direct answers to the research questions, concluding remarks, and suggestions for future avenues of research.

2. Research Methodology

Research design and methodology have implications for interpretation of research results and the production of knowledge, but also reflect the worldview of the researcher. This section will thus begin with a shorter discussion of the epistemological and ontological positioning of the research in this dissertation, followed by more detailed descriptions of why a quantitative methodology is used for the aim of this dissertation. Finally, the specific research methods used to answer the research questions are described.

2.1. Scientific Reasoning and Positioning

The two central ontological theories, objectivist and subjectivist, can both be applied to the energy transition of the building stock; this is a direct consequence of the transition's intrinsic interaction between people and technological systems. For example, although there might be an objective reality of energy savings after retrofitting or changes in behaviour, the reality of due process during retrofitting or changes in indoor environment is more subjective. To fully understand the socio-technical energy transition, it is thus necessary to apply methodologies that support both objective and subjective ontological beliefs.

The aim of this dissertation is to contribute to improved understanding of the energy transition in general, and of the implications that the energy transition of the multifamily building stock has on social justice for residents in particular. More specifically, it was described in section 1.1 that this was needed in order to fill the research gap on distributive justice of energy transitions in building stocks. Additionally, section 1.2 detailed the practical relevance of such research for the current situation in Sweden where challenges of conducting socially just energy retrofitting and refurbishment, along with inadequate policy-driven remedies, call for an improved knowledgebase for policymaking.

In light of the identified purposes, a quantitative, data-driven methodology was chosen. There are two reasons for this. First, presuming that energy savings in buildings constitute an objectivist rather than a subjectivist development, quantitative analyses of energy savings in buildings are superior to methods that pay more attention to in-depth focus on a more limited number of buildings when it comes to describing the

development of energy performance of a national building stock. Second, the research interest regarding distributive justice in the energy transition is, in this dissertation, limited to the quantitative distribution of energy saving requirements (based on buildings' energy performance) rather than the subjectively perceived distribution of such requirements among residents and property owners.

With the chosen methodology, an objectivist ontological approach is implicit [68]. It is not the intention of this research to claim that there is an objective reality of this energy transition; that it can be understood merely through quantitative analyses of socio-technical data; or that it is equally perceived by everyone, everywhere. The intention is instead to provide comprehensive and representative data that can support and add to an already existing dialogue that comprises objectivist as well as subjectivist perspectives.

Additionally, in accordance with the objectivist ontology, this research places itself in the postpositivist epistemological paradigm where it is presumed that the research findings are probable to be true – even though they only reveal *part* of the truth – but that new findings can come to overthrow current knowledge [68]. For example, access to data with higher quality and resolution could potentially conflict with research findings from current data.

By applying quantitative methods on data for parts of (Paper I, Paper II and Paper IV) or close to all of (Paper III) the Swedish multifamily building stock, this research aims to describe the energy transition in the *analysed part of the building stock* at the *given time*. It is thus not the intention to generalise the research findings beyond this time and space through an inductive approach, but instead to shed new light on this specific context by analysing unprecedented datasets.

2.2. Reasons for a Quantitative Approach

In the previous section (2.1), a quantitative approach was motivated by the aim to improve the socio-technical understanding of the energy transition in the entire multifamily building stock, and by the aim to study the objective and quantitative distributive justice of energy saving requirements. In this section, this reasoning is further developed.

2.2.1. Studying Energy Performance Improvement

There are different ways to study energy performance development over time. Since 1976, the Swedish Energy Agency (Energimyndigheten) has conducted recurring surveys of energy supply and demand in the building sector which have constituted the foundation for the official energy statistics in Sweden [69]. For the multifamily

building stock, surveys are sent out to owners of randomly sampled buildings in approximately 5% of the multifamily building stock. The recurrence of the surveys has made it possible to observe the energy performance improvement over time, but the relatively small sample raises questions regarding the generalisability and representativity of the survey, and the fact that new buildings are sampled for every survey makes it impossible to detail the building-specific reasons for the observed energy savings. It can thus be argued that two major drawbacks of this method to monitor energy performance development are (i) the lack of data quantity and (ii) the lack of building-specific observations of energy performance development.

Other types of studies can partly alleviate these drawbacks. For example, case studies of energy retrofits in individual buildings are useful when determining energy performance improvement from specific measures. However, the question of generalisability and representativity remains as it would require a large number of such studies to reach quantities that suffice for statistically significant results, and as knowledge regarding the frequency of specific measures would still be uncertain. Case studies can consequently contribute with detailed knowledge of the feasibility of specific measures in certain building types, but have limited contributions to the understanding of what drives the energy transition of an entire building stock.

Comparing old and renewed EPCs to quantitatively study building-specific energy performance improvement thus complements current methods to study buildings' energy performance, and the only reason why quantitative and building-specific studies have not been conducted before is that there has been a lack of data. The fact that Swedish EPCs contain measured values of energy use also makes this approach superior to bottom-up building stock modelling. Three reasons make longitudinal applications of EPCs a suitable methodology to detail the progress of a building stock's energy transition: (i) building-specific interventions can through statistical methods provide knowledge of how much energy is usually saved from a specific intervention, (ii) the frequency of specific interventions in the building stock or in part of the building stock can be analysed, and (iii) the energy savings in specific building categories can be compared. How to enable longitudinal analyses of EPCs is addressed in Paper I.

2.2.2. Studying Distributive Justice

In section 2.1, the motivation for using quantitative analysis to study distributive justice in the energy transition was that quantitative analysis is suitable for studying the objective distribution of the imposition of the energy transition among residents. I will here elaborate on this motivation. The main reason why this analysis is best performed quantitatively is that the aim is to seize the general picture. The first presumption here is that the energy transition of the multifamily building stock is imposed on owners of buildings with low energy performance. The second presumption is the principle that

disadvantaged residents should not be subject to disproportionate demands for energy savings and retrofitting. The analysis of distributive justice must thus investigate whether disadvantaged residents (here defined as residents with low affordability) are disproportionately represented in buildings with low energy performance. However, on building-level and even city-level, the variance in correlations between households' incomes and buildings' energy performance is expected to be high. To seize the general picture, it is thus necessary to analyse great quantities of data. Only then can general conclusions regarding the distributive justice of the imposition of the energy transition in the Swedish multifamily building stock be drawn. This type of analysis is applied in Paper III.

Why is it relevant to compare area-normalised energy use and per capita energy use in the multifamily building stock? Returning to the principle that disadvantaged residents should not be subject to disproportionate demands for energy savings and retrofitting, introducing a new energy performance metric can contribute to the understanding of disproportionality. More specifically, it can be argued that it is disproportionate if residents with a relatively low per capita energy use to a greater extent are faced with requirements for energy savings than residents with a relatively high per capita energy use. Beyond analysing whether low-income households are overrepresented in buildings with low energy performance, Paper IV thus also analyses whether low-income households in general use less energy per capita. This hypothesis is supported by the fact that low-income households tend to live more dense than households with higher incomes. Consequently, the analyses in Paper IV can reveal whether the indicated distributive injustice is one-fold (disproportionate imposition of energy transition on households with low income) or two-fold (disproportionate imposition of energy transition on households with low income and low per capita energy use).

2.3. Research Methods

Here, the quantitative methods derived from the reasoning in section 2.1 and 2.2 are described. Although methods to answer all research questions are described, more extensive descriptions are provided for RQ1 and RQ2 as these required specific methods to be developed. For RQ3, where new methods were not developed, a shorter description is provided.

2.3.1. Research Question 1

RQ1 How can a building database be enriched with renewed EPCs and enable quantitative and longitudinal studies of the energy transition?

The first of the three research questions is addressed in Paper I. The aim of the paper was to develop methods to make buildings' old and renewed EPCs comparable so they could be used to analyse and outline building-specific energy performance improvement over time. To overcome issues of comparability between old and renewed EPCs, caused by inconsistencies and changes in the EPCs between 2008 and 2018, and to allow for more accurate longitudinal analyses of energy performance, a three-step method was developed in Paper I. The method is illustrated in Figure 2.1.

The first step of the method was to perform the actual match of old and renewed EPCs. This was obstructed by two factors: (i) renewed EPCs cannot by any quantitative means be connected to the EPC it is replacing, and (ii) there are no readily accessible unique identifiers for individual buildings which makes it difficult to use a building as the common denominator to connect two EPCs. To solve this problem, available data on geographic location, property, and intra-property building-ID were combined to generate a unique identifier for each individual building. The generated identifier was then used to match old and renewed EPCs.

In the second step, mis-matched EPCs were to be excluded. Two main issues were found that compromised the comparability between old and renewed EPC. The first issue was inconsistencies in the level of building aggregation between old and renewed EPCs. Although EPCs are supposed to be issued for individual buildings, it is not uncommon that several similar and adjacent buildings are aggregated in one EPC. If such aggregations have been conducted differently in buildings' old and renewed EPCs, the comparability is reduced and longitudinal analyses would be impaired.

The second issue was caused by regulatory changes in how to determine the heated floor area between the issuing of the first and the second EPC. Whereas the heated floor area initially could be converted from other area measures, a change of regulation required the heated floor area to be measured. Other studies have found that the initial method caused a systematic underestimation of the heated floor area, which in turn caused an overestimation of the energy performance. In longitudinal analyses, this systematic error will thus overestimate the energy performance improvements.

To evaluate whether EPCs had been correctly matched, the heated floor area of matched EPCs were compared. It was found that the vast majority of EPCs had been correctly matched, but that some of the matched EPCs showed deviating differences in heated floor area. Three common reasons for differences in heated floor area between matched EPCs were found: (i) EPCs were simply mis-matched due to errors in the unique building identifier, (ii) matched EPCs contained different levels of building aggregation, and (iii) the heated floor area was underestimated in the first EPCs due to faulty conversion from other area measures. Detailed analysis of data showed that by excluding the 10% of matched EPCs with the greatest deviations in heated floor area, most mis-matched EPCs and EPCs with differing levels of building aggregation were removed, while most EPCs with differences in heated floor area due to changed methods for area determination remained in the dataset. By keeping the latter and

correcting the error, a relatively high share of all matched EPCs could be used for analysis.

