DOCTORAL THESIS

Analysis of Regional Patterns in Apartment Building Renovation Subsidies

Lauri Lihtmaa

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for doctoral or equivalent academic degree.

Lauri Lihtmaa

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Korterelamute renoveerimistoetuste regionaalsete mustrite analüüs

LAURI LIHTMAA

TALTECH KIRJASTUS

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Abstract

Analysis of Regional Patterns in Apartment Building Renovation Subsidies

Governments intervene in markets to address inefficiencies and mitigate market failures. One notable example of this intervention is the acceleration of building renovation programmes, which are designed to achieve climate and energy policy objectives by providing, among other support mechanisms, financial incentives such as subsidies. While these policies alleviate cost burdens on property owners, they may also result in unintended negative spillover effects that exacerbate existing disparities. This study investigates these consequences, particularly in the context of Estonia, to ascertain the impact of targeting in renovation policies on regional equity.

The conceptual framework is grounded on established theories of energy and spatial justice, which encompass both equality and equity. In a novel approach, the regions are analysed as subjects of justice to determine whether government interventions in fostering deep energy renovations align with regional development goals. Estonia serves as a compelling case due to its pronounced regional disparities and high rate of apartment ownership, offering a relatively homogeneous group for policy analysis. Between 2010 and 2018, Estonia allocated renovation subsidies without specific regional or social targeting. Partly due to this research, energy policy was updated with regional targeting in 2019, enabling a longitudinal assessment of the effects of energy policy.

The overarching aim of this study is to explore how non-targeted government interventions in energy policy contribute to spatial inequalities and social polarisation. Four research questions are posed:

1. In what ways do non-targeted subsidy policies influence regional disparities in Estonia?
2. How do population trends at the regional level influence residential vacancy and renovation patterns?
3. What hinders the adoption of innovations for accelerating the deep energy renovation rate?
4. To what extent do informed changes in energy policy contribute to a more equitable distribution of renovation grants at the regional level in Estonia?

A multi-method approach is adopted, combining quantitative and qualitative methodologies. Spatial and statistical analyses assess the distribution of renovation grants, while content analysis of energy policy documents and in-depth stakeholder interviews provide further insights into policy effectiveness and equity considerations.

Two indexes are proposed for evaluating the equal and equitable distribution of grants. The first, the proportionality index, shows the ratio of subsidy applications to the building stock in a region, allowing for rigorous comparisons between regions. The second, the regional development index, is a composite measure of socio-economic indicators to distinguish between the development levels of regions.

The findings indicate that renovation subsidies are unequally distributed among regions. The design of subsidy programmes creates varied spatial patterns, with non-targeted programmes favouring economically stronger areas and worsening inequalities between growing and shrinking regions. This reflects the “success to the successful” systemic trap. From a national strategic standpoint, these policies are counterproductive, reinforcing polarisation instead of fostering balanced development.

Regionally targeted renovation grant programmes, though still unequal, promote a more equitable distribution of funds. The analysis shows that moving from non-targeted to regionally targeted subsidies reduces grant concentration in affluent areas and improves financial access for disadvantaged regions. This shift fosters balanced development and lessens disparities in housing quality. Interviews with policymakers reveal a growing awareness of the need to incorporate justice principles into energy policy. However, challenges persist in defining suitable metrics for evaluating and developing Long-term Renovation Strategies, leading to ad hoc assessments and policy adjustments.

Intensified urbanisation and domestic migration from lagging regions to growing ones suggest that residential buildings will increasingly be abandoned. Clearly, such buildings should not be targeted by renovation programmes, and vacancy trends should be addressed more closely. Analysis shows that residential vacancy rates significantly influence the distribution of renovation grants, with buildings exceeding a 23 per cent vacancy threshold rarely receiving support. This underscores the necessity of integrating vacancy data into national renovation strategies to avoid ineffective investments in declining regions. The proportionality index proposed in this thesis already accounts for the vacancy factor and excludes such buildings from the calculation of building stock that requires renovations.

The study also examines barriers to the adoption of mass-renovation innovations, such as industrialised and district-based renovation. While the latter is theoretically promising, it faces practical challenges due to coordination difficulties among property owners. Interviews reveal that a top-down approach, with local authorities facilitating collective action, may be more effective than community-led initiatives.

The concept of justice in energy policy remains ambiguous for many policymakers and stakeholders, impeding the development of inclusive regulations. The lack of an explicit monitoring methodology for energy justice further complicates policy evaluation and refinement. Negative spillovers, including rising energy costs for low-income communities and the shifting of environmental degradation to less regulated areas, demonstrate the complexity of energy policy interventions.

Based on this research, it can be suggested that incorporating principles of spatial justice into energy policies ensures that vulnerable communities are not disproportionately affected. This requires the consideration of more refined subsidy targeting and addressing different spatial scales, as equal distribution of subsidies among regions does not guarantee equity within those regions, settlements, and neighbourhoods.

In conclusion, equitable energy policy is not a panacea for reversing current regional trends and disparities. However, energy policy should not exacerbate existing inequalities; instead, national strategies advocating for balanced regional development must be upheld. By considering justice in energy policy, governments can create sustainable and socially responsible frameworks that anticipate and mitigate negative spillovers, fostering a more balanced and just energy transition.

Keywords: *targeted subsidies, justice, inequality, renovation patterns, spatial analysis, energy policy, regional development, multi-family buildings, housing vacancy rate*

Lühikokkuvõte

Korterelamute renoveerimistoetuste regionaalsete mustrite analüüs

Valitsused sekkuvad turgudesse, et suurendada tõhusust ja leevendada turutõrkeid. Üks märkimisväärne näide sellisest sekkumisest on hoonete renoveerimiste kiirendamine, mille eesmärk on saavutada kliima- ja energiapoliitika sihid, pakkudes muu hulgas rahalisi stiimuleid, näiteks toetusi. Kuigi need poliitikad vähendavad kinnisvaraomanike kulukoormust, võivad need kaasa tuua ka soovimatuid negatiivseid kõrvalmõjusid, mis võimendavad olemasolevaid ebavõrdsusi. Käesolev uurimus käsitleb neid tagajärgi Eesti kontekstis.

Kontseptuaalne raamistik tugineb energia- ja ruumilise õigluse teooriatele, mis hõlmavad nii võrdsust kui ka õiglust. Uuendusliku lähenemisena käsitletakse piirkondi õigluse subjektidena, et hinnata, mil määral valitsuse sekkumised renoveerimise turule on kooskõlas regionaalarengu eesmärkidega. Eesti on siinkohal kõnekas juhtum seniste piirkondlike erinevuste ja kõrge korteriomandi osakaalu tõttu, pakkudes poliitikaanalüüsiks suhteliselt homogeenset sihtrühma. Aastatel 2010–2018 jaotas Eesti renoveerimistoetusi ilma konkreetse piirkondliku või sotsiaalse sihtimiseta. Osaliselt selle uurimistöö tulemusel ajakohastati 2019. aastal energiapoliitikat ning võeti kasutusele piirkondlik sihtimine, mis võimaldab nüüd hinnata energiapoliitika mõjusid pikaajaliselt.

Uurimuse eesmärgiks on selgitada, kuidas sihtimata valitsuse sekkumised energiapoliitikas aitavad kaasa ruumilistele ebavõrdsustele ja sotsiaalsele polariseerumisele. Väitekirjas püstitatakse neli uurimisküsimust:

1. Millisel viisil mõjutavad sihtimata renoveerimistoetused piirkondlikke lõhesid Eestis?
2. Kuidas mõjutavad piirkondliku tasandi rahvastikutrendid elamufondi tühjenemist ja renoveerimismustreid?
3. Mis takistab innovatsioonide kasutuselevõttu tervikrenoveerimiste tempo kiirendamiseks?
4. Mil määral aitavad teadlikud muutused energiapoliitikas kaasa renoveerimistoetuste õiglasemale jaotusele Eesti piirkondade vahel?

Uurimisküsimistele vastamiseks on kasutatud erinevaid võtteid, ühendades nii kvantitatiivsed kui ka kvalitatiivsed meetodid. Ruumi- ja statistiline analüüs hindab renoveerimistoetuste jaotust, samas kui energiapoliitika dokumentide sisuanalüüs ja süvaintervjuud sidusrühmadega pakuvad täiendavaid teadmisi poliitika tõhususe ning õigluse kaalutluste kohta.

Toetuste võrdse ja õiglase jaotuse hindamiseks pakutakse välja kaks indeksit. Esimene, proportsionaalsusindeks (PRI), näitab toetustaotluste suhet piirkonna hoonefondi, võimaldades ranget piirkondade vahelist võrdlust. Teine, regionaalarengu indeks (RDI), on sotsiaal-majanduslike näitajaid koondav liitnäitaja, mille abil eristada piirkondade arengutasemeid.

Tulemused näitavad, et renoveerimistoetused jaotuvad piirkondade vahel ebavõrdselt igas toetuse voorus aastatel 2010–2024. Toetusprogrammide reeglid tingivad, spetsiifilised ruumilised mustrid. Sihtimata programmid soosivad majanduslikult tugevamaid piirkondi ning süvendavad seega olemasolevat ebavõrdsust kasvavate ja kahanevate piirkondade vahel. See trend peegeldab süsteemset lõksu “edu edukatele”

ning riiklike strateegiliste eesmärkide vaatenurgast on sellised poliitikad vastupidise mõjuga, tugevdades polariseerumist tasakaalustatud arengu edendamise asemel.

Piirkondlikult sihitud renoveerimistoetuste programmid, kuigi endiselt ebavõrdsed, soodustavad õiglasemat rahajaotust piirkonniti. Analüüs näitab, et üleminek sihtimata toetustelt piirkondlikult sihitud toetustele vähendab toetuste koondumist jõukatesse piirkondadesse ning parandab rahalist ligipääsu ebasoodsamas olukorras olevates piirkondades. See nihe toetab tasakaalustatud arengut ja võimaldab tõsta elamukvaliteedi ka piirkondades, kus elamute uusarendusi napib. Poliitikakujundajatega tehtud intervjuud osutavad samas teadlikkuse kasvule, et lõimida õigluse põhimõtteid ka energiapoliitikasse. Siiski püsivad väljakutsed sobivate mõõdikute määratlemisel pikaajaliste renoveerimisstrateegiate hindamiseks ja arendamiseks.

Intensiivistuv linnastumine ja sisemine ränne maha jäävatest piirkondadest kasvavatesse viitavad sellele, et osad elamud jäävad üha enam tühjaks. On selge, et selliseid hooneid ei ole otstarbekas toetustega sihtida ning tühjenemistrende tuleb käsitleda märksa tähelepanelikumalt. Analüüs näitab, et elamute tühjenemismäär mõjutab oluliselt renoveerimistoetuste jaotust: hooned, mille tühjenemise määr ületab 23%, saavad toetust vaid erandkorras. See omakorda rõhutab vajadust lõimida tühjenemisandmed riiklikesse renoveerimisstrateegiatesse, et paremini planeerida toetuste mahte. Käesolevas väitekirjas pakutud proportsionaalsusindeks arvestab juba tühjenemist ning jätab perspektiivitud hooned renoveerimist vajava hoonefondi arvestusest välja.

Uurimus käsitleb ka massrenoveerimise innovatsioonide (nt tööstuslik ja piirkonnapõhine renoveerimine) kasutuselevõtu tõkkeid. Kuigi massrenoveerimine on teoreetiliselt paljulubav, seisab see praktikas silmitsi raskustega, mis tulenevad kinnisvaraomanike vahelise koordineerimise probleemidest. Intervjuud näitavad, et ülalt-alla lähenemine, kus kohalikud omavalitsused soodustavad kollektiivset tegutsemist, võib olla tõhusam (vähemalt esilagu) kui kogukonnapõhised algatused.

Õigluse mõiste energiapoliitikas jääb paljude poliitikakujundajate ja sidusrühmade jaoks ebamääraseks, takistades kaasavate regulatsioonide väljatöötamist. Selge energiaalase õigluse seiremetoodika puudumine muudab poliitika hindamise ja täiendamise veelgi keerukamaks. Selle uurimistöö põhjal võib soovitada, et ruumilise õigluse põhimõtete lõimimine energiapoliitikasse aitab tagada, et haavatavaid piirkondi ei mõjutataks ebaproportsionaalselt. See eeldab täpsemat toetuste sihtimist ning erinevate ruumiliste skaalade arvestamist, sest toetuste õiglasem jaotus piirkondade vahel ei pruugi tagada õiglust nende piirkondade sees – asulates ja naabruskondades.

Toetuste õiglasem jaotus piirkondade vahel ei ole imerohi praeguste piirkondlike trendide ja ebavõrdsuste ümberpööramiseks. Sellest hoolimata ei tohi energiapoliitika olemasolevaid ebavõrdsusi süvendada. Selle asemel tuleb ka meetmete väljatöötamisel järgida juba varem kokku lepitud strateegiaid, mis on Eestis sihiks seadnud tasakaalustatud regionaalarengu. Õigluse arvestamine energiapoliitikas võimaldab valitsustel kujundada kestlikke ja sotsiaalselt vastutustundlikke sekkumisi, mis ennetavad ja leevendavad negatiivseid kõrvalmõjusid ning toetavad õiglasemat energiaüleminekut.

Võtmesõnad: sihitud toetused, õiglus, ebavõrdsus, renoveerimismustrid, ruumianalüüs, energiapoliitika, regionaalareng, korterelamud, elamute tühjenemismäär, innovatsioon.

List of publications

The list of author's publications on which the thesis has been prepared with:

I Lihtmaa, L., Baldwin, D., Leetmaa, K., Hess, D. B., 2018. **Intersection of the global climate agenda with regional development: Unequal distribution of energy efficiency-based renovation subsidies for apartment buildings**. Energy Policy, 119, 327–338

II Lihtmaa, L., Kalamees, T. 2020. **Preliminary assessment of preconditions to deliver carbon neutrality in apartment buildings by 2050**. E3S Web of Conferences 172, 18004

III Lihtmaa, L., Kalamees, T. 2024. **Emerging renovation strategies and technical solutions for mass-construction of residential districts built after World War II in Europe**. Energy Strategy Reviews, 51

IV Lihtmaa, L., Kalamees, T. 2025. **How vacancy of dwellings influences renovation strategies of multifamily buildings.** Energies, 18, 603

V Lihtmaa, L., Kuusk, K., Kalamees, T., 2025. **Revisiting spatial distribution of residential energy renovation grants: evaluation of policy change for more equitable use of public funds**. Energy Policy, 208, 114843

Author's contribution to the publications

Contribution to the articles in this thesis are as following:

I *Lauri Lihtmaa*: conceptualisation, methodology development, data collection, formal analysis, writing original draft, submission to journal.
Daniel Baldwin Hess: conceptualisation of literature review, original draft preparation, writing-reviewing and English editing, supervision.
Kadri Leetmaa: conceptualisation of literature review, original draft preparation, writing-reviewing and editing, supervision.
The qualitative data collection was assisted by Coline Dalimier. Annika Väiko helped the data collection form Statistics Estonia.

II *Lauri Lihtmaa*: conceptualisation, methodology development, data collection, formal analysis, writing original draft, submission to journal.
Targo Kalamees: original draft preparation, writing-reviewing and editing, funding acquisition, supervision.

III *Lauri Lihtmaa*: conceptualisation, methodology development, data collection, formal analysis, writing original draft, submission to journal.
Targo Kalamees: original draft preparation, writing-reviewing and editing, funding acquisition, supervision.

IV *Lauri Lihtmaa*: conceptualisation, methodology development, data collection, formal analysis, writing original draft, submission to journal.
Targo Kalamees: original draft preparation, writing-reviewing and editing, funding acquisition, supervision.

V *Lauri Lihtmaa*: conceptualisation, methodology development, data collection, formal analysis, writing original draft, submission to journal.
Kalle Kuusk: preparation and writing the section 2 of the manuscript.
Targo Kalamees: original draft preparation, writing-reviewing and editing, funding acquisition, supervision.

Abbreviations

AGRI	Ministry of Regional Affairs and Agriculture
CF	Cohesion Fund
COP21	Paris Climate Agreements
DBR	District-based renovation
EFTA	European Free Trade Association
EIS	Estonian Business and Innovation Agency
EKYL	The Estonian Union of Co-operative Housing Associations
ELVL	Estonian Association of Cities and Municipalities
EOKK	Estonian Owners' Association
EPBD	Energy Performance of Buildings Directive
EPC	Energy performance certificate
ERDF	European Regional Development Fund
ESIF	European Structural and Investment Funds
ETS2	EU Emissions Trading System 2 (for buildings and road transport)
EU	European Union
GDP	Gross domestic product
GHG	Greenhouse gas
HVAC	Heating, ventilation and air conditioning
KLIM	Ministry of Climate
LCA	Life-cycle assessment
LTRS	Long-Term Renovation Strategy / Strategies (required under the EPBD)
NBRP	National Building Renovation Plan(s) (successor to LTRS under recast EPBD)
NECP	National Energy and Climate Plan
NZEB	Nearly zero-energy building
NUTS	Nomenclature of Territorial Units for Statistics (EU regional classification)
PRI	Proportionality Index (indicator for comparing regional grant allocation with needs)
REELIH	Residential Energy Efficiency for Low-Income Households
RES	Renewable energy sources
RQ	Research question

1 Introduction

This thesis comprises a compilation of five publications, including four journal articles and one conference paper. The studies utilise data spanning from 2010 to 2024. Each publication contributes to a unified objective of addressing the spatial justice dimensions associated with increasing the renovation rate in the residential sector. The overarching research theme seeks to link predominant energy policy objectives with the national strategic aim of balanced regional development by examining how government interventions in the market might generate unintended impacts – negative spillovers.

Next, the research problem, along with research questions, empirical hypotheses, and an outline of the study is introduced.

1.1 Research problem

1.1.1 Deep energy renovations of residential housing stock

Throughout the EU, new residential construction contributes merely 0.5–1 per cent to the overall housing stock each year (BPIE 2011), while energy-related renovations impact approximately 1 per cent of existing dwellings annually, with deep renovations accounting for only 0.2–0.3 per cent (BPIE 2021). At current rates, the majority of the housing that will still exist by 2050 is already constructed today. This renewal rate is evidently inadequate to meet the current climate targets, which strive for a decarbonised building stock by 2050 (EU Directive 2018).

Despite some emotional suggestions in grey literature that most older buildings should be demolished in favour of modern constructions, the renovation of older buildings has a significantly lower environmental impact compared to new builds (Abbey et al. 2022; Morelli, Harrestrup, and Svendsen 2014). There are also cultural (Wise et al. 2019), health implications (Künn and Palacios 2024), and socio-economic (Jacobs 1961; Johansson, Olofsson, and Mangold 2017; Wu et al. 2024) reasons for preserving old buildings. Therefore, renovation is the primary strategy, with energy efficiency serving as one key driver for the renewal of the European housing stock.

Reasons for residential renovations can be classified in various ways, depending on the specific focus of the subject matter. For this study, a global-national-local division is adopted, as it provides a structured framework for analysing multi-level impacts and policy coordination (**Figure 1**). On the global level, the main concern is the environment, which is essential for the continuation of humanity. Therefore, it is understandable that purposeful and strong energy policy has been adopted within the last decades. Global agreements on environmental targets are fixed in the Paris Climate Agreements (COP21) (UNFCCC 2015). Considering the European continent, the most notable policy tool is the Energy Performance of Buildings Directive (EPBD) which is mandatory for implementation in both Member States and European Free Trade Association (EFTA) countries such as Norway, Iceland, and Liechtenstein (EU Directive 2024).

While global reasons for energy renovations are primarily driven by planetary boundaries, national reasons are considerably more diverse and dependent upon specific national contexts. However, in addition to meeting EPBD energy targets, there are several common reasons for renovations across EU countries. One of the most prominent motivations is energy security, as reliance on external energy supplies and evolving geopolitical challenges pose risks of energy shortages, price volatility, and economic instability.

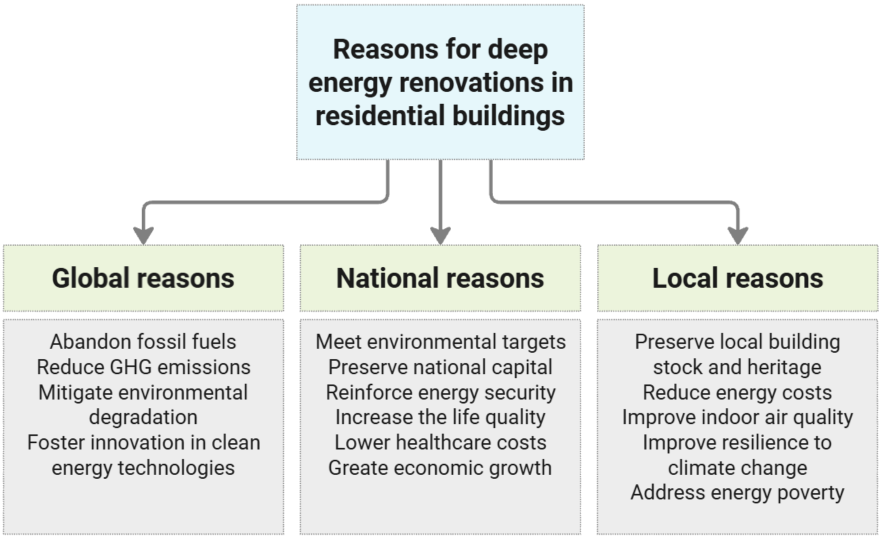

Figure 1 *Deep energy renovations, reasoned between global, national and local level.*

Secondly, it is important to note that in Europe a large portion of the housing stock was constructed after the Second World War; therefore, its designed service life is close to expiring or has already expired. This housing stock, regardless of ownership, now urgently requires renovation to preserve national capital.

In general, enhanced energy security, the preservation of capital, and economic growth are closely aligned with national interests in Europe. Consequently, these factors serve as self-interested motivations, particularly for certain political factions that express scepticism towards anthropogenic climate change and environmental protection.

The third and final level of renovation reasons can be classified at the local level, encompassing factors most directly associated with individuals, communities, and local authorities. These stakeholders are anticipated to make significant decisions regarding deep energy renovations of residential buildings. Their motivations towards energy renovations are more pragmatic compared to the global and national aspirations.