Finally, an analysis of data representativity showed significant overrepresentations of municipally owned housing and buildings that had undergone deep renovation between the issuing of their two EPCs. Although these overrepresentations were not corrected for, it was important to be aware of them for a correct interpretation of the final results.

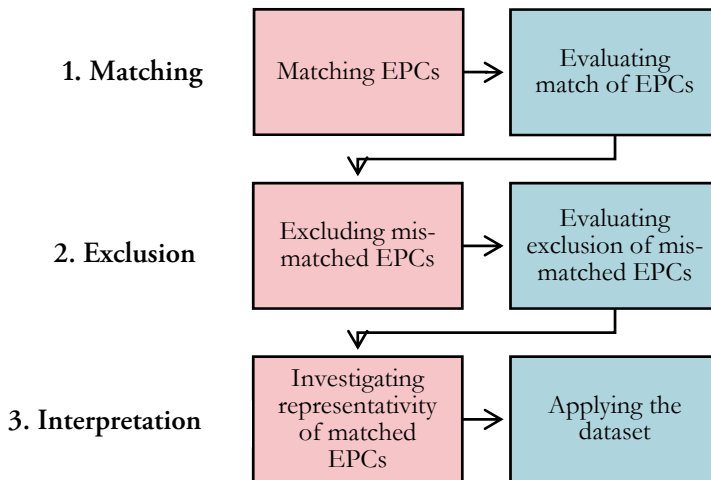


Figure 2.1 The three-step method developed in Paper I to obtain a dataset of buildings' old and renewed EPCs, and to ensure that these EPCs are comparable and suitable for analysis of energy performance development over the past decade.

2.3.2. Research Question 2

RQ2 How can machine learning methods be used to enrich national building databases with new information relevant for studying the energy transition?

The second research question, which is addressed in Paper II, concerns the continued improvement of quantitative, building-specific analyses through further database enrichment. As many building characteristics are missing or difficult to find in national registers, it is of interest to be able to find ways to add new information to existing building databases. An effective way to do this is by using machine learning methods.

In this case, the building characteristics *building type* and *suitability for additional façade insulation* were requested in order to improve estimations of the energy savings potential in the multifamily building stock. The analysis was limited to the multifamily building stock constructed between 1945-1975 as (i) a great part of the multifamily building stock was constructed during this period, and as an increasing share of these

buildings are facing needs for refurbishment there is a window of opportunity to integrate energy conservation measures in the refurbishment plan, and (ii) the construction methods and building types were quite consistent throughout this period which facilitates a distribution of rather similar energy retrofitting measures. The characteristic *building type* was thus defined according to the most common multifamily building types from this period: slab block, panel block and tower block. For *suitability for additional façade insulation*, two qualities were considered: (i) the building should not have a brick façade, as these often should be preserved due to cultural and historical values, and (ii) the building should have eaves overhang since this leaves room for additional façade insulation without having to extend the eaves, which makes the intervention less invasive. *Suitability for additional façade insulation* was thus rather narrowly defined in this paper and can be interpreted as describing buildings that are readily available for additional façade insulation.

With numerous different approaches and model types available within machine learning, some main methodological choices were made. The first methodological choice was to use supervised machine learning as the authors wanted to dictate which characteristics that were to be predicted (*building type* and *suitability for additional façade insulation*). Consequently, labelled training data was first collected through approximately 500 observations in Google Street View, as seen in the illustration in Figure 2.2. If the aim had been to search for unknown patterns, unsupervised machine learning could have been used for e.g. cluster analysis where the machine learning algorithms search for patterns in data that are not predetermined by the researcher.

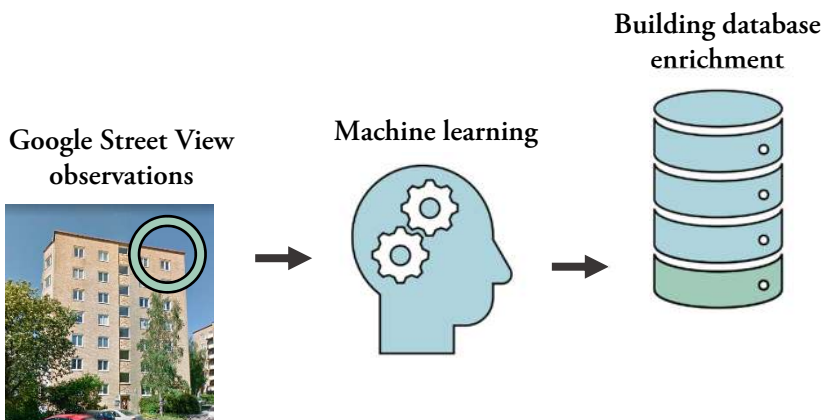


Figure 2.2 Illustration of the process from building-specific observations of approximately 500 buildings in Google Street View to database enrichment using machine learning methods.

The second methodological choice was to use the available data in the building database as feature input in the machine learning models instead of using image recognition. This was motivated by (i) access to a lot of feature data in the building database, and (ii) a will among the authors to utilise expert knowledge on the Swedish multifamily building stock in the development of machine learning models. Expert knowledge of the domain of study can be incorporated by influencing feature selection from non-imagery data, but is more difficult to incorporate when using image data. By allowing expert influence in the generation of machine learning models, a higher level of transparency and interpretability is maintained than had the process been kept in a “black-box”. Although these traits are not required in order to obtain adequate results from the machine learning algorithms, they add value to the research by making the process illustrated in Figure 2.2 more understandable.

A combination of expert influence and stepwise linear regression was thus used to select appropriate features for the prediction models for *building type* and *suitability for additional façade insulation*. Different machine learning models were then developed and tested in order to find the best fitting model for prediction of each of the two building characteristics. After *building type* and *suitability for additional façade insulation* had been predicted for all multifamily buildings from 1945-1975, the energy savings potential in this part of the building stock was estimated based on retrofitting packages designed for the specific building types. For each building type, three energy retrofitting packages of different magnitude were available where only the most extensive package included additional façade insulation. Each multifamily building was allocated a retrofitting package according to the decision tree in Figure 2.3.

2.3.3 Research Question 3

RQ3 How can social and technical data be combined to reveal new knowledge about distributive justice regarding the burden of the energy transition among residents?

The third research question is addressed in Paper III and Paper IV. In both these papers, the database with the enriched data is used in statistical analyses relating to distributive justice of burdens in the energy transition among different groups of income. In Paper IV, methods from Paper I were used to study changes in area-normalised energy use and per capita energy use over time. To determine whether differences in energy use between different income groups were statistically significant, statistical analyses of variance (ANOVA) between group means were conducted in both Paper III and Paper IV. In Paper IV, multiple linear regression models were also developed to investigate how different technical and non-technical variables correlated with development in area-normalised energy use and per capita energy use.

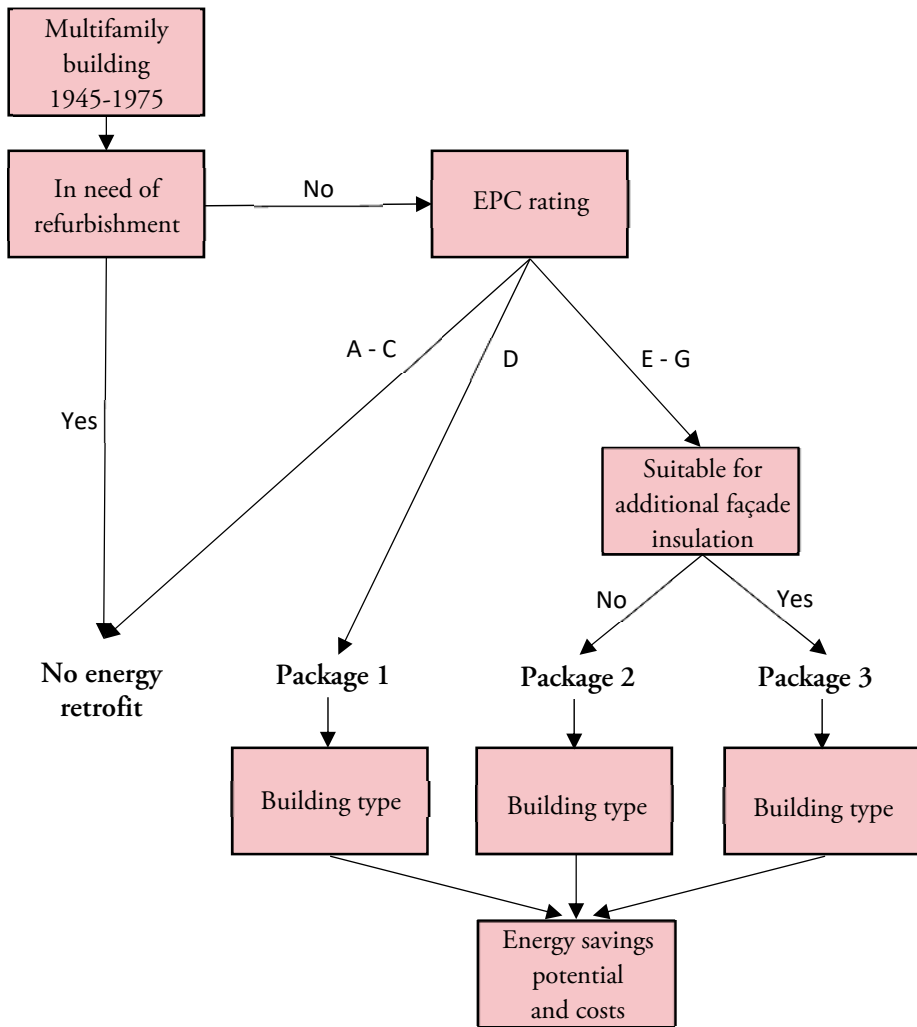


Figure 2.3 Decision tree showing how each individual multifamily building from 1945-1975 was allocated an energy retrofit package (1-3) that would transform the building into nearly zero-energy standard.

3.Assembling a Database

For this dissertation, building-specific data from several national registers were assembled to create one comprehensive database. A comprehensive database lays the ground for data-driven research that can provide decision support in intersecting policy areas in the energy transition of the Swedish multifamily building stock. This research can thus be viewed as both hypothesis-driven and data-driven. This is illustrated in Figure 3.1.