In conclusion, it is essential to emphasise that, in addition to climate targets, renovation plays a crucial role in achieving significant national and local socioeconomic objectives. This aspect should be highlighted more effectively as an opportunity or catalyst for comprehensive energy renovations of residential buildings.

1.1.2 Challenges in deep energy renovations

Deep energy renovations face a myriad of interconnected challenges that significantly impede their widespread adoption (Dolšak 2023; Palm and Reindl 2018). Foremost among these obstacles are high (upfront) costs and financial barriers, which render large-scale implementation problematic (Bertoldi et al. 2020). The substantial capital required for upgrades places renovations beyond the financial reach of many homeowners and communities. This issue is exacerbated by the limited availability of affordable financing options and a general lack of awareness surrounding government grants and subsidies (Kuusk and Kalamees 2016). Even when financial assistance is accessible, prolonged payback periods often dissuade investment, particularly in regions where low energy prices extend the time necessary to recover initial costs (Papadopoulos, Theodosiou, and Karatzas 2002).

Compounding these financial difficulties is the issue of limited homeowner awareness and motivation. Many homeowners remain uninformed about the long-term benefits that deep renovations can offer, such as reduced energy consumption, enhanced indoor environmental quality, and improved health outcomes. Even when these benefits are acknowledged, split incentives in rental properties further discourage investment; landlords, who bear the costs of renovations, do not directly reap the energy savings that accrue to tenants (Charlier 2015). Additionally, the potential disruption associated with renovations significantly deters homeowners, as the prospect of considerable disturbances to daily life often overshadows the anticipated long-term gains. In an attempt to relate the awareness challenges to the reasons for renovation illustrated in **Figure 1**, one could argue that global and national renovation reasons might not be particularly meaningful for residents who are expected to invest in energy renovations. Instead, local reasons that highlight the tangible benefits for residents could provide a more practical approach to promoting renovations.

These motivational barriers intersect with a myriad of technical challenges, particularly when addressing older properties in need of renovations. Such buildings frequently require substantial structural interventions to rectify outdated electrical systems, HVAC installations, or deteriorating foundations. The absence of standardised solutions further complicates this process, as each property presents unique characteristics that necessitate bespoke renovation strategies. This tailored approach escalates project costs and prolongs timelines, an issue exacerbated by a shortage of skilled professionals trained in deep energy renovations. Without an adequate workforce, the pace of renovations remains sluggish, thereby limiting progress towards broader energy efficiency objectives (Meijer and Visscher 2014).

Interwoven with these technical concerns are regulatory and policy barriers that complicate renovation projects due to inconsistent building codes and regionally varying energy standards (Dauda and Ajayi 2022). Where building regulations are poorly enforced or inconsistently applied, homeowners encounter additional uncertainty. Lengthy or unclear permitting processes prolong projects and could result in delays and cost overruns. Compounding this issue is the general lack of supportive policies, such as tax rebates, subsidies, or mandatory renovation regulations, which leaves many homeowners without the financial or regulatory impetus to undertake improvements.

The lack of certainty surrounding renovation outcomes introduces an additional source of hesitation, as many homeowners and investors remain sceptical about whether the projected energy savings will materialise. This uncertainty is often linked to variability in contractor expertise and inadequate quality control, leading to inconsistent results. Poorly executed renovations can produce suboptimal energy performance, discouraging further investments and eroding public confidence in large-scale renovations.

These risks are exacerbated by the fragmented nature of the renovation market, where homeowners must coordinate multiple professionals, such as architects, engineers, and HVAC specialists (Mlecnik, Straub, and Haavik 2019). Without an integrated approach, miscommunication and delays become commonplace, and homeowners frequently find themselves overwhelmed by the complexity of managing the entire process. This lack of streamlined services not only prolongs project timelines but also contributes to inefficiencies that inflate costs and diminish overall project satisfaction.

Finally, behavioural and cultural barriers further impede progress, as homeowners frequently resist the aesthetic or structural changes required for deep renovations (Owen et al. 2023). Many individuals are emotionally attached to the current appearance or layout of their homes and are reluctant to make significant modifications (Bobrova et al. 2024). This resistance often stems from past experiences with poorly managed or over-budget renovations, leading to a pervasive lack of trust in contractors, officials, and other stakeholders (De Wilde 2019).

Consequently, overcoming these challenges necessitates a multi-faceted strategy that not only addresses technical and financial barriers but also fosters trust and demonstrates the value of deep renovations through well-executed projects and clear communication of long-term benefits.

1.1.3 Overcoming challenges in deep energy renovations

To mitigate and overcome the challenges associated with deep energy renovations, central governments have adopted national energy and renovation policies. The main design of such policies is to stimulate demand and address specific market barriers to promote greater adoption of deep energy renovations.

Regarding to residential buildings, the obligations to meet climate targets via renovation trajectories are left to the EU Member States. This means that central governments are free to choose their own intervention strategies to comply with the Directives. Considering incentives that could foster voluntary deep energy renovations in the residential sector, there are three broad policy methods adopted throughout the EU (adapted from Bertoldi et al. 2020):

› Financial support: Offering subsidies, tax incentives, or on-bill financing to reduce renovation costs.
› Raising awareness and motivation: Educating demand-side about the reasons and benefits of deep renovations including but not limited to the introduction of renovation passports and establishments of one-stop-shops.
› Standardisation and bundling: Creating standardised renovation packages for different building types to simplify planning and implementation including industrialised technical solutions.

In addition to local polices, the EU Emissions Trading System 2 (ETS2) is expected to increase residential renovation rates as fossil fuels become more expensive. Such an expectation is justified as the increased energy costs decrease the payback period of energy renovations. To mitigate the impact of ETS2 on energy poverty, a social climate fund is adopted. Although the ETS2 might increase renovation rates, there is evidence that carbon taxing alone might be insufficient to meet the climate targets and, therefore, more ambitious local renovation obligations are still needed (Müller et al. 2024).

The primary concern is that the energy transition is too slow to achieve current decarbonisation targets in the EU. Therefore, the fundamental task of energy policy is to accelerate the transition process while ensuring adequate ambition in energy efficiency and greenhouse gas (GHG) reductions in buildings.

To meet climate targets, it is irrelevant who makes the contributions or where they originate, as long as the emission reductions are substantial and aligned with the timeline necessary for planetary preservation. However, such an approach could lead to policies that overlook national and local interests, potentially resulting in negative spillover effects that can be difficult to manage if not anticipated. The following section will examine the spillover effects and their origins in greater detail.

1.1.4 Spillover effects of government interventions

It is evident that governments regulate and intervene in the market with the aim of mitigating market failures, fostering new technologies, and initiating broader transformations intended to benefit society. Contrary to the intended outcomes, policy and regulatory interventions often lead to spillover effects – unintended consequences that extend beyond the targeted area or population, as was suggested by 19th-century economists John Stuart Mill (Medema 2007). These effects can manifest as both positive and negative consequences across various sectors. Positive spillovers strengthen the intended outcomes and function as reinforcing feedback loops, whereas negative spillovers may exacerbate existing problems and give rise to new and unexpected issues.

It could be argued that spillover effects are not necessarily flaws; rather, they are features of the system within which regulatory policy is applied. This argument is supported by general systems theory (Bertalanffy 1973), which suggests that societies, economies, and policies function as interconnected systems comprised of multiple subsystems, such as regional economies, local governments, and infrastructure networks. Such systems are complex and non-linear, possessing the ability to self-regulate and demonstrating a certain degree of resilience to disruptions. Based on the properties of complex systems, changes in one part of the system can trigger cascading effects across other parts due to feedback loops and interdependencies (Meadows 2011).

One distinct property of complex systems is emergence, which refers to behaviours or characteristics that arise from the interactions of individual components but are not predictable from the properties of the individual parts (Corning 2002). Thus, spillover effects can also be attributed to emergence as unpredictable outcomes.

Systems theory also identifies another characteristic of systems, referred to as system traps. In the context of this thesis, one such trap is termed “success to the successful,” as highlighted by the influential systems thinker Donella Meadows (Meadows 2011). This trap posits that communities with already higher financial and social capacities are better positioned to benefit from common resources, such as renovation grants, compared to more vulnerable communities, thereby exacerbating the disparity in capital accumulation.

Consequently, drawing upon Luhmann's theory of social systems (Luhmann 1995), if we accept the premise that energy policy operates within a complex system and is an integral and explicit part of such a system, it is reasonable to expect that policy interventions will also result in spillover effects.

Literature identifies several spillover effects associated with significant transitions in general and energy policy in particular. Some of these spillovers can yield positive outcomes. For instance, in the context of renovations, it has been observed that already renovated buildings encourage neighbouring communities to renew their properties (Irwin 2019). While positive spillovers may be unexpected, they align with the intended objectives of market interventions.

Negative spillovers, on the other hand, represent the unintended consequences of a policy. In 2017 Turcu already suggests that the distribution of renovation grants may be distributing inequitably, drawing attention to a grant programme in Bucharest, Romania (Turcu 2017). The research underscores that local government interventions do not impact municipalities with the greatest need and potential. As Turcu focuses on data within a specific region, there is a lack of evidence regarding grant distributions on a regional scale.

State renovation programmes can significantly impact regional economies, creating disparities between areas with high renovation demand and those that are neglected. A recent study indicates that when demand is concentrated in certain areas, it can create imbalances by fostering economic growth in regions with higher demand while leaving others behind (Mikulić, Keček, and Slijepčević 2021). Regions receiving substantial funding may experience increased local employment, business activity, and rising property values, attracting further investments. Conversely, overlooked areas may suffer stagnation and population decline, widening the gap between thriving and struggling regions.

A significant spillover effect of subsidies, particularly regarding energy renovations, is linked to the targeting of communities in need. Poor targeting allows free-riders to benefit from financial support, even though they could have renovated their properties without any assistance (Neef, Egner, and Klöckner 2024). A high ratio of free riders diminishes the cost-effectiveness of the policy and highlights issues of injustice, as valuable public resources are allocated to communities that do not require financial aid.

While free-riding is most commonly associated with specific members of a community, it can also be extended to larger spatial scales, suggesting that more capable districts act as free-riders in comparison to their less developed counterparts.

1.1.5 Justice influencing energy policy

The natural environment and the justice system are indispensable foundations for the survival of a functioning society (Rawls 1971; Rockström et al. 2009). While global energy policy attempts to protect the environment, the actions that follow must also be justified and perceived as just.

Justice is a multifaceted concept that encompasses fairness, equality, and moral righteousness in the distribution of rights, resources, and responsibilities within society. The essence of justice has been debated by philosophers from ancient times, such as Aristotle, to contemporary thinkers like John Rawls. Aristotle defined justice as giving each individual their due based on merit and need, whereas Rawls emphasises fairness as equity, ensuring equal opportunities for all members of society (Rawls 1971).

Justice is not merely an abstract philosophical ideal but a fundamental expectation within any functioning society. Sociologists and political theorists contend that individuals inherently pursue justice as part of the social contract, wherein they consent to adhere to laws in exchange for protection and fairness. This expectation arises from the human need for security, stability, and predictability in interactions with others. In democratic societies, the rule of law guarantees accountable governance, ensuring that individuals are afforded equal opportunities irrespective of their background.

Building on the works of Aristotle, justice is often categorised into various forms, including distributive justice (the equitable allocation of resources), procedural justice (fairness in legal processes), and retributive justice (fair punishment for wrongdoing). Within the context of a functioning society, justice ensures that individuals are treated equitably, conflicts are resolved through legitimate means, and social cohesion is maintained.

In this thesis, distributive justice is the main concept for understanding the spillover effects of energy policy. Distributive justice entails the equitable allocation of resources, wealth, and opportunities within society, ensuring that benefits and burdens are distributed according to principles of equality, equity, merit, or need. It addresses the mechanisms for resource allocation that promote fairness and social stability.

John Rawls, in *A Theory of Justice* (1971), introduced the Difference Principle, positing that inequalities should be structured to benefit the least advantaged members of society. He proposed the concept of a veil of ignorance to ensure impartiality in the formulation of justice principles. In contrast, Robert Nozick, in "*Anarchy, State, and*

Utopia", offered a critique of redistribution, advocating for an entitlement theory grounded in property rights and voluntary exchanges (Nozick 1974). Amartya Sen's *The Idea of Justice* presents the capability approach, which emphasises individuals' actual freedoms to attain well-being rather than merely focusing on the distribution of resources (Sen 2009).

Within the overarching concept of distributive justice, several subcategories have emerged to address specific domains. The domains pertinent to this research include: (1) energy justice and (2) spatial justice.

Energy justice ensures the fair distribution of energy resources and services while minimising environmental and social burdens. It addresses energy access, affordability, sustainability, and social impacts on marginalised communities, advocating that everyone should have access to clean, affordable, and reliable energy.

Benjamin K. Sovacool has been a key theorist, promoting equitable energy distribution, inclusive policy-making, and addressing the needs of disadvantaged communities during transitions (Sovacool and Dworkin 2015). Scholars like Gordon Walker and Harriet Bulkeley have explored the intersection of energy justice with climate change and environmental governance, highlighting the need to protect vulnerable populations during the shift to renewable energy (Bulkeley, Edwards, and Fuller 2014; Walker, Simcock, and Day 2016). Energy justice is vital in discussions on renewable energy policies, just transitions, and climate justice, influencing decisions on fossil fuel phase-outs, electrification in developing nations, and fair energy pricing to ensure an ethical and inclusive low-carbon future.

Spatial justice introduces an additional dimension to the concept of distributive justice, encompassing the fair and equitable distribution of resources, opportunities, and services across geographical spaces, ensuring that all communities – regardless of their location or socio-economic status – have access to the benefits of development and policies (Lefebvre 1997). It is deeply rooted in the idea that physical space is not neutral but is shaped by power dynamics, policies, and historical inequalities (Soja 2010). In the context of energy policy, spatial justice emphasises that the benefits of energy investments (such as subsidies for energy efficiency) and the burdens of energy systems (such as pollution) should be distributed fairly across different regions and communities.

By combining the notions from energy and spatial justice, this thesis forms a theoretical framework for addressing energy policy that aims to mitigating climate change.

Energy transitions are not just technical shifts – they are also socio-spatial transformations (Garvey et al. 2022) that can either reduce or exacerbate existing inequalities. Considering spatial justice in energy policy seeks to ensure that no region or community is excluded in the pursuit of cleaner, more efficient energy systems. By addressing geographic disparities and involving marginalised communities in decision-making, energy policies can become more effective, inclusive, and politically sustainable, ultimately supporting broader objectives of equity and sustainability.

Focusing on the inequitable distribution of subsidies as a key negative spillover of subsidy adoption for deep energy renovations is an important area of research in this thesis for several compelling reasons, even in the presence of numerous other spillovers listed previously.

In their recent comprehensive review, Garvey et al. (2022) point out that social justice is central to sustainable transitions meaning that the main driver of energy policies must be fair to different social groups and spatial contexts. As governments push for energy transitions, the burden of the transition should not disproportionately fall on marginalised communities. If energy renovation subsidies primarily benefit wealthier households and free-riders (Risch 2020), it risks exacerbating energy poverty and inequality. Research can identify such mechanisms to ensure equitable access to subsidies, but it is up to policymakers to consider and adopt the knowledge for more just policies.

Neglecting equity in energy policies could lead to widespread public dissatisfaction, social backlash, or reduced political feasibility for climate-related policies. Therefore, energy policies should balance environmental objectives with social equity to avoid creating or worsening social divides.

Failing to address geographic disparities in energy policy could leave entire regions stuck in cycles of poverty, poor housing, and high energy costs. If disadvantaged communities feel excluded from energy policy benefits, they may resist future environmental initiatives, delaying progress on climate goals. Concentrating investments in already advantaged areas limits the potential for widespread societal and environmental benefits.

1.1.6 Conceptual framework for the thesis

Based on the arguments presented in previous chapters, this section aims to formulate the conceptual framework for the thesis. In doing so, the subject matter of the study is defined, and the research intent, along with the concepts employed, is clarified. The conceptual framework forms the basis for the purpose statement and research questions with corresponding empirical hypotheses in the thesis and is presented in section 1.2.

Governments frequently intervene in markets to address perceived inefficiencies, promote social welfare, or achieve specific policy goals. One such intervention is renovation acceleration programmes, which are driven by global climate targets. Among the various policy tools available, subsidies are particularly significant because they can alleviate financial barriers and boost demand for renovations. By reducing the cost burden on property owners, subsidies can encourage upgrades that might otherwise be financially unfeasible.

However, the implementation of these policies can lead to unintended consequences or spillover effects. Negative spillovers arise when the benefits of the intervention are unevenly distributed, resulting in outcomes that conflict with principles of equity and justice. This investigation specifically examines these negative spillovers and their spatial distribution across regions, emphasising how subsidies may worsen existing inequalities or create new disparities.

Regions in this framework are treated as subjects to spatial justice, and addressed as fractals, meaning that individual rights can be consolidated into groups, neighbourhoods, and regions, as the properties of any larger entity depend on individuals that operate within a region.

The spatial justice for regions is grounded in national interests, which stem from national strategies and spatial plans. The idea is to extend the perception of justice from individual level to the regional scale and examine how subsidy distributions are aligned with the national interests, and to conclude if government interventions can be considered as spatially justified.

A significant aspect of national interests, such as preserving national capital (including housing) and ensuring energy security, aligns closely with global energy policy. However, regional aspirations are contingent upon the adoption of energy policy within specific regions, taking into account local contexts such as long-term population trends and economic growth.

The primary reasons for grounding this research in the case of Estonia include the evident existing regional disparities (Heidenreich and Wunder 2007; Kebza, Nováček, and Popjaková 2019; Raagmaa 2023) which require a holistic approach for addressing (Lange 2015), and the significant need for extensive renovation of the residential building stock, despite global climate targets. Additionally, data concerning multifamily buildings, including their type and occupancy rates, are well documented and readily accessible. Estonia represents one of the European countries with a high rate of apartment ownership (72% according to census 2021 data), which creates a relatively homogeneous group of potential clients for state subsidy incentives. In terms of energy policy and its equity aspects, Estonia began extensive distribution of subsidies in 2010, without specific regional or social targeting. This situation allows for a temporal examination of the evolution of energy policy. Finally, the author of this thesis can relate the complexities of energy policy development to research findings based on prior experiences within the field in Estonia.

By framing regions as subjects of justice and situating negative spillovers within the broader context of regional disparities, this framework provides a foundation for examining how interventions can inadvertently perpetuate or exacerbate spatial inequalities. Consequently, the research helps to inform policy design that can anticipate adverse spillovers and promote balanced, equitable regional development.

1.2 Aim and research questions

The overarching aim of this study is to explain how central government intervention in the renovation market, when disregarding considerations of justice, can exacerbate existing spatial disparities, intensify inequality, and contribute to social polarisation, thereby undermining the national strategic aim of even regional development. This research seeks to analyse the regional patterns that emerge from support for apartment building renovations, guided by energy policies that prioritise energy and climate targets. In this context, it aims to clarify the relationships between subsidies and the characteristics that define regional development, such as economic indicators and population dynamics.

Given that the motivation for this study arises from the currently inadequate pace of renovations across Europe, one of its objectives is to examine the barriers to innovations, such as industrialised and district-based renovation. Consequently, the study aims to contextualise empirical research within the framework of justice, with a particular emphasis on distributive justice and its associated subdomains. To achieve the purpose of the study, four research questions along with supporting hypotheses are organised as follows:

Research question 1: In what ways do non-targeted subsidy policies influence regional disparities in Estonia?

Hypothesis 1.1: Non-targeted renovation grants converge to more prosperous regions in Estonia.

Hypothesis 1.2: Energy policy in the European Union and at the member-state level does not explicitly address issues of social and spatial justice.

Research question 2: How do population trends at the regional level influence residential vacancy and renovation patterns?

Hypothesis 2.1: Multifamily buildings become more underused as the distance from the regional centre increases.

Hypothesis 2.2: Once a specific threshold for the vacancy rate is exceeded, the probability of receiving renovation support approaches zero.

Research question 3: What hinders the adoption of innovations for accelerating the deep energy renovation rate?

Hypothesis 3.1: National renovation policies in Europe do not explicitly address and promote innovations in mass renovations.

Hypothesis 3.2: The supply side faces significant challenges in adopting innovations for mass renovation on its own.

Research question 4: To what extent do informed changes in energy policy contribute to a more equitable distribution of renovation grants at the regional level in Estonia?

Hypothesis 4.1: Regionally targeted renovation subsidy programmes lead to a more equitable distribution of grants between regions.

Hypothesis 4.2: Policymakers and stakeholders struggle with adopting equity in energy policy due to difficulties in conceptualising and monitoring equity.

1.3 Outline of the study

The thesis presents five research articles that address the proposed research questions. Chapter Two provides an overall overview of the methodology of the study and argues for the chosen case. All the research questions, along with the hypotheses, are next answered in Chapter three and discussed in Chapter four. The conclusions for the thesis are presented in Chapter five, followed by Chapter six, which explains the prospects for future work.

Four research questions are addressed in five articles (**Figure 2**) The Article I establishes the framework for the unequal distribution of renovation grants in Estonia. During the research for this article, the significance of underutilised buildings in calculating the regional distribution of subsidies became apparent. It was evident that regional trends, such as population decline, play a crucial role in determining renovation potential, as many regions in Europe are also experiencing shrinkage. Consequently, Article II sought to quantify the influence of population trajectories by forecasting changes in housing stock by 2050. At that time, the housing vacancy rate was poorly understood in Estonia. Thus, an overarching assumption was made that vacancy rates increase with the distance of buildings from regional centres, which was incorporated into the calculations. This assumption was tested in the research presented in the fourth article. Given that the acceleration of renovation is a primary objective of the global climate agenda, Article III explored the role of innovations that promise to enhance the pace of renovation. The final question of the thesis aimed to address policy changes in the context of regionally targeted subsidy distribution, which was initiated by the results of Article I.