The increased availability of data, and improved computational capacity to store and manage big amounts of data, have started a shift from hypothesis-driven research towards data-driven research [70]. In traditional hypothesis-driven research, the formation of a hypothesis is followed by hypothesis-driven data collection to allow a falsifiable test of the hypothesis to be conducted. This approach often leads to a reductionist description of reality, where fundamental parts of a system are studied and explained independently to eventually create a coherent picture of the analysed system [71]. In data-driven research, it is possible to start in the other end: by painting a holistic picture of the system [71].

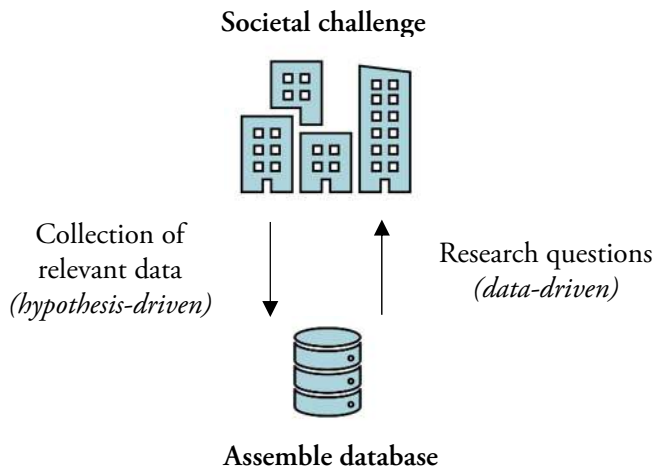


Figure 3.1 An illustration of how the database is assembled through traditional hypothesis-driven research methodology, while contributing to the formation of research questions according to data-driven methodology.

As the database used in this dissertation is assembled for a specific cause, this research is not purely data-driven. In fact, collecting data to answer to a specific problem is in line with traditional hypothesis-driven methodology [72]. However, in this case, data was not collected to answer to *one* specific research question, but rather to create a foundation that can support an area of research. With the database in place it becomes possible to study previously unquantifiable correlations, and research questions thus emerge from the possibilities generated by mere data access. From this perspective, the research follows a data-driven methodology, as seen in Figure 3.1.

In this chapter, the research conducted by Mangold and Johansson will first be described as their work has led up to the assembling of the national database used in this dissertation. The national registers from which the data have been retrieved will then be described, along with their respective strengths and limitations in data. Finally, the chapter is concluded with an overview of the main challenges of assembling the different data registers into one comprehensive database.

3.1. Previous Work on Data Assembly

Many researchers have explored accessible data on the Swedish building stock for analyses of energy performance and other building characteristics [73, 74]. However, few researchers have systematically mapped the available building registers in an attempt to assemble a comprehensive building database. Mangold [17] and Johansson [64] belong to the minority of researchers who have explored national building-specific data registers and combined these in order to assemble a database that enables multifaceted analyses of the built environment. While they both have been temporally concentrated on descriptions of the status quo, their geographical and scientific focus has however been directed in slightly different directions.

In his doctoral thesis from 2016, Mangold processed data on multifamily buildings in the city of Gothenburg. The research focused on exploring data availability, ensuring data quality and achieving inter-registry data compatibility. The quality-assured combined database for Gothenburg was then used to study the impact of ownership on investments in refurbishment and energy retrofitting, and the economic impact of such investments on socioeconomically disadvantaged residents [17].

Similarly, the research in Johansson's doctoral thesis from 2017 focused on combining building data from different registers in general, and combining spatial and non-spatial building data in particular. The combined databases were then used for 3D visualisation of buildings' energy performance as well as of social values from survey data. Central to this research was the development of methods to automate the process of combining large data registers using Extract, Transform and Load (ETL) technologies [64].

In joint efforts, Mangold's knowledge on available building data registers and their compatibility has been combined with Johansson's ETL methods to accurately and efficiently combine national building data registers [75]. The national database that is developed and used in this dissertation is directly built on this research and continues to explore the relevant data registers identified by Mangold and Johansson.

3.2. Energy Performance Data

As previously stated, it is the EPBD that regulates the requirement for member states to have a functioning system for EPCs. The national EPC regulation in Sweden was implemented in 2007 and demanded all owners of multifamily buildings to obtain a registered EPC no later than December 31st 2008. It is The Board of Housing, Building and Planning (Boverket) that is responsible for supervising property owners' compliance with the EPC regulation, and they monitor all EPCs in a database called Gripen. EPCs can only be issued after an on-site assessment by an independent and certified energy expert, and every building should have a separate EPC. In some cases, similar and adjacent multifamily buildings for which energy use is measured collectively are however joined in one EPC.

In Gripen, old EPCs are removed and replaced when a new EPC is issued for a building. Consequently, as EPCs for multifamily buildings expire after 10 years and now are being renewed, old excerpts from Gripen are needed in order to make a comparison between old and renewed EPCs. Only limited EPC data is publicly available, but researchers can make full EPC excerpts from Gripen if an agreement has been established. Under such an agreement, one excerpt from 2015 (containing the first round of EPCs conducted 2008-2009) and consecutive excerpts from 2018 and onwards (containing an increasing amount of renewed EPCs) have been used in the appended papers.

Due to the regulatory requirements, more than 90% of Swedish multifamily buildings have a registered EPC [75]. The EPC contains information on building characteristics such as number of storeys, stairwells and apartments; how the building area is distributed between different types of usages; the heated floor area of the building; the building's use of different energy carriers; the building's energy use for heating and cooling; electricity use for non-domestic purposes; and type of ventilation system. Households' electricity use is not included. Almost all energy use data in Swedish EPCs are based on operational values, with an exception for newly constructed buildings that initially must have an EPC with calculated values for energy use, i.e. an asset rating. In the vast majority of EU member states, EPCs are based on asset ratings which are known to deviate from the operational energy use. This deviation is known as "the energy performance gap" and has been the subject of study among many researchers [76-79], but is naturally a non-issue in studies of Swedish EPCs.

However, despite the lack of an energy performance gap, there are other concerns regarding quality and reliability of Swedish EPC data. First, studies have shown that the influence of the certified energy expert on the outcome of the EPC rating is significant [80], with variations in the range of $\pm 20\%$ in the assessment of energy use among different experts [81]. Second, interviews with certified energy experts have revealed a rather frequent occurrence of uncertain estimations and arbitrarily distributed values in Swedish EPCs [82]. Third, the reliability of the heated floor area, which is used in the calculation of energy performance, has been proved to be insufficient [83, 84]. This is due to a previous regulation that allowed heated floor area to be derived from other area measures which has caused a systematic underestimation of buildings' heated floor area. Today, the heated floor area must be measured.

These types of regulatory changes regarding the issuing of EPCs have contributed to improved EPC quality and reliability over the years. However, changes in the EPC become a problem when new EPCs are to be compared to old ones. As previously stated, this issue is addressed in Paper I.

Overall, EPCs provide valuable information about multifamily buildings and their energy use. The high coverage of the multifamily building stock makes EPCs suitable for statistical analyses on building-stock level, and the known variations in energy use data also motivates statistical analyses rather than detailed analyses of individual buildings. It is however important to be aware of the flaws in the EPC data and to correct for the systematic underestimation of energy performance in old EPCs.

3.3. Resident Data

Resident data were retrieved from Statistics Sweden (SCB), which is a government agency with responsibility to provide official statistics to the public. Anyone can access tabled and aggregated data from Statistics Sweden, but researchers can buy data on a higher level of granularity under the establishment of specific agreements.

The highest level of granularity on which resident data could be retrieved was aggregated to property-level. Resident income data were thus generalised to median income for each property. As a property can contain more than one building, the median income for residents on a specific property was assumed to be the same for residents in all buildings on that property. As the national database for multifamily buildings is based on the EPCs and thus have building as the most detailed level of aggregation, there was no need to further disaggregate the income data. Although income varies among households in the same building, let alone on the same property, it is assumed that the median income of residents on a certain property provides an adequate representation of the concerned households' incomes for the intended purpose of data use. However, it should be noted that income data do not provide a

full representation of the affordability or economic wealth of a household as assets could be held in other forms.

Data on the number of residents were also retrieved on property level. To disaggregate the data to building-level, the total number of residents on a property were distributed among the property's buildings with floor area as base for allocation. The residential density was thus assumed to be the same in all of the property's buildings. It should finally be noted that the statistics on number of residents on a property comprise residents that are registered on the property. Owing to the increase of illegal subleases of apartments, it is thus likely that the number of residents will be underestimated in some parts of the multifamily building stock.

Unlike in Gripen, where old EPCs are replaced when a new one is issued, Statistics Sweden retain historical data. For the requested data on residents' income and number of residents per property, records were available from 2011 and onwards. To achieve the best match possible with the EPC data, where old EPCs are from 2008-2009 and new EPCs are from 2018 or later, resident data from Statistics Sweden were purchased for 2011 and 2016-2017. When data were purchased in 2018, later records than 2016-2017 were not available.

3.4. Property Data

Property data were retrieved from The Swedish mapping, cadastral and land registration authority (Lantmäteriet), which is a government agency that provides information on Swedish property and geography. Data on ownership, coordinates, and degree of renovation have been purchased annually since 2016.

As the property owner owns all buildings on the property, no assumptions have been made in the disaggregation of ownership data to building-level data. Coordinate data are received as one coordinate per property (i.e. a point and not an area) and have been kept intact in the disaggregation to building-level data.

Degree of renovation can be determined using Equation 1 [85] based on the variables construction year, year of reconstruction, and the adjusted value year. A property's value year is adjusted by Lantmäteriet at reconstruction based on the cost of the investment in relation to the cost of new construction, as reported to the Swedish Tax Agency (Skatteverket). The exact correlation between value year, investment cost, and degree of renovation can be seen in Table 3.1.

$$\frac{\text{Value year} - \text{Construction year}}{\text{Reconstruction year} - \text{Construction year}} = \frac{\text{Renovation cost}}{\text{New construction cost}} \quad \text{Equation 1}$$

Table 3.1 The correlation between degree of renovation, investment cost, and value year.