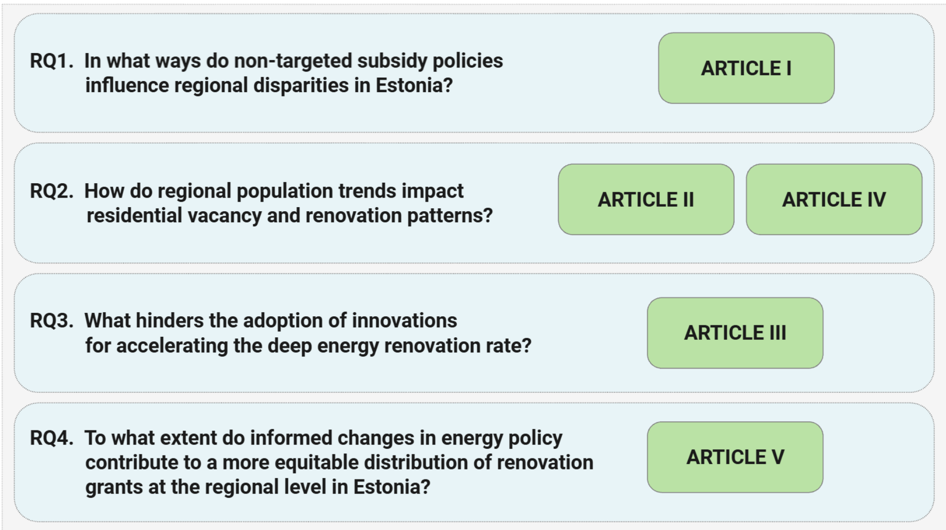

Figure 2 *Research questions (RQ) relations to published articles.*

1.4 Scientific novelty

This dissertation advances research at the intersection of energy-efficient building renovation, regional development, and energy justice. While European and international climate policies increasingly emphasise deep renovation and decarbonisation of the building stock, most academic and policy work still treats renovation primarily as a question of technical performance and aggregate cost-effectiveness (Sovacool and Dworkin 2015; Zangheri et al. 2022). Low-carbon transitions are inherently geographical and reshape centre–periphery relations and regional development paths (Bridge et al. 2013). The uneven social and spatial consequences of renovation incentives, particularly in shrinking and regionally polarised countries, remain under-examined (Ricci, Konstantinou, and Visscher 2025).

First, the dissertation provides a novel operationalisation of spatial energy justice for renovation subsidies. Energy justice scholarship has developed rich conceptual frameworks around distributional, procedural, and recognitional justice, but it rarely translates national regional development goals into explicit quantitative criteria for fair subsidy allocation. Most empirical work either maps socio-spatial inequalities in energy use and efficiency or assesses programme uptake descriptively at coarse spatial scales (Sovacool and Dworkin 2015). Building on this literature, the thesis develops and applies a Proportionality Index (PRI) that evaluates whether renovation subsidies are distributed in line with state goals for balanced regional development. The PRI links normative targets (for example, renovating a given share of the apartment stock in each type of region) with realised subsidy flows. This goes beyond earlier studies that documented unequal subsidy uptake but did not embed their analysis in a clearly defined national equity benchmark (Lekavičius et al. 2020; Turcu 2017).

Second, the dissertation integrates building vacancy and demographic decline into renovation policy analysis, an aspect that is largely absent from both building decarbonisation modelling and energy justice studies (Kavgic et al. 2010). Existing work on vacancies and shrinking regions tends to focus on fiscal stress, changing housing markets, or municipal service provision, without connecting these dynamics to renovation support schemes or long-term decarbonisation pathways (Haase et al. 2014; Martinez-Fernandez et al. 2012; Nordvik and Gulbrandsen 2009). By combining building-level data on physical characteristics, energy performance, and occupancy status with regional demographic trends, the thesis develops models of how vacancy could alter Long-term Renovation Strategy. It shows that in persistently shrinking regions, equal access to renovation grants does not automatically translate into equal long-term benefits, because a substantial share of the stock is likely to exit effective use before 2050. This represents a novel contribution to debates on "who should we renovate for?" by explicitly linking renovation support to the future viability of residential buildings in different types of regions (Huuhka 2016).

Third, the work bridges technological research on mass renovation with the design of renovation policy instruments. Technical and policy literature on mass renovation have largely evolved in parallel. Engineering and construction research explores prefabricated off-site serial renovation(Kuusk, Pihelo, and Kalamees 2019), zero energy renovations (Kuusk et al. 2020) and district-based approaches (Vendel et al. 2026), but rarely examines how subsidy schemes, planning rules, and governance arrangements would need to change to support these models at scale. While the barriers to industrialised renovations are already addressed in the literature (Chauhan et al. 2024; Pikas et al. 2021), the novelty of this thesis is in the evaluation of how EU-wide mass renovation aims are addressed in national strategies to pursue climate targets.

Fourth, the dissertation offers a rare ex-post evaluation of policy change towards more equitable grant allocation (Darmais, Glachant, and Kahn 2024). Many authors call for better targeting of renovation subsidies towards vulnerable households and places (Lewis, Hernández, and Geronimus 2020; Reames 2016; Ricci, Konstantinou, and Visscher 2025). However, there is limited evidence on whether concrete reforms actually improve spatial fairness in practice (Willand et al. 2020). The dissertation analyses a major policy redesign that introduced new targeting rules and eligibility criteria. Using building-level microdata and the new proportionality indicators, it compares pre- and post-reform subsidy distributions and tests how far the changes move the system towards the national objectives of balanced regional development and adequate housing in all regions. This empirical ex-post analysis of a national renovation scheme, grounded in energy justice concepts and regional development goals, is an important step beyond more generic evaluations of programme effectiveness framed often in terms of energy saved or the number of renovations completed (Giandomenico, Papineau, and Rivers 2022).

Finally, the dissertation's multi-scalar and mixed-methods approach is itself innovative (Kanger and Sovacool 2022; O'Sullivan and Howden-Chapman 2017). It connects EU-level decarbonisation and renovation commitments with national strategies, regional development policies and building-level decisions in a single analytical framework. The work combines: (i) quantitative spatial analysis of renovation subsidies and building vacancy; (ii) econometric modelling of renovation uptake probabilities; (iii) qualitative analysis of Long-term Renovation Strategies and interviews with policy and industry actors; and (iv) counterfactual policy scenarios using the PRI and vacancy-adjusted indicators. This design allows the thesis to show not only that inequalities in renovation benefits exist, but also why they arise in the current policy mix and how alternative instrument designs could improve distributive justice.

2 Materials and methods

2.1 Methodological framework

The aim of this thesis necessitated a multi-method approach that combined both quantitative and qualitative research methodologies. The overall relationships between the methods, research questions, and published articles are illustrated in **Figure 3**. The subsequent section explains the methodological framework and its rationale.

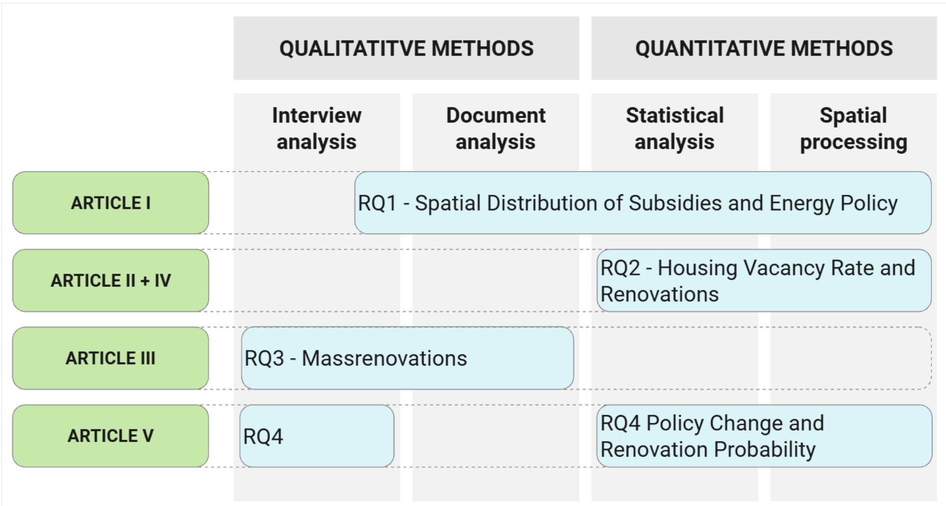

***Figure 3** Relationship between published articles, research questions (RQ) and analysis methods.*

Based on the assumption that government interventions may lead to negative spillovers, and relying on preliminary observations of national data on grants, the first research question (RQ1) was formulated: "**In what ways do non-targeted subsidy policies influence regional disparities in Estonia?**" To address this question, it was essential to measure the distribution of renovation grants across regions and to identify the variables that can elucidate such distribution. The underlying hypothesis posited was: "Non-targeted renovation grants converge to more prosperous regions in Estonia." To test this hypothesis, spatial, numerical, and statistical methods were employed (see Article I).

The results from testing the first hypothesis warranted additional examination of whether spillovers are anticipated within energy policy across Europe. Consequently, the second hypothesis was articulated as follows: "Energy policy in the European Union and at the member-state level does not explicitly address issues of social and spatial justice." It was found that the Energy Performance of Buildings Directive (EPBD) and national Long-Term Renovation Strategies (LTRS) could provide systematic insights for testing this hypothesis. Content analysis of these sources was subsequently conducted (see Article I).

The formulation of the second research question was partly prompted by the challenges encountered in testing the first hypothesis of RQ1. It became evident that measuring the equality of renovation distribution necessitates consideration of the vacancy of residential buildings, which is influenced by demographic factors and domestic migration. Thus, the second research question (RQ2) was proposed: "**How do population trends at the regional level influence residential vacancy and renovation patterns?**". This question was investigated in Articles II and IV, employing solely quantitative methods. RQ2 was further delineated by two hypotheses. The first stated: “Multifamily buildings become increasingly underused as the distance from the regional centre increases.” In Article II, this hypothesis served as a foundational assumption for forecasting residential building vacancy by 2050. Article IV tested this hypothesis by correlating vacancy with electricity consumption data.

The second hypothesis of RQ2 was formulated as follows: “Once a specific threshold for the vacancy rate is exceeded, the probability of receiving renovation support approaches zero.” Statistical methods were deemed most appropriate for testing this hypothesis; however, spatial and numerical processing was also required to prepare the data for statistical analysis.

The third research question focused on the fundamental issue of global energy policy, wherein the insufficient speed of the renovation rate is identified as a primary barrier to mitigating climate change. The concept for Article III emerged from recent technical advancements in industrial serial renovations applicable to multifamily buildings mass-produced in Europe after World War II. In addition to these technical innovations, renovations could also be executed across multiple buildings within a district simultaneously. Both approaches were conceptualised as mass renovations, which strongly reflect the manner in which the post-war housing crisis was addressed through the construction of prefabricated multifamily districts.

To explore the challenges surrounding mass renovations, the third research question (RQ3) was articulated as follows: “**What hinders the adoption of innovations for accelerating the deep energy renovation rate?**”. This question was further refined by two hypotheses. The first, which addressed RQ3 at the EU level, stated: “National renovation policies in Europe do not explicitly address and promote innovations in mass renovations.” This hypothesis was substantiated by the premise that any evidence contradicting it could serve as examples for enhancing energy policies that might facilitate mass renovations in other Member States. The method of content analysis for testing this hypothesis was based on the available LTRS data for each EU member state.

The second hypothesis of RQ3 aimed to investigate the barriers and enablers to mass renovations at the local level. It was articulated as follows: “The supply side faces significant challenges in adopting mass renovation innovations on its own.” To gather evidence supporting this hypothesis, the in-depth interview method was selected, as it was deemed beneficial for exploring previously unexamined concepts related to the adoption of mass renovations.

The fourth and final research question (RQ4) revisited the ideas presented in Article I. The research findings regarding the unequal grant programme had influenced policymakers, prompting them to reconsider subsidy allocation and introduce regional targeting. Given that data were already available for new subsidy allocations in practice, RQ4 was framed as follows: “**To what extent do informed changes in energy policy contribute to a more equitable distribution of renovation grants at the regional level in Estonia?**” The first proposed hypothesis sought to determine whether regional targeting was effective and was articulated as: “Regionally targeted renovation subsidy programmes lead to a more equitable distribution of grants between regions.”

The conception of the second hypothesis for RQ4 was influenced by informal discussions with policymakers, which suggested that concepts of equality and justice are rather nebulous within energy policy. To capture greater detail on how the policy design process influences the outcomes of specific rules and regulations, the second hypothesis was established: “Policymakers and stakeholders struggle with adopting equity in energy policy due to difficulties in conceptualising and monitoring equity.” The nature of this hypothesis and the limited number of stakeholders warranted the use of in-depth interview methods for data collection.

Next, the case of Estonia is presented along with arguments for selection rationality. The following chapters explain data collection and introduce the analysis methods adopted.

2.2 Case of Estonia

Estonia serves as an exemplary case study for investigating residential renovation patterns, particularly in the context of mass-produced multi-family apartment buildings and the associated governance mechanisms. The country’s unique socio-economic and policy landscape provides a robust and analytically advantageous setting for research on renovation distributions, making it an ideal subject for in-depth examination.

Firstly, Estonia’s apartment ownership and occupation structure is remarkably homogeneous. According to 2021 census data, private ownership constitutes 90 per cent of all apartments, with 72 per cent being owner-occupied and 18 per cent rental dwellings. This homogeneity significantly reduces variability in tenure-related factors, allowing researchers to isolate other determinants of renovation patterns, such as financial incentives, governance structures, and regional disparities. The energy renovation programme in Estonia also establishes equal conditions for applicants, ensuring that variations in outcomes arise not from programmatic biases but from structural and socio-economic factors. Furthermore, primary responsibility for renovation is vested in apartment associations, which serve as key decision-making bodies. This centralised approach reduces the complexity of governance and administrative oversight, thereby enhancing the reliability of empirical analyses.

Secondly, Estonia's housing stock presents an ideal scenario for renovation research due to its historical construction patterns. The majority of apartment buildings (90%) were constructed prior to 1990, with Soviet-era housing estates forming a significant proportion of the residential landscape. These estates, originally conceived as “micro-regions,” consist of large clusters of apartment buildings with similar architectural and material compositions, making them suitable for district-level renovation strategies.

Governance mechanisms further enhance Estonia’s relevance as a case study. The country’s renovation framework is characterised by a clear division of responsibilities between central and local governments (**Figure 4**). While the central government primarily drives demand through grants and financial incentives, local governments play a limited role, issuing construction permits but exerting minimal influence on renovation projects. This structure provides an opportunity to assess the effectiveness of centralised policy interventions in stimulating renovation demand and mitigating market failures, particularly in economically weaker regions where renovation efforts have historically lagged. Additionally, the compulsory formation of apartment associations as of January 2018 establishes an institutional framework for collective decision-making, ensuring that the dynamics of community-led renovation initiatives can be systematically studied.

Finally, Estonia presents a compelling case for examining the impact of regional demographic trends on housing renovation and abandonment. The country’s overall population projection between 2022 and 2050 remains relatively stable, with only a 1 per cent decrease (based on Statistics Estonia’s 2024 baseline scenario and Eurostat’s EUROPOP2023 projections). However, significant regional disparities exist. For instance, while the capital region of Harjumaa grows, certain regions, such as Ida-Virumaa, are projected to experience population declines of up to 36 per cent, raising critical questions about the sustainability of housing investments in shrinking areas. These dynamics facilitate an exploration of how demographic shifts influence housing maintenance decisions, create regional inequalities in access to renovation funding, and potentially lead to the emergence of abandoned housing stock (OECD 2022).

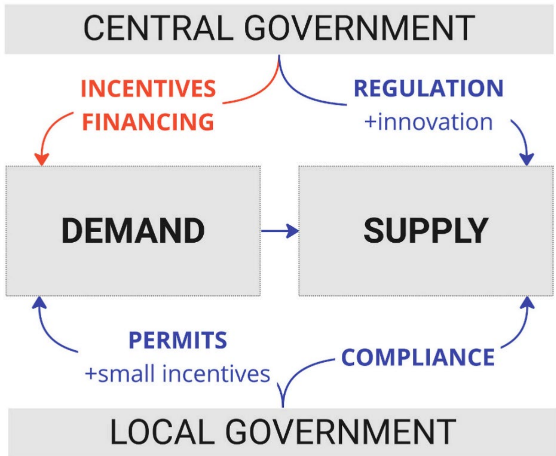

Figure 4 *Governing residential renovation demand and supply in Estonia. Source: based on Article III.*

The Estonian renovation subsidy programme was established to improve the energy efficiency of multifamily residential buildings in line with the EU's carbon reduction goals. Launched in 2010, it has evolved through several phases, adjusting financial mechanisms, eligibility criteria, and technical requirements.

The initial phase (2010–2014) used emissions trading funds to provide grants based on energy performance improvements. Apartment associations could receive grants based on projected energy savings and the Energy Performance Certificate (EPC) class achieved, resulting in renovations for 661 buildings and average energy savings of 43 per cent. The second phase (2015–2017) implemented stricter technical requirements and increased the largest grant from 35 to 40 per cent to promote advanced heat recovery ventilation systems.

In the third phase (2019), grant allocations were adjusted for regional economic disparities, addressing previous imbalances favouring urban centres like Tallinn and Tartu. The new scheme offered higher subsidies (up to 50%) in areas with lower real estate values and reduced support (to 30%) for major cities. Buildings of cultural or historical significance were exempt from achieving EPC class C.

The fourth phase (2020) responded to COVID-19 by removing regional funding allocations and allowing partial renovations in economically weaker regions without strict energy-saving requirements. In 2021, a specialised grant scheme promoted prefabricated renovation technologies, offering 50 per cent subsidies to early adopters.

The most recent phase (2023) built on the 2019 principles while enhancing accessibility and affordability, increasing financial support for smaller apartment buildings (fewer than 18 units) and including accessibility improvements like elevator installations.

Overall, the Estonian renovation subsidy programme has transformed from a broad energy efficiency initiative into a targeted, regionally responsive scheme, successfully facilitating deep energy renovations while prioritising economic feasibility and environmental sustainability.

In conclusion, Estonia's combination of a highly structured housing ownership model, a substantial stock of Soviet-era (1945–1991) apartment buildings, a centralised governance framework, and pronounced regional demographic shifts renders it an ideal case study for research on renovation distributions. The homogeneity of its housing sector, coupled with state-driven renovation initiatives, ensures a controlled environment for analysing policy effectiveness, financial accessibility, and regional disparities in housing sustainability. Therefore, adopting Estonia as a case study not only provides valuable insights into the intricacies of mass-renovation efforts but also offers broader implications for similar housing markets across Europe.

2.3 Data collection and processing

The methodologies employed across the articles are structured around a comprehensive combination of approaches, categorised into six major groups: numerical data processing, spatial data processing, spatial interpolation of real estate values, statistical analysis, document and content analysis, and interview analysis. These categories collectively address key aspects of renovation patterns, building occupancy, socio-economic dynamics, and policy impacts, offering an integrated perspective to support targeted renovation policies and strategies.

The quantitative analysis is based mostly on secondary data that originates from different registries and statistical databases. However, qualitative data was collected during the research directly from original sources. Next, the origin of the data and the processing methodology are explained and reasoned.

2.3.1 Numerical data processing (Articles I, II, V)

Numerical data processing, utilised in Articles I, II, and V, forms the foundation of quantitative analysis, involving the acquisition, transformation, and analysis of large-scale datasets. The data sources include renovation grant records, population projections, building registries, real estate transactions, and energy consumption data. In Article I, numerical data from the renovation grant programme is processed to quantify renovation rates, assess regional disparities, and identify renovation hotspots. This processing involves estimating the share of renovations (SH_REN) and calculating the relative share of renovations (REL_SH_REN) to compare renovation efforts across different regions. Article II extends this approach by integrating population forecasts from the National Statistical Bureau, allowing the prediction of future occupancy trends and renovation needs under various scenarios, including base, optimistic, and pessimistic projections. Article V focuses on building-specific data, processing information related to building types, energy performance certificates, floor area, construction dates, and occupancy rates derived from electricity consumption. This comprehensive approach enables the identification of external barriers to renovation, such as low occupancy and poor building condition, which are beyond the control of apartment associations but critical for policy interventions.

2.3.2 Spatial data processing (Articles I, II, IV, V)

Spatial data processing, applied in Articles I, II, IV, and V, complements numerical analysis by incorporating geographical dimensions into the study of renovation distribution and occupancy rates.

The primary unit of analysis is a multi-family apartment building for which data regarding building attributes, vacancy rates, and renovation status are accessible. The primary spatial unit is a county, which encompasses various municipalities. Estonia is divided into 15 counties, serving as the foundation for regional classification within the country. The regional development aims are therefore measured at the county level. The last spatial analysis unit is regional centres, which are significant nodes within each region. Regional centres are the second-tier cities that organise economic activity and higher-level services for a wide surrounding region and structure Estonia's spatial development below the county centres (RAKE 2015; Small Settlement Viability Study 2017). In the thesis, regional centres also include all county centres. The Estonian map of regional division, along with regional centres, is shown in **Figure 5**.

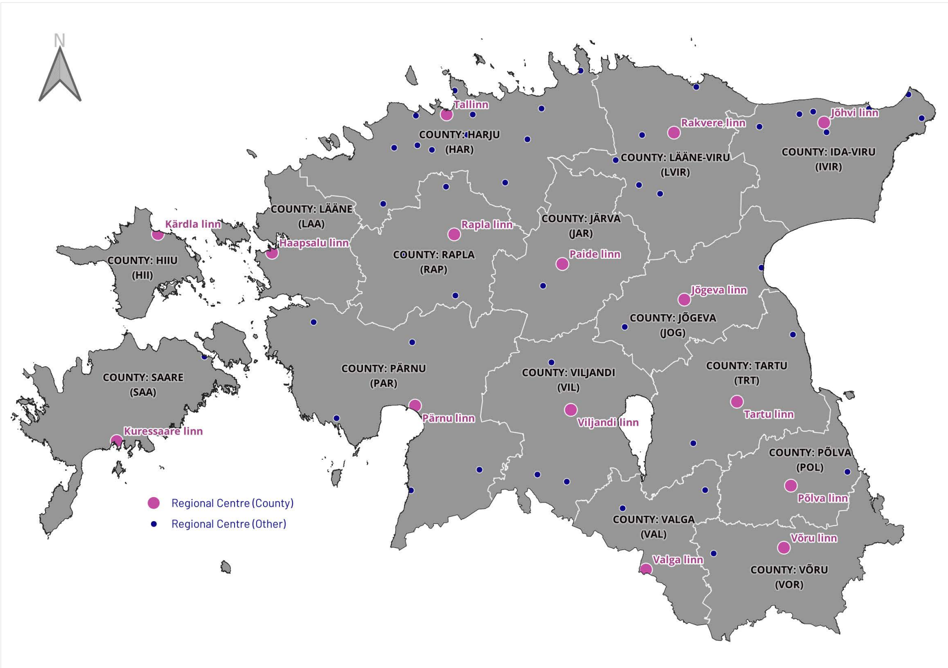

***Figure 5** Estonian regional division and regional centres. Source: Article IV.*

Using GIS tools of ArcGIS 10.2, QGIS v3.28 and SAGAGIS v7.8.2, spatial data processing involves mapping multifamily buildings, analysing spatial clusters of under-renovated regions, and examining the proximity of buildings to regional centres. Article I employs this technique to assess how renovation activity varies across urban and rural areas, considering factors such as regional economic conditions and building densities.