Degree of renovation	Investment cost	Value year
Light renovation	Less than 20% of cost for new construction	Value year is same as year of construction
Medium renovation	Between 20-70% of cost for new construction	Value year is between year of construction and year of reconstruction according to Equation 1
Deep renovation	More than 70% of cost for new construction	Value year is same as year of reconstruction

There is no way to disaggregate renovation status from property-level to building-level. It is thus unavoidable to assume that all buildings on a specific property have undergone the same degree of renovation, although intra-property variation is to be expected. More so, the degree of renovation is only a representation of the relative amount of money that has been invested in the property. It is thus not possible to specify what interventions that have been conducted, which also makes it difficult to compare e.g. energy savings between buildings that have undergone different degrees of renovation as the interventions may be incomparable.

3.5. A Comprehensive National Database

The described data registers have been combined to a national building-specific database under the above described assumptions, and an overview of the database can be seen in Table 3.2. However, as most of the described data were property data rather than building data, the choice of aggregation level is not self-evident. As seen in Table 3.3, approximately 74% of all properties only contain one multifamily building. With an average of 4.1 multifamily buildings on properties containing more than one building, this means that only 40% of the multifamily buildings are located on properties with only one building. In other words, most multifamily buildings in the database (approximately 60%) are located on properties with more than one building and will thus suffer from impaired data quality due to assumptions of equivalence and disaggregation of property data to building-level data.

These data uncertainties could have been avoided if the database was property-specific rather than building-specific. However, returning to the intended use of the database, which is to gain a building-specific and data-driven understanding of the energy transition of the multifamily building stock, it is clear that an analysis of properties would be methodologically incorrect. The energy transition of the multifamily building stock, as defined and studied in this dissertation, is carried out in

one building at a time. Changes in buildings' energy systems and measures for improved energy efficiency are implemented within the closed system of one building, and making the majority of buildings subject to aggregation on property-level would thus be unjustifiable.

The assembling of this database showcases some of the practical and theoretical challenges that are faced when merging data from several different national registers. However, in most cases, the conversion from property-level data to building-level data is acceptable. The greatest uncertainty concerns the building-specific degree of renovation as there is a lack of adequate methods to disaggregate the investment in a property to its individual buildings. Apart from that, there are many advantages of the database, including measured values for energy use, comprehensive socio-technical data, and, above all, a high coverage of the Swedish multifamily building stock.

Table 3.2 An overview of the data included in the assembled database.

Data Category	Data Source	Relevant Data	Level of Aggregation	Transformation	Year
Energy system and performance data (EPC)	Boverket	Energy performance, heated floor area, heating system, ventilation system	Building	None	2018-2019
Resident data	Statistics Sweden	Residents' median income	Property	None	2011; 2016
		Number of residents	Property	Dis-aggregated to building level	2011; 2017
Property data	Lantmäteriet	Owner, coordinates, renovation status	Property	None	2016-2020
Enriched data	Boverket	EPC data (see above)	Building	None	2008-2009
	Google Street View	Building type, suitability for additional façade insulation	Building	None	2019

Table 3.3 Instances (%) when a property equals a building and vice versa.

	One building per property	More than one building per property
Share of Properties	74.4%	25.6%
Share of Buildings	40.4%	59.6%

3.5.1. Limitations in Data

Limitations in the data used to assemble this database ultimately becomes limitations in the research conducted on this database. Besides the already described issues of quality in the data – such as arbitrary values in the EPC data and assumptions of generalisability from property level to building level – there are other more and less obvious limitations in the data.

First, while it is possible to derive interventions such as change of heating or ventilation system from comparisons of old and renewed EPCs, it is not possible to extract information of other types of energy efficiency measures such as additional façade insulation. Similarly, the degree of renovation derived from investments in the property does not provide any details on what type of interventions that were conducted. This means that it is not possible to differentiate between energy retrofits and renovations with e.g. more aesthetic purposes, and as a consequence, it might be difficult to draw general conclusions regarding the energy savings from different degrees of renovation. More so, although property owners have economic incentives to report their renovation investments to the Swedish Tax Agency, such reports are still voluntary, and it is thus likely that some renovations are not registered.

Second, the longitudinal analyses of energy performance are limited by the EPCs, which currently are available in two rounds with ten years apart. Determining energy savings from specific interventions will consequently be difficult as a lot can happen over a decade that affects a building's energy performance, and many interventions are not to be found in any registers. More accurate analyses of energy savings from specific measures would require EPCs to be issued shortly before as well as shortly after an intervention.

Finally, the fact that energy use data in the EPCs do not contain households' electricity use limits the potential to fully analyse changes and differences in residential energy use. However, this decoupling of households' contribution to residential energy use limits the analyses in this dissertation to the energy use induced by the characteristics of the building, which in this case is actually an advantage. This is because this dissertation aims to investigate the correlation between energy-related housing inequalities and the imposition and development of the energy transition.

4. Results

Adhering to the aim of this dissertation, the research presented in the appended papers has made contributions to an improved data-driven and socio-technical understanding of the energy transition of the Swedish multifamily building stock. How the appended papers relate to different processes in this transition can be seen by returning to Figure 1.1.

In Paper I, methods are developed that enable evaluation of the past decade's energy transition with an unparalleled level of detail, and with the possibility to show correlations between energy savings and characteristics of the building, renovation, energy efficiency measures, and residents' income. These methods have been used to show that energy performance is improving, but if the past decade's pace of improvement continues, the national target to reach 50% of 2005's energy performance in 2030 will not be reached.

Paper II focuses on the multifamily building stock constructed between 1945-1975 and predicts the energy savings potential through novel applications of machine learning methods in studies of energy retrofitting. The results of this paper show that there is great potential to save energy in the multifamily building stock, but that energy performance improvements of 50% are costly and not available for a significant part of the analysed building stock. These results thus provide a glance of what would be required in order to reach the national target by 2030, especially in terms of trade-offs between energy savings and historical values in the building stock.

Paper III addresses the issues related to increasing the pace of energy performance improvement by showcasing the negative social implications of a recent energy policy. The results of this paper show how already existing inequalities in the multifamily building stock risk being magnified in the energy transition if such inequalities are not acknowledged in the creation of energy policies. This raises questions of social and distributive justice in the energy transition and problematises current approaches to push the expected development (the dotted line in Figure 1.1) towards the required development to reach national targets (the dashed line in Figure 1.1).

Finally, Paper IV takes an overhead perspective by questioning the way in which we currently measure energy performance ($\text{kWh}/(\text{m}^2 \cdot \text{year})$) and offers new insights in the energy transition by measuring per capita energy use instead ($\text{kWh}/(\text{capita} \cdot \text{year})$). In doing so, distributive injustices are revealed and conceptualised, a different view of energy efficient housing is proposed, and new ways to approach the energy transition of the multifamily building stock emerge.

Together, the appended papers provide a foundation of methods, concepts and findings that allow to tell a new story of the development of the energy transition. This is a story that includes challenges; both to meet national and international targets for energy efficiency, but also to make this transition in a way that is socially just and sustainable. In the following sections of this chapter, the results of the appended papers will be described in more detail.

4.1. A Gap Between Actual Progress and Targets

Figure 1.1 shows that there is a gap between the energy performance improvements that occurred over the past decade and the energy performance improvements that are requested in national targets. While Paper I offers a description of the past decade's development, Paper II showcases how a more ambitious retrofitting strategy could be developed. The results from these two papers will be described here.

The results from the building-specific analysis of old and renewed EPCs in Paper I can be seen in Figure 4.1. Three findings stand out in this analysis. The first finding is that the energy performance in general has improved more in buildings constructed between 1945-1975 than in the rest of the stock, as seen in Figure 4.1(b). It is likely that this can be explained by a relatively high degree of renovations among the buildings from this era due to needs for refurbishment. There is thought to be more energy savings potential to tap into in this part of the stock, and the increased refurbishment and energy retrofitting potential of the multifamily buildings from 1945-1975 is further investigated in Paper II.

The second finding concerns the correlation between renovation and energy performance improvement. It can be seen in Figure 4.1(c) that the most significant improvements in energy performance, not unexpectedly, are found in buildings that have undergone deep renovation over the past decade. It should however be noted that buildings in this renovation category constitute less than 1% of the entire multifamily building stock. Buildings that have undergone medium and light renovations show significantly lower levels of energy performance improvement, and do not markedly differentiate from the energy performance improvement seen in buildings that have not undergone any renovation at all. These results indicate that some degree of energy performance improvement occurs even without renovation, and that it is primarily in deep renovation that energy performance improvement appears to be a priority. It should however be remembered that the renovation categories are based on registered investments in the property, making it difficult to separate energy retrofits from investments with little to no impact on the building's energy performance.

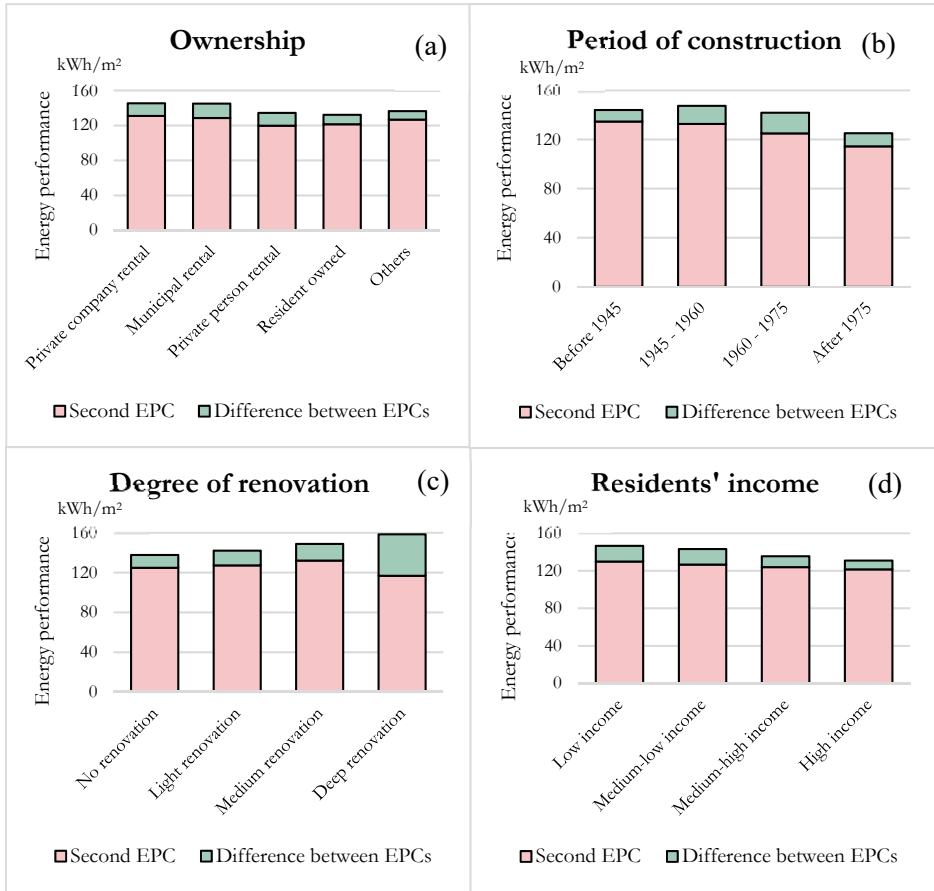


Figure 4.1 Energy performance improvement between a building's first EPC (~2008) and second EPC (~2018), divided into categories of ownership (a), period of construction (b), degree of renovation (c), and residents' income (d).