Article II combines spatial data with population migration models, predicting how urbanisation trends and the movement of populations from smaller settlements to larger centres will impact future renovation needs.

Articles IV and V further refine spatial analysis through distance-based classification, grouping buildings into zones according to their distance from regional centres. By integrating spatial data with socio-economic indicators, the study identifies spatial patterns of renovation inequality and provides evidence for geographically targeted interventions.

Spatial interpolation of real estate values, a specialised form of spatial analysis featured in Article I, estimates property values in regions with limited transaction data. Real estate prices often influence the willingness of property owners to invest in renovations, as lower property values can reduce expected returns on investment. Article I addresses this issue by interpolating real estate values across regions, filling data gaps and allowing for a more comprehensive assessment of regional economic conditions. **Figure 6** illustrates the map of real estate value zones that are based on transaction data between 2010 and 2017.

The interpolated property values are then used to refine the Proportionality Index (PRI), which measures the balance between the distribution of renovation grants and the regional stock of apartment buildings. This approach helps identify regions where low property values may act as a barrier to renovation, even in the presence of subsidies, suggesting the need for additional financial incentives or targeted outreach programmes.

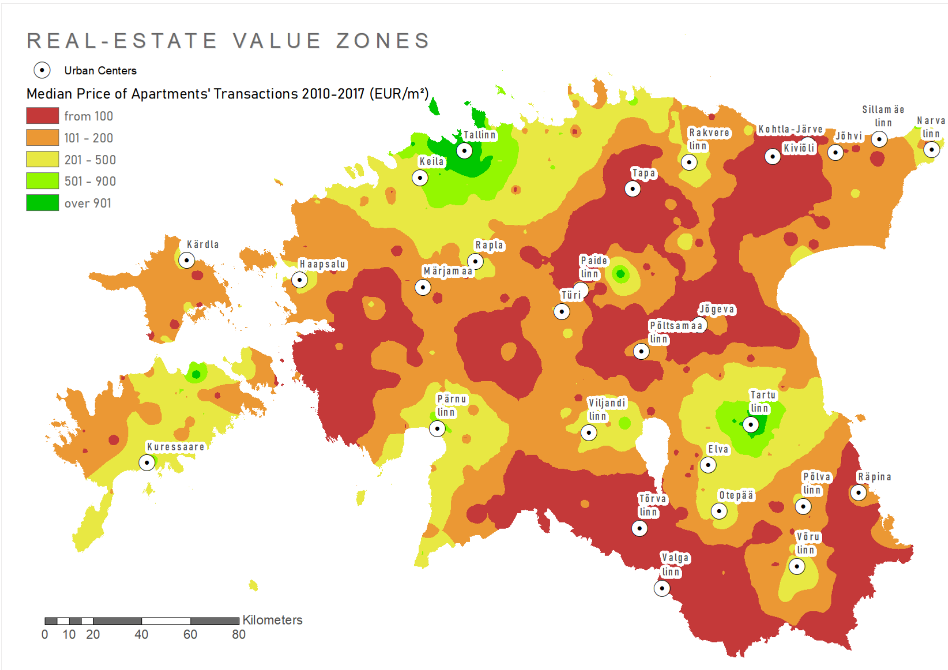

Figure 6 *Real-estate value zones. Data source: Estonian Land and Spatial Development Board. Illustration is based on calculations of Article I.*

2.3.3 Statistical analysis (Articles I, IV, V)

Statistical analysis, a critical component of Articles I, IV, and V, provides the analytical backbone for evaluating the relationships between renovation outcomes and key influencing factors.

Article I introduces the Proportionality Index (PRI) as a statistical measure to assess whether renovation grants are distributed equitably across regions based on their building stock. Canonical correlation analysis (CCA) is applied to explore the correlations between socio-economic variables, such as demographic dynamics and real estate values, and renovation activity. This method identifies the most influential variables driving renovation disparities and helps exclude those with minimal impact.

Article IV employs logistic regression to model the probability of a building receiving a renovation grant based on factors like occupancy rates and building type.

Article V extends the statistical analysis by comparing renovation patterns before and after policy changes, evaluating whether regionally targeted subsidies have effectively addressed disparities. Statistical analysis not only quantifies key drivers of renovation success but also provides actionable insights for improving policy design. Article V also proposes the Regional Development Index (RDI) to explore renovation subsidy distribution patterns. The RDI is a composite index that includes economic and social indicators at the regional level (**Table 1**). The yearly RDI values for 2010–2024 are presented in Annex **Table B2** in Article V. In the analysis, the average RDI values are used as the annual variation of the RDI is low.

Regional RDI variation in Estonia is notable, particularly between the two largest growing regions, Harju (HAR) and Tartu (TRT), and the rest of the country, consistent with previous findings (OECD 2025; Raagmaa 2023). The RDI is categorised into five classes across various regions using logarithmic distribution, as shown in **Figure 7**. While most regions cluster within a relatively narrow middle range, the high-performing outliers skew the national average significantly. Although there are no formal statistical outliers in the lower tail, the severe underdevelopment of the Ida-Viru region (IVIR) in comparison to the mean carries significant policy implications and should be considered when evaluating subsidy distributions.

Table 1 *Indicators in Regional Development index (RDI). Source: Paper V.*

Pillar	Source in Statistic Estonia	Indicator	Unit
Social	RV06U	DEMOGRAPHIC LABOUR PRESSURE INDEX	index
Social	RV088	POPULATION PROJECTION 2020-2080	percentage
Social	SK15	SHARE OF PENSIONERS IN TOTAL POPULATION	percentage
Economic	TT442	UNEMPLOYMENT RATE	percentage
Economic	RAA0050	GROSS DOMESTIC PRODUCT	EUR/per capita
Economic	ST14	MEAN EQUIVALISED ANNUAL DISPOSABLE INCOME	EUR/per capita

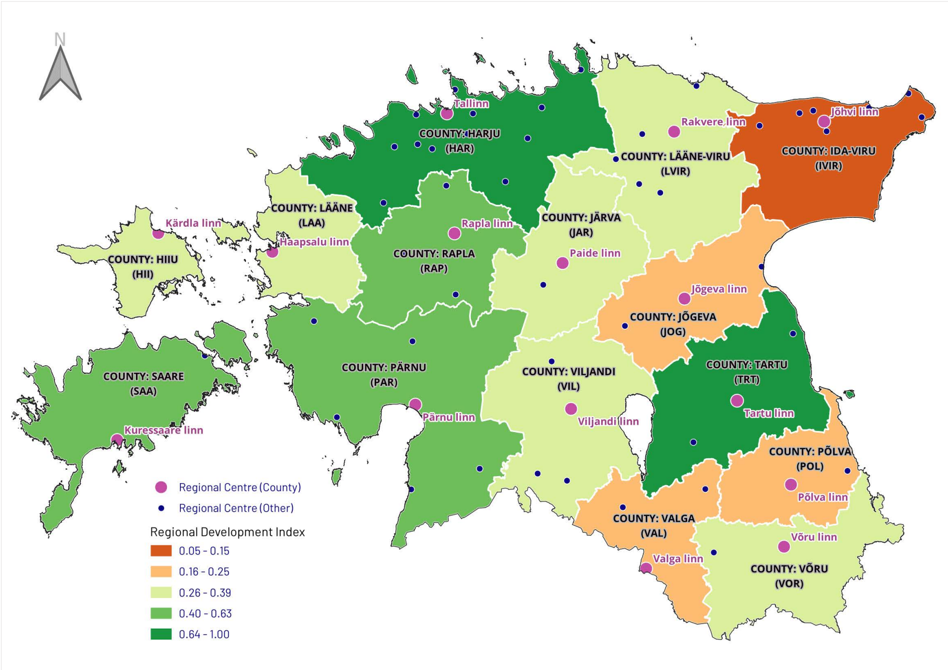

Figure 7 *Regional development levels and reginal centres among regions in Estonia. Source: Illustration is based on calculations of Article V.*

2.3.4 Document analysis (Articles I, III)

Document and content analysis, utilised in Articles I and III, adds a qualitative dimension to the research by examining policy documents, renovation strategies, and stakeholder narratives.

In Article I, content analysis focuses on institutional documents and government reports, providing context for understanding how regional development plans influence renovation policies. Article III conducts a more extensive analysis of Long-term Renovation Strategies (LTRS) submitted by EU Member States, using keyword searches to identify references to mass renovation concepts such as offsite prefabrication, district-level renovations, and modular construction.

The documents are categorised into five levels of ambition, ranging from minimal references to detailed action plans, allowing for comparative analysis across countries. This classification highlights which regions have advanced plans for scaling up renovations and which are lagging, offering valuable insights for cross-regional learning and policy harmonisation. Content analysis is further supported by qualitative interviews and observations, ensuring that both policy intentions and practical challenges are considered.

2.3.5 Interview analysis (Articles III, V)

Interview analysis, featured in Articles III and V, involves collecting qualitative data through in-depth interviews with key stakeholders, including construction contractors, renovation consultants, prefabricators, policy designers, and representatives of local government.

Article III relies on interviews to understand the experiences and perspectives of stakeholders involved in mass renovation projects, focusing on practical barriers such as mistrust among stakeholders, financial constraints, and information asymmetry. These interviews, conducted using semi-structured formats, provide detailed insights into the challenges of scaling up renovations and potential solutions. The data is analysed thematically, with recurring themes such as the need for better coordination between policymakers and service providers and the importance of community engagement in overcoming resistance to renovations.

Article V supplements interview analysis with stakeholders who influence energy policy, particularly those who determine subsidy allocation. The method of in-depth interviews enhances the reliability of quantitative findings, supporting the formulation of practical recommendations for improving policy implementation.

3 Results

The results of the research are divided into four main sections and are directly related to four research questions. Each section attempts to answer the research questions by providing empirical evidence to test the proposed hypothesis.

3.1 Non-targeted subsidy policies influencing the regional disparities

The first research question of the thesis asks: "*In what ways do non-targeted subsidy policies influence regional disparities in Estonia?* (RQ1). This question was addressed in Article I. Evidence indicated that subsidies are not distributed equally between regions; therefore, it was reasonable to propose the empirical hypothesis (H1.1): "Non-targeted renovation grants converge to more prosperous regions in Estonia".