The third finding concerns the correlation between energy performance and residents' income. It can be seen in Figure 4.1(d) that at the issuing of the first EPCs, there was a clear positive correlation between energy performance and income, i.e. energy performance was better in buildings inhabited by residents with higher incomes. At the issuing of the second EPCs, this correlation remains, but with a slightly lower inclination. As can be seen, improvements in energy performance have been greater in buildings occupied by residents with lower incomes.

With an average energy performance improvement of approximately 10% in ten years, it is evident that significant efforts are required in order to reach the national target for energy efficiency in 2030 in the multifamily building stock. Reaching this target would require an increased amount of renovations, and especially an increased focus on energy performance improvement in light and medium renovations.

Estimating the energy savings potential from renovations with increased focus directed towards energy performance improvement was explored in Paper II. With the overarching goal to convert existing buildings into nearly zero-energy buildings, each multifamily building from 1945-1975 was allocated an energy retrofitting package that would improve the building's energy performance to nearly zero-energy standard. After predicting *building type* with an accuracy of 88.9% and *suitability for additional façade insulation* with an accuracy of 72.5%, three energy retrofitting packages were available for each building type where the most extensive energy retrofitting package (3) included additional façade insulation. The predicted characteristics *building type* and *suitability for additional façade insulation* were thus used to correctly match retrofitting packages to buildings according to Figure 2.3. However, in order to base estimations for energy savings potential of a rather realistic assumption where trade-offs between cultural preservation and energy savings occur, 50% of buildings that were characterised as *suitable for additional façade insulation* were even so allocated retrofitting package 2.

Assuming that buildings were to undergo refurbishment when they reach a service life of 50 years, and that pent-up needs for refurbishment were to be spread out over a ten-year period, the results in Figure 4.2(a-b) were obtained. Figure 4.2(a) shows significant energy savings from energy retrofitting package 3 (the most extensive retrofitting package with energy savings of approximately 50%). However, these energy savings come at a considerable cost, as seen in Figure 4.2(b).

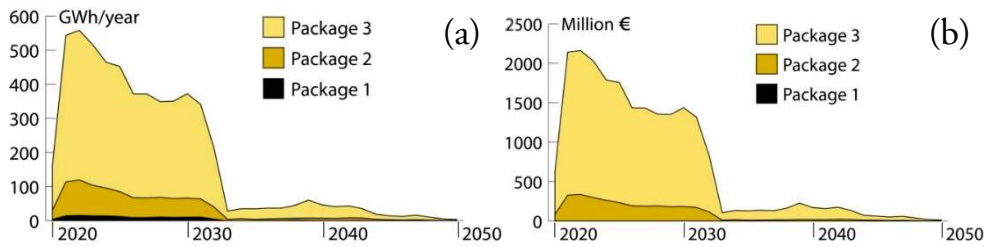


Figure 4.2(a-b) The figure shows yearly, cumulative: (a) Energy savings potential from the different energy retrofitting packages and (b) The associated costs.

Notably, the results in Figure 4.2(a) reflect the energy savings potential that is possible if energy conservation measures are prioritised during renovations that aim to extend buildings' service life. However, the results from Paper I show a different reality where energy savings do not appear to be a priority in the vast majority of renovations. Even in deep renovations, results from Paper I show that energy savings are far from 50%.

The results of Paper II emphasise the discrepancy between the energy savings that are required during refurbishment in order to reach nearly zero-energy building standard, and the energy savings that have occurred during refurbishment during the past decade as seen in Paper I. This discrepancy is problematic in the light of reaching targets for energy efficiency, but could also be used as an argument to re-think the

existing targets. This will be explored in the following sections where results from Paper III and Paper IV are described.

4.2. Social Risks of Closing the Gap

Although it is on the political agenda to close the above identified gap between expected and required energy savings, it is of high importance to be aware of the effects this might have on residents. In Figure 1.1, Paper III is positioned in this gap as it analyses a recently passed energy policy in Sweden. The policy concerned individual metering and billing of energy for heating in multifamily buildings. In Sweden, there has been a tradition of collective payment for heating in multifamily buildings, where the buildings' total demand for heating is divided among the households with apartment size as base for allocation. However, to comply with directive 2012/27/EU on energy efficiency [86], Sweden has for a long time been pressured by the EU to find a way to implement individual metering and billing of energy for heating. The reason why this is requested by the EU is the belief that individual metering and billing of energy for heating will reduce households' energy use for heating.

In 2019, it was decided that individual metering and billing of energy for heating should be required in multifamily buildings with an energy performance above 180 kWh/(m²*year) in the northern parts of Sweden, and in multifamily buildings with an energy performance above 200 kWh/(m²*year) in the rest of Sweden. An analysis of the number of residents affected by this new regulation in each income decile and their corresponding per capita energy use can be seen in Figure 4.3. In the figure, the colour of the circles represents the per capita energy use and the size of the circles represents the residential density, i.e. the number of square meters per capita.

In accordance with results regarding the correlation between buildings' energy performance and residents' income from Paper I, Figure 4.3 shows that low-income residents are strongly overrepresented among residents affected by the new requirement for individual metering and billing of energy for heating. In particular, residents in the lowest income decile are severely affected. These results present a problematic situation where a regulation aiming at reducing households' energy use through economic incentives mainly affects economically vulnerable households with low per capita energy use.

However, beyond showcasing an unjust distribution of burdens in the energy transition of the Swedish multifamily building stock, the requirement for individual metering and billing of energy for heating has introduced an unprecedented risk for energy poverty among the affected low-income households. Owing to the tradition of collective payment of heating, energy poverty has for a long time been considered a non-issue in the Swedish multifamily building stock. The collective payment has acted as protection against energy poverty as households have lacked economic incentives to

restrict heating expenses, but with this new regulation, this protection is removed among the affected households in Figure 4.3. Consequently, low-income households are put at the frontline of the energy transition, causing a risk for reproduction and deepening of already existing inequalities. These results showcase negative effects that can occur when closing the “energy savings gap” with a mere technological approach, and with a lack of consideration for the structural inequalities that are embedded in the multifamily building stock.

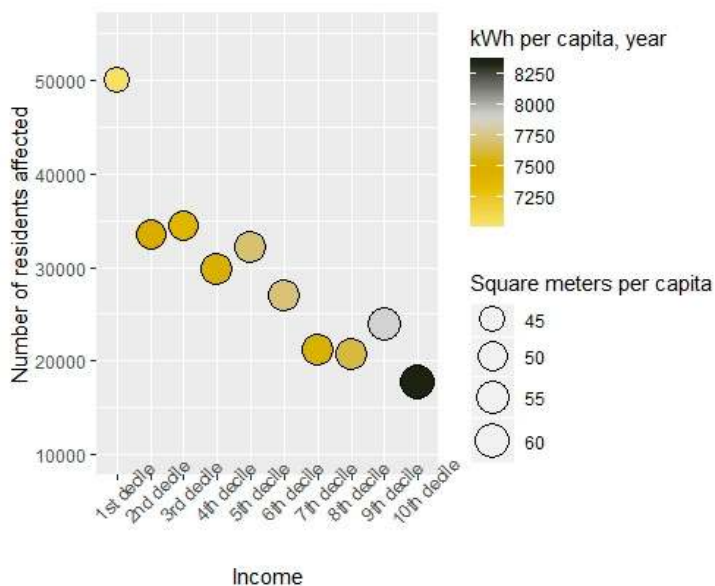


Figure 4.3 The number of residents in each income decile (low to high income) affected by the new regulation for individual metering and billing of energy for heating.

4.3. New Metrics Reveal Injustice and can Reduce Risks

The reason for the negative effects that risk occurring from the regulation described in Paper III is the overrepresentation of low-income households in buildings with low energy performance. In Paper IV, the perception of buildings with low energy performance as the most energy inefficient part of the building stock is challenged. By measuring per capita energy use instead of area-normalised energy use, the aim of Paper IV was to analyse and evaluate the past decade’s energy transition in the multifamily building stock from a new perspective, and to analyse the implications for distributive justice among residents.

In Paper IV, methods from Paper I were used to analyse per capita energy use in 2008 as well as in 2018 in different income deciles. The results from this analysis can be seen in Figure 4.4. As per capita energy use is closely connected to residential density, Figure 4.4 also includes information about the number of square meters per capita, represented by the size of the circles. Opposed to the negative correlation between income and area-normalised energy use found in Paper I, Figure 4.4 shows a positive correlation between income and per capita energy use. More so, while the results from Paper I showed that the income-related differences in area-normalised energy use had decreased over the past decade, Figure 4.4 shows that the income-related differences in per capita energy use have increased during the same period of time.

There are two reasons for the increased differences in per capita energy use among different income deciles. The first reason is that the area-normalised energy use has decreased more in buildings occupied by low-income households than in buildings occupied by high-income households, as seen in Paper I. The second reason is that the residential density has increased significantly in low-income households as seen in Figure 4.4, whereas it has remained seemingly unchanged in high-income households. This is likely to partly be driven by the increased income inequality and segregation in Sweden.

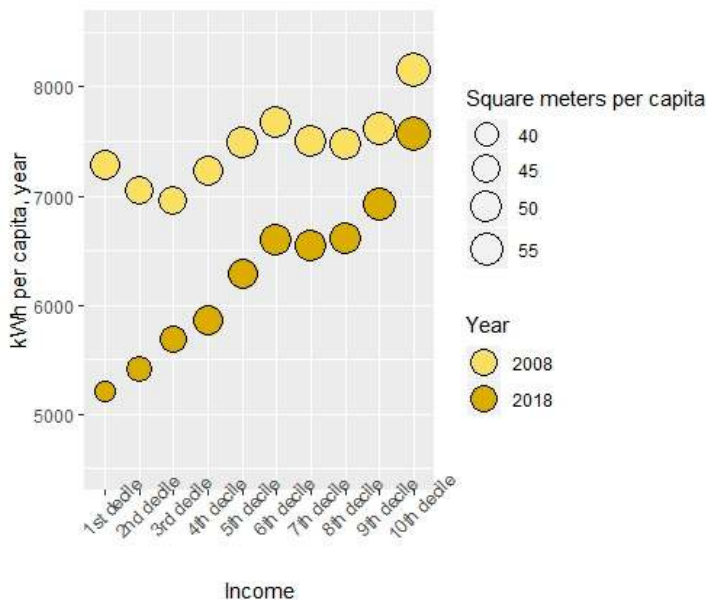


Figure 4.4 Median energy use per capita and year in 2008 and 2018 for different income deciles (low to high income). The size of the circles corresponds to the median number of square meters per capita.

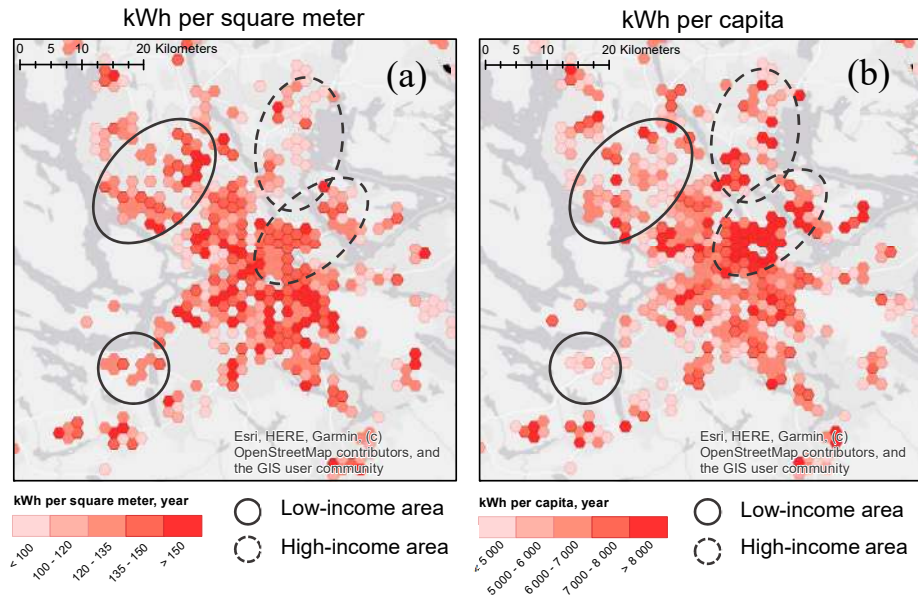
To visualise how different energy performance metrics impact where in urban areas multifamily buildings with high versus low energy efficiency are found, thematic maps of Sweden's two largest cities, Stockholm and Gothenburg, were created. Figure 4.5

shows the energy use in residential multifamily buildings in Stockholm (a and b) and Gothenburg (c and d) in 2018. The left-hand maps of Stockholm as well as Gothenburg (a and c) show buildings' yearly area-normalised energy use whereas the right-hand maps (b and d) show buildings' yearly per capita energy use. The lined circles mark suburban low-income areas that are in many cases (but not exclusively) from the Million Homes Programme. The dashed circles mark high-income areas for reference. It should be noted that the map scales are different for Stockholm and for Gothenburg.

From these maps, it can be seen that high-income areas are favoured by measuring area-normalised energy use, whereas low-income areas are favoured by measuring per capita energy use. This indicates a lack of “objectivity” of energy performance metrics regarding how efficiently energy is being used in buildings, and highlights the need to initiate informed discussions on metrics and their impact on decision-making in the energy transition of the housing stock. As policies often are directed towards buildings with high area-normalised energy use, as seen in Paper III, the current way of measuring buildings' energy performance causes an unjust distribution of burdens in the energy transition where the residents with the lowest per capita energy use are met with the highest demands for energy savings. Low-income residents are thus requested to bear an unproportionally large share of the energy transition. More so, it can be assumed that the true number of residents in already resident-dense areas is in fact higher than revealed by the statistics as the second-hand and third-hand markets in these areas are likely to house many unregistered residents. This would further stretch the differences in per capita energy use between income groups.

In summary, it is evident that Figure 1.1 presents an overly simplified illustration of the progression of the energy transition and the appended papers' contributions to the understanding of this development. Nonetheless, it captures some main elements such as forthcoming challenges and raises questions that for a long time have been overlooked: Is it worth closing the “energy transition gap” at the expense of deepened social inequalities? Is it a sustainable transition if it is achieved through unjust means? And how should we measure and value energy use in buildings?

Stockholm



Gothenburg

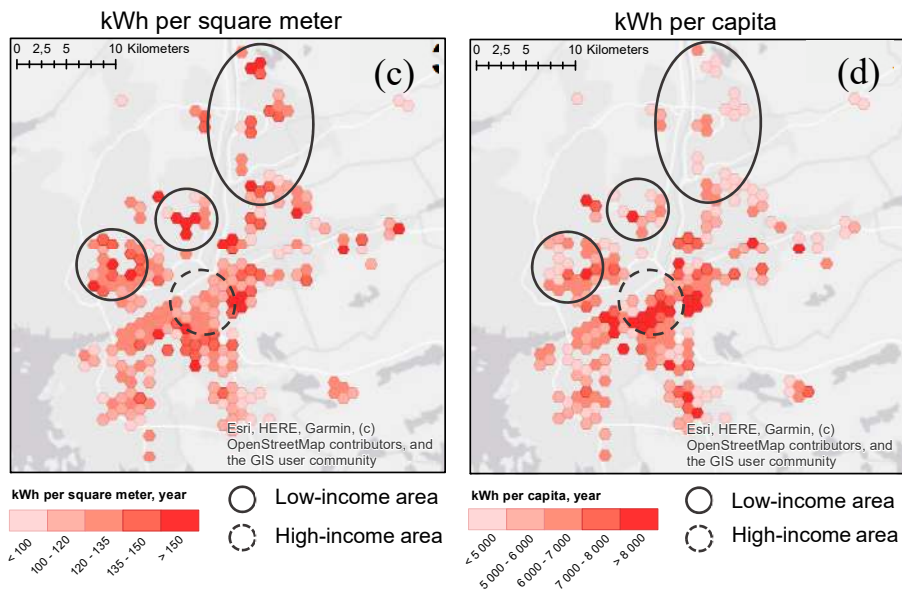


Figure 4.5 Thematic maps showing annual energy use in multifamily buildings in Stockholm (a and b) and Gothenburg (c and d) in 2018, normalised to floor area (a and c) and to number of capita (b and d).

5. Discussion

In this chapter, comments regarding the interpretation of results are first provided, followed by a review of the conducted research and the reach of the research findings. A discussion on the main contributions of the research in a theoretical and a practical context ends the chapter.

5.1. Interpretation and Reach of Results

In this discussion, the presented research and research findings are put in a wider perspective in order to highlight how results should be interpreted, and to explore the implications these results might have in a greater context.

5.1.1. Interpretation of Research Results

Given the quantitative and objectivist research methodology, the results are best interpreted as providing an overarching picture of general trends in Sweden. Not all low-income households live in energy inefficient buildings, and there are most likely many buildings in high-income areas that have significantly improved their energy performance over the past decade. The research results should thus not be interpreted as describing local phenomena and correlations, nor should they be seen as describing the experience of individual residents. But in an unparalleled way, the results of this dissertation show, on a national scale, who benefits and who loses from the current approach to the energy transition. These benefits and losses do not only concern who is affected by certain energy policies and not, but also include who is deemed as “energy inefficient” and who is not. In this sense, the results of this research can be interpreted as having conceptual implications regarding the way we think around energy efficient housing.

On a more detailed level, results should be interpreted with the issues of deficient data quality in mind. Rather than focusing on the exact energy use in different income groups, it is e.g. more appropriate to focus on the fact that there are statistically significant differences between such groups. This is also true when looking at residential

density, and when interpreting the results of the past decade's development of energy performance in Paper I. As stated above, it is the general trends and correlations that should be in focus when interpreting the results from this dissertation, as this is where data are most reliable.

5.1.2. Should Energy Savings in Low-Income Housing be Opposed?

In Paper IV, it is argued that the greater energy savings in low-income housing than in high-income housing over the past decade constitute a case of distribute injustice when accounting for per capita energy use. But is it really a bad thing that inequalities in buildings' energy performance among different income groups have been reduced?

To answer this question, it is necessary to emphasise the difference between social justice in the multifamily building stock in general, and social justice in the energy transition of this building stock in particular. The criticism against disproportionate requirements for energy savings in buildings mainly occupied by low-income households in the energy transition does *not* conflict with the quest to reduce structural differences in buildings' energy performance among different groups of income. The former concerns justice and social sustainability in transitions, whereas the latter concerns fundamental inequalities in society that constitutes the starting point of any transition.

In this case, the starting point is a building stock in which deep societal inequalities are embedded and manifested: as segregation; as differences in tenure; as differences in residential density; as differences in the condition of residences; and as differences in the energy performance of residences. The fact that low-income households disproportionately bear the (figurative and economic) costs of energy inefficient housing is not a good thing. The fact that these buildings are favoured by measuring per capita energy use instead of area-normalised energy use, due to low-income households living more crowded than higher-income households, is not a good thing. These are inequalities that should be opposed. Ultimately, this means that one way to reduce these inequalities is to improve the energy performance of buildings occupied by low-income households. In many EU member states, specific policies to improve energy performance of low-income housing are e.g. used as successful strategies to combat energy poverty. The key to success is here that the social issue – energy poverty – is the primary target of the policy and achieving energy savings is a subordinate goal.

However, if reducing inequalities in energy performance is exploited as a pure means to save energy, chances are that this would make the building stock a reproducer of inequalities, as seen in Paper III. If existing inequalities are to be reduced in the energy transition, they must be acknowledged and help navigate the transition. Putting low-income residents at risk at the frontline of the energy transition merely because of macroeconomic reasoning does not rhyme with reducing inequalities. If the energy

transition of the multifamily building stock is to reduce inequalities, the primary objective must be that – to reduce inequalities – and energy savings must be secondary. Such an approach would enable both objectives to be achieved.

Consequently, there is no conflict between the quest to improve energy performance of low-income housing and the opposition of putting low-income households at the frontline of the energy transition. It is a matter of priorities and how to approach this transition, where the top priority should be to make the multifamily building stock more equal. The view of it as an untapped source of energy savings should be secondary.

5.1.3. Further Aspects of Sustainability in Transitions

Central to the research and the research findings is the potential conflict between energy savings and social justice; two equally important aspects of a sustainable transition. There are, however, other important aspects of sustainability that have been neglected or that have not been sufficiently accounted for in this research: economic, ecological and cultural sustainability.

The first perspective that is lacking is the economic viewpoint. No economic calculations or reasoning have been conducted either on macro-scale (national) or micro-scale (property owner/household). Regarding the micro-scale, it is for example not implicit that energy retrofitting is a cost burden for residents. Nor is it implicit that individual metering and billing of energy for heating will induce higher energy costs for residents. On a macro-scale, an important aspect is that it is usually more cost-effective to save energy in buildings with high area-normalised energy use, as effective measures might not have been implemented yet. More so, measures for energy efficiency become even more cost-efficient when integrated in renovation projects driven by technical deficiencies and general needs for refurbishment. This could be used as an argument to stick to measuring area-normalised energy use rather than per capita energy use. However, a main idea of this research is to criticise this purely macro-economic analysis as it risks to structurally burden the micro-economy of low-income households. In that sense, the economic perspective is central to the research conducted in this dissertation, but it is applied conceptually rather than explicitly. Through frameworks of justice, theoretical questions of who *should* and *should not* pay for, and be put at risk in, the energy transition have here been prioritised over economic evaluations of who is paying and how much.

Another important economic aspect is type of tenure and ownership. As the Swedish multifamily building stock has a mixture of rental and resident-owned apartments, owned by both public and private housing companies as well as resident co-operations, the economic implications of energy retrofitting differ. Although the owner's investment is likely to be indirectly paid by the residents if it's not profitable, type of tenure has significant implications for residents' influence in retrofitting decisions and

consequently for their influence on their own cost burdens. By conducting more detailed analyses of energy performance and tenure, further perspectives of justice could be added to the general understanding of justice in the energy transition. Correlations between ownership and energy retrofitting have to some extent been studied before [85, 87, 88], although the perspective of justice has not been explicitly pronounced. That being said, many regulations (as the one described in Paper III) are binding independent of type of tenure and ownership, and issues of distributive justice are thus partly decoupled from these aspects.

Second, apart from the economic perspective, the research lacks other traditional components of sustainability such as ecological sustainability. In many ways, ecological sustainability is however embedded in the topics discussed in this dissertation: energy use has implications for ecological sustainability, and refurbishing the existing building stock to some degree dampens the need for new construction and thus reduces a lot of resource and land use. Whereas these factors support increased energy retrofitting as ecologically sustainable, the per capita energy use metric takes a different perspective on ecological sustainability where effective utilisation of space is put to the fore. This is a different approach to ecological sustainability where energy and resource use are reduced by a more effective use of building area rather than by improving the energy efficiency of buildings. Similar perspectives have previously been proposed [11, 39, 89], and energy performance metrics that incentivise effective space utilisation have been suggested as factors that can facilitate an adoption of such perspectives in practise [90].

Finally, this research has only briefly covered buildings' historical and cultural values, which can restrict the energy savings potential and also dictate which buildings (and indirectly which residents) that are faced with requirements for energy savings. In Paper II, rough assumptions regarding historical preservation were made for the sake of showcasing how machine learning can be used to generate new building-specific information that can improve estimations of energy savings potential. However, more realistic estimations could have been made if an extended analysis of criteria for preservation had been included.

While the research in this dissertation has been limited to energy savings and social sustainability, it is evident that the research findings have implications for additional aspects of sustainability. Future research could continue to explore the potential trade-offs, or perhaps benefits, that might occur among different aspects of sustainability when prioritising social justice in the energy transition.

5.1.4. Beyond the Available Data

As described in section 3.5.1, the quality of this research is ultimately limited by the quality of data. On a similar note, the scope of this research is also limited to the data availability. One such example concerns the fact that the observed inequalities are likely

to stretch beyond income and include several orders of inequality. As ethnic discrimination is known to occur on the Swedish housing market [91, 92], it is likely that some ethnic minorities are overrepresented in parts of the multifamily building stock with high residential density and where area-normalised energy use is high. Increased intersectional perspectives in analyses of per capita energy use could thus reveal how different orders of inequality in the multifamily building stock such as ethnicity, age, and gender, could translate into injustices in the energy transition.

Looking beyond the multifamily building stock, it can be expected to find even greater differences in per capita energy use if the scope is extended to the entire building stock. In this dissertation, analyses have been limited to the multifamily building stock partly due to the abundance of available data for this part of the stock. However, the energy transition of the housing stock encompasses single-family houses as well. In one way, the energy transition has progressed further in single-family houses than in multifamily buildings; a rapid increase of heat pumps over the past decades (along with advantageous subsidies for retrofitting) has significantly improved the energy performance of single-family houses. But although the average area-normalised energy use in single-family houses is lower than in multifamily buildings [93], the average living area per capita is higher [94]. Locally, this has been shown to have an equalising effect between the per capita energy use in single-family houses and multifamily buildings [95], but studies of larger geographical areas have not been conducted. As residents in the single-family housing stock in general have higher incomes than residents in the multifamily building stock, the potential differences in per capita energy use between single-family houses and multifamily buildings are likely to have implications for the differences in per capita energy use between different income groups in the building stock. Including single-family houses in the analyses would however require that differences in residential density between urban and rural areas are accounted for, as urban areas naturally are more densely inhabited.

Extending the perspective beyond the multifamily building stock also opens up for wider interpretations of what constitutes “sustainable living”. These kinds of analyses can be interpreted in the light of research conducted by Bradley [96], where strategies for urban sustainability are criticised for being tokenistic in its focus on symbolic behaviour such as recycling, and for being supported by middle-class norms. According to Bradley, this approach neglects deeper unsustainable societal structures [96]. In terms of buildings’ energy use, it is evident that energy performance defined as area-normalised energy use in similar ways constitutes a false and symbolic marker for sustainability; the fact that spacious living – despite high energy performance of the building – contributes to increased use of energy and resources is ignored. The deeper structures of unsustainability are thus lost, and in this case as well as in the research by Bradley [96], this is often for the benefit of middle-class households and at the undeserved expense of low-income households.

Considering the above, a reasonable hypothesis is that the differences in per capita energy use that were found between income groups in this research only show the tip

of the iceberg; if the perspective is widened, then so are the differences. There is much progress to be made in terms of revealing the true structures of unsustainability and discarding our synthesised and sometimes disoriented symbols of sustainable living. Measuring and acknowledging per capita energy use is one step in this direction that opens up for a more socioeconomically diverse and inclusive understanding of sustainability. Hopefully, such perspectives can contribute to improved recognition of distributive injustices in the energy transition of the multifamily building stock.

5.2. Contribution of Research Findings

Here, the main contributions of the research findings will be highlighted; first in terms of implications for the scientific community, then in terms of implications for the energy transition of the Swedish multifamily building stock, and finally in terms of how the assembled database can support an increased inclusion of perspectives of justice in energy policy.

5.2.1. Academic Contributions

Above all, this research contributes to a more pronounced recognition of the building stock as a socio-technical system where distributive injustice in the energy transition can cause existing inequalities to be deepened. Returning to the theoretical framework of environmental justice, this research shows that buildings can be viewed as the local environment of communities; what we find then is that disadvantaged communities, in this case low-income households, are disproportionately burdened with (i) energy inefficient housing and (ii) imposition of the energy transition. Increased integration between energy and environmental justice has previously been requested in the scientific community [97] and can contribute to an improved recognition of these socio-technical linkages.

In addition, a significant contribution of this work is the nation-wide analysis of building-specific per capita energy use; such analyses have previously not been possible due to lack of sufficient quantity and/or quality of data. The results of Paper IV reveal a new dimension to distributive injustice in the energy transition where we find that over the past decade, residents with the initially lowest per capita energy use have carried the greatest amount of energy savings. The fact that residents contributing the least to the total end use of energy have (at least indirectly) contributed the most to the past decade's energy savings exposes fundamental flaws in our overall approach to the energy transition and can be considered an infringement on the polluter-pays principle. Using a different energy performance metric, the results of Paper IV thus contribute to a new conceptualisation of distributive (in)justice in the energy transition of residential

building stocks. Unlike prior research, where methods to balance the perceived trade-offs between social sustainability and energy savings are examined, this work partly overthrows previous approaches by proposing a new take on sustainability.

In particular, the results from this dissertation add to the understanding of how energy use in the building stock is best examined. Ultimately, as heated floor area is one of the main drivers for the end use of energy in buildings [12], significant energy savings potential in building stocks is lost when creating policies around area-normalised energy use. This has previously been raised as a deficiency in our understanding of residential energy use [11], and the results in this dissertation thus emphasise that beyond mere technological progress, more comprehensive changes in lifestyle – such as more compact living – are required to reduce energy use in the building stock.

Finally, this research showcases the benefits of combining building-specific social and technical quantitative data. The assembled database was used to confirm correlations that had been found in local contexts on a national level. This demonstrates how quantitative analyses can complement other types of studies to provide an objectivist view of (in)justice in the energy transition. Similar methods could be used on residential building stocks in other jurisdictions and in local as well as national contexts.

5.2.2. Contributions for Approach to the Swedish Energy Transition

The practical contributions of this research concern the approach to the energy transition of the Swedish multifamily building stock. More specifically, these research results have implications for the general perception of where in the Swedish multifamily building stock the energy transition must proceed. The results from Paper IV sharply challenge the notion that buildings from the Million Homes Programme constitute the least energy efficient part of the multifamily building stock by showing the relative inefficiency in per capita energy use in less dense urban areas. Although this in practise does not mean that measures for energy efficiency should be directed towards buildings in high-income city centres, it contributes to an improved holistic understanding of where energy is more and less efficiently used in the multifamily building stock. Ultimately, this challenges artefacts (such as energy efficient buildings) as markers for sustainability and proposes sustainable lifestyles (such as compact living) as superior markers for sustainability. This could promote policies that support and reward efficient building utilisation, and ultimately provide an official recognition of efficient building utilisation as a sustainable alternative to deep energy retrofits that might not be economically feasible for all residents.

This also has implications for the approach to refurbishment in buildings from the Million Homes Programme, as it downplays excessive measures to save energy as a top

priority. If adhered to, this finding could contribute to less invasive refurbishment of these buildings, where only the most necessary measures to secure adequate living conditions are conducted. As previously suggested by several researchers, this could have benefits for residents as costs for refurbishment, and associated rent increases, would be held down.

Another important contribution is the demonstrated inseparability of different processes in the multifamily building stock. As seen in the results of Paper IV, the increase in residential density in low-income areas over the past decade played a significant role in the decrease in per capita energy use in these areas. This shows how societal processes influence the energy efficiency in different parts of the building stock. The fact that social inequalities continue to grow in the multifamily building stock should, if anything, support the notion that the energy transition should not be disproportionately imposed on already disadvantaged residents.

Finally, this research showcases the unwanted side-effects that energy policy can induce on social justice and sustainability in the multifamily building stock if buildings are not recognised as socio-technical systems in the policy-making process. The results from Paper III show how a purely technical approach, based on macroeconomic principles, risk leading to deepened social inequalities through energy poverty. These results stress the importance of preceding energy policies with socio-technical analyses to avoid making the energy transition an unjust transition.

5.2.3. Contribution of Assembled Database

Beyond enabling the analyses and overall research results presented in this dissertation, the assembled database will hopefully continue to support analyses to allow more successful integration of social aspects in future policy processes. As previously mentioned, the database was used by the Swedish National Audit Office for their review of the subsidy for refurbishment and energy efficiency “in some residential areas”. This enabled them to draw conclusions regarding how the subsidy could have been more accurately targeted. More so, the database was used to inform policymakers on the risks associated with the requirement for individual metering and billing of energy for heating through analyses similar to those in Paper III. The effect of this was, however, evidently limited.

Above all, the database allows concrete analyses of how policies targeted at buildings ultimately end up targeting residents. Such analyses can focus on how many residents that will be affected, which residents that will be affected, and whether specific groups of residents are proportionally or disproportionately affected by certain policies. In doing so, the database can facilitate protection of disadvantaged residents and support an increased inclusion of values of justice in the energy transition of the Swedish multifamily building stock.

6. Conclusions

This concluding chapter will briefly address each of the research questions, followed by concluding remarks and suggestions for future avenues of research.

6.1. Addressing the Research Questions

The first two research questions (RQ1 and RQ2) concerned database enrichment:

RQ1 How can a building database be enriched with renewed EPCs and enable quantitative and longitudinal studies of the energy transition?

The results of Paper I showed that renewed EPCs can be applied in longitudinal analyses of the energy transition of the multifamily building stock if three methodological steps are accounted for: (i) matching of old and renewed EPCs, (ii) exclusion of mis-matched EPCs, and (iii) representativity of the matched EPCs. The first step requires available data to be combined in order to create unique identifiers for buildings, as EPCs lack building IDs. The second step is necessary as the created unique identifier is not always correct, and as EPCs sometimes contain different levels of building aggregation. In order to ensure a database with comparable EPCs that constitute a reliable basis for analyses, it is thus important to remove matched EPCs that are not truly comparable. Finally, the third step was required as not all buildings had a renewed EPC at the time of analysis. For a reliable interpretation of the results of the past decade's energy performance improvement, it was important to investigate any skews in the analysed data.

RQ2 How can machine learning methods be used to enrich national building databases with new information relevant for studying the energy transition?

The results of Paper II showed that through a limited number of building-specific observations in Google Street View, enough labelled training data to develop machine learning algorithms to predict building-specific characteristics could be collected. Through a combination of supervised machine learning and expert influence in the generation of machine learning models, two building characteristics were predicted: the characteristic *building type*, which was predicted with an accuracy of 88.9% for the

multifamily buildings constructed between 1945 and 1975, and the characteristic *suitability for additional façade insulation* (defined as buildings with eaves overhang and not brick façade), which was predicted with an accuracy of 72.5% for the same part of the building stock. The predicted building characteristics were used to estimate the national energy savings potential in the concerned part of the multifamily building stock.

The last research question (RQ3) concerned socio-technical analysis of the energy transition:

RQ3 How can social and technical data be combined to reveal new knowledge about distributive justice regarding the burden of the energy transition among residents?

Social and technical data were combined in two ways to improve the understanding of distributive justice in the energy transition. First, such data were combined in Paper III to investigate the quantitative impact of a specific energy policy on residents in different groups of income. It was found that the policy, which affected residents in buildings with particularly low energy performance, disproportionately affected low-income residents and exposed these already disadvantaged residents to a risk for energy poverty.

Second, social and technical data were combined to compare per capita energy use among residents in different income groups. In Paper IV, this analysis was conducted for 2008 as well as for 2018, which showed that low-income residents, who had the lowest per capita energy use in 2008, have carried most of the energy savings over the past decade. This can be considered a distributive injustice as (i) low-income residents have been burdened with a disproportionately great share of the energy transition in the multifamily building stock, and as (ii) residents with the lowest per capita energy use are put at the frontline of the energy transition despite their low contribution to the total end use of energy in the multifamily building stock.

6.2. Concluding Remarks

In this dissertation, a database has been assembled and enriched in order to create a strong foundation for a socio-technical understanding of the energy transition in the Swedish multifamily building stock. The quantitative methodology has contributed to an objectivist representation of this energy transition that contains two main elements: a gap between the objectives for, and the reality of, energy efficiency in the multifamily building stock, and a glimpse of the social injustices that may occur at the closing of this gap. In this way, the results of this research tell an important story of how inequality in the multifamily building stock can translate to injustice in the energy transition. It is primarily the overrepresentation of low-income households in buildings with high area-normalised energy use that creates a risk for injustice in the energy transition. But

it is the lack of recognition of this overrepresentation in policymaking that causes this risk to be realised as tangible injustices. The fact that low-income residents are put at risk despite their relatively low per capita energy use further adds to the conceptualisation of injustice in this transition.

Owing to that, the main takeaway from this dissertation should be that by shifting focus from area-normalised energy use to per capita energy use, the perception of what constitutes energy efficient housing changes. Current energy performance metrics offer a narrow description of energy efficiency where buildings and building stocks are reduced to mere technological systems. By introducing a metric of per capita energy use in buildings, the energy efficiency of a building and its technological system is put in relation to how efficiently it is actually being used. This ultimately means that a well-insulated building with an efficient energy system will be deemed extremely energy inefficient if it is not being used. In this way, the deeper structures of sustainability are put to the fore instead of being neglected. Although these ideas are not new, the database that was assembled for this dissertation enabled unparalleled analyses of different energy performance metrics, and established a novel connection between energy performance metrics and justice in the energy transition. Unlike prior research, where methods to balance the perceived trade-offs between social sustainability and energy savings are examined, this work thus overthrows such approaches by proposing a broader definition of sustainability in the building stock that recognises efficient building utilisation as an alternative to energy retrofitting.

We are facing a challenge to meet national and international objectives for energy efficiency. Improving the energy performance of existing building stocks is undoubtedly an important undertaking in order to achieve what is necessary. But for far too long, the focus of the energy transition in building stocks has been far too narrow, and the results from this dissertation show that this narrow mindset structurally has burdened low-income residents. Hopefully, the presented results can contribute to a wider understanding of energy efficiency in building stocks, alleviate some of the burdens from already disadvantaged residents, and support a more socioeconomically inclusive definition of sustainable living.

6.3. Future Research

This licentiate dissertation has only begun to explore matters of justice in the energy transition of the housing stock. To verify the results in this dissertation, there is a need for quantitative studies that include the actual cost burden among residents that have been subjected to energy retrofits or other energy conservation measures. Adding the economic dimension would help concretise the discussion on whether benefits and burdens of the energy transition are justly distributed or not.

More so, to fully grasp matters of justice in the energy transition, intersectional research that includes socio-demographic data beyond income is needed. In the multifamily building stock, quantitative studies could provide new insights regarding how e.g. ethnic segregation affects justice for ethnic minorities in the energy transition. In addition, qualitative studies should explore how factors such as age and gender affect residents' susceptibility to inadequate indoor climate and sensitivity to increased rents. In combination, perspectives of income, ethnicity, age, and gender will reveal even more regarding who benefits and who loses in the energy transition in general, and with the current metrics within the current sustainability-paradigm in particular.

Future research should also include analyses of the entire housing stock so that multifamily buildings and single-family houses can be fairly compared in terms of area-normalised energy use and per capita energy use. Only after such studies will we have a holistic picture of where in the housing stock energy is more and less efficiently used, and where policies and measures in the energy transition should be prioritised.

Finally, there is a need to continue to challenge current markers for sustainability by revealing more fundamental and underlying structures of unsustainability. This is necessary in order to acknowledge that most people are, or can be, part of a sustainable transition and make significant contributions to it.

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