The Proportionality Index (PRI), designed for the assessment of grant distribution, revealed notable disparities among regions. Over 60 per cent of grants were concentrated in the capital region. A PRI value of one suggests perfect equilibrium between grant acquisition and housing stock in a region, while values exceeding one indicate a larger concentration of grants. The PRI values for the regions are presented in **Figure 8**. For instance, the contrast between the regions of IVIR and TAR illustrates a tenfold difference in PRI, despite the comparable size of their multifamily housing stock.

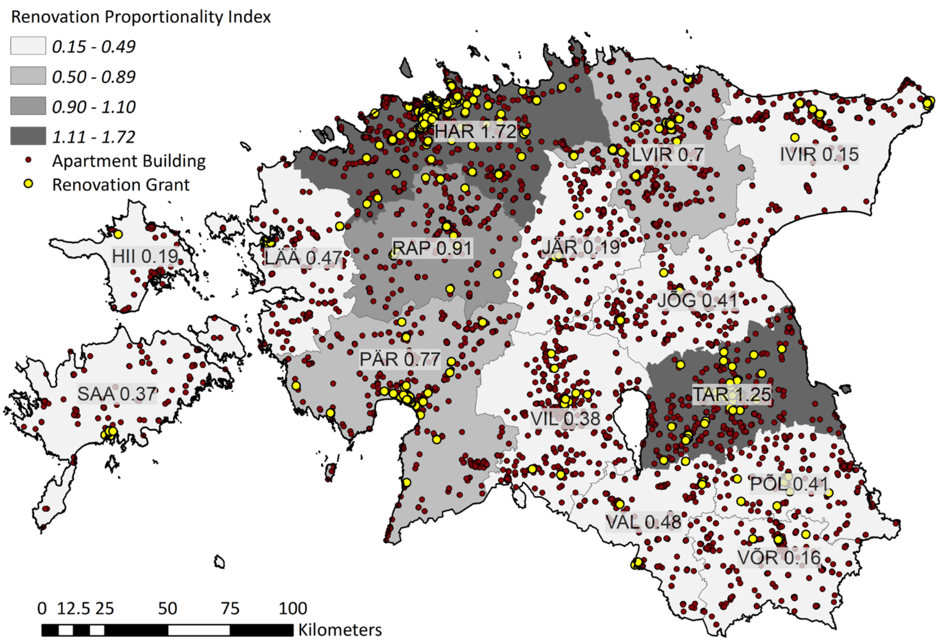

Figure 8 *Distribution of renovations subsidies across regions. Source: Article I.*

The statistical methods of canonical correlation and linear regression analysis confirmed hypothesis H1.1. This indicates that if a subsidy programme does not target a specific group or region, instead relying on formally equal access principles and focusing solely on energy efficiency, the more prosperous and capable communities tend to acquire the majority of the subsidies. In terms of climate targets, such a distribution can be considered inconsequential, as the overall amount of greenhouse gas reduction is what truly matters.

However, national strategies in Estonia clearly state that balanced regional development is a specific objective (SIM 2005, 2014). The National Spatial Plans further elaborate on the goal of preserving the settlement structure (KEM 2000; SIM 2012). As the inequitable distribution of grants exacerbates existing disparities, energy policy must also take into account other national strategic aims in addition to global climate targets.

Regarding the second empirical hypothesis (H1.2) of RQ1: "*Energy efficiency policy in the European Union and at the member-state level does not explicitly address issues of social and spatial justice*", the content analysis of relevant documents suggests that at the time of the publication of Article I, European energy policy was indeed predominantly focused on energy efficiency. Even the official impact assessments of the Energy Performance of Buildings Directive of 2010 did not report any negative spillovers that might arise from strong market interventions by member state governments. Such discourse was similarly evident in Estonian energy policy, which focused exclusively on the techno-economic advancements of deep energy renovations (Kurnitski et al. 2014; Kuusk and Kalamees 2016). A significant illustration of the discourse surrounding energy policy is the abandonment of the distinct Housing Strategy (MKM 2008), which was ultimately condensed into a set of energy targets within the Estonian Energy Strategy in 2013 (ENMAK 2017).

3.2 Population trends influencing renovation patterns

The second research question (RQ2) of the thesis states: "*How do population trends at the regional level influence residential vacancy and renovation patterns?".* This question is specifically addressed in Articles II and IV. As the results of population trends determine the vacancy of buildings, this overarching theme is also utilised in Articles I and V.

Research for Article I indicates that in order to compare regional building stock, the vacancy of buildings must be addressed more specifically. Regional trends, particularly demographic change and domestic migration, have a significant impact on the usage of residential buildings. Population declines, alongside substantial economic transformations and urbanisation in Estonia, support the proposal of the first hypothesis (H2.1) of RQ2: "*Multifamily buildings become more underused as the distance from the regional centre increases*.".

In Article II, the hypothesis H2.1 was not tested but rather used as a primary assumption to estimate the abandonment of residential buildings by 2050. The population forecast for 2050 projected a 3.5 per cent decrease in residents, with only two counties experiencing growth due to domestic migration. By utilising spatial processing to combine population projections with housing occupancy data, it was revealed that 5,322 apartment buildings, representing 17 per cent of the total surface area of apartment buildings, will be out of service by 2050. This methodological approach to the decommissioning of residential buildings was also adopted in the Estonian Long-term Renovation Strategy (LTRS) by the central government (LTRS 2020).

Article IV aimed to test the hypothesis H2.1 by categorising all Estonian apartment buildings according to distance zones originating from regional centres. Subsequently, the occupancy rate, derived from electricity consumption statistics, was compared against these distance zones. The results, illustrated in **Figure 9**, confirm the hypothesis by clearly demonstrating that as the distance from the centre increases, the occupancy rate decreases. This finding confirms the assumption made in Article II, upon which the premise of housing abandonment was based.

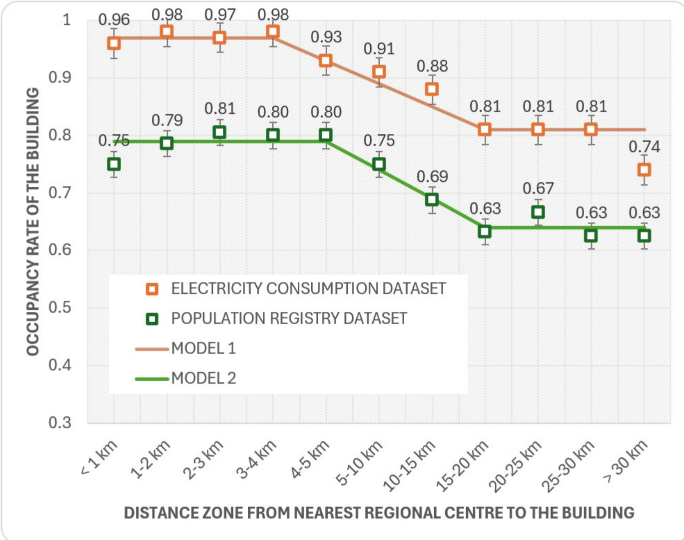

***Figure 9** Occupation rate of multifamily buildings within distance zones. Source: Article IV.*

The second hypothesis (H2.2) of RQ2 stated: "*Once a specific threshold for the vacancy rate is exceeded, the probability of receiving renovation support approaches zero*". This hypothesis was warranted by the results of Article IV and was statistically tested in Article V. The hypothesis was confirmed through logistic regression by evaluating the odds ratios. The dependent binary variable categorised all multifamily buildings into two groups based on whether a renovation grant was received. The results confirm that exceeding a specific threshold of 77 per cent occupancy rate causes the probability of acquiring grants to approach zero. Although some outliers were present, the overall result is clear: vacancy represents a significant barrier to achieving climate targets in low-occupancy buildings. The best chance for renovation exists in buildings that are occupied at least 95 per cent; furthermore, 40 per cent of the renovated buildings observed were fully occupied.

Additionally, it was found that the type of multifamily building (as defined in Article IV) is also a significant factor explaining the distribution of renovation grants. Logistic regression indicated that medium-sized, typical mass-constructed buildings have the highest likelihood of receiving grants. As building size increases, the probability decreases. The same is true for smaller buildings compared to medium-sized buildings; the probability diminishes as buildings become smaller. The most disadvantaged position is held by small, non-typical wooden buildings that contain 3-10 apartments. The probability of receiving State aid for such apartment associations is very low, approaching zero.

3.3 Innovations accelerating the pace of deep energy renovations

New technologies, such as industrial serial renovation and innovative processes like district-based renovation (DBR), are anticipated to substantially enhance deep energy renovation within typical mass-constructed buildings. Therefore, the third research question (RQ3) of the thesis states: "*What hinders the adoption of innovations for accelerating the deep energy renovation rate?*". This question is addressed in Article III, which focuses on the most pressing objectives of energy policy, specifically the need to accelerate the pace of renovations.

The first hypothesis (H3.1) of RQ3 states: "*National renovation policies in Europe do not explicitly address and promote innovations in mass renovations*". The hypothesis was confirmed through comprehensive content analysis based on reports of Long-term Renovation Strategies (LTRS) submitted by EU Member States in 2020 (LTRS 2020). At that time, LTRS represented the most significant policy documents, specifically outlining how energy targets in buildings would be achieved. Content analysis revealed that, in general, national renovation strategies lack a comprehensive approach to mass renovation (**Figure 10**).

	Mass-renovation levels	Concept	AT	BE-B	BE-W	BE-F	BG	HR	CY	CZ	DK	EE	FI	FR	DE	EL	HU	IE	IT	LV	LT	LU	MT	NL	PL	PT	RO	SK	SL	ES	SE
1	Related keywords to mass-renovation are unmarked or are irrelevant to scale up	PREFAB		○		○	○	○	○	○	○		○	○		○	○	○	○		○	○	○			○	○	○	○	○	○
		DBR					□		□	□	□	□		□	□	□		□	□	□	□	□	□		□	□	□	□	□	□	□
2	Mass-renovation is recognised superficially	PREFAB	○		○																				○						
		DBR	□																					□							
3	Mass-renovation is recognised as a solution for scale up and theoretical benefits are introduced	PREFAB										○																			
		DBR				□		□					□				□			□											
4	Mass-renovation is addressed explicitly as one aim in LTRS	PREFAB													○									○							
		DBR																													
5	Specific action plan for adopting mass-renovation is described	PREFAB																													
		DBR		□	□																										

○ *Prefabrication* ; □ *District based renovation* ; *BE-B Brussels region; BE-W Wallonia region; BE-F Flanders region*

***Figure 10** EU Member States' mass-renovation plans in LTRS. Source: Article III.*

Several factors may contribute to this deficiency. For instance, industrial serial renovation remains a relatively novel method for updating older buildings, necessitating a significant re-evaluation of the design process, as prefabricated insulation elements must be precisely tailored to the existing structures of these buildings. Additionally, DBR presents considerable challenges in engaging and coordinating building owners within a neighbourhood to achieve a collective decision. Furthermore, it is possible that LTRS documents do not explicitly address mass renovation strategies. This is exemplified by the Estonian LTRS, which highlights the potential of mass renovations and already has extensive piloting behind it but still fails to incorporate such an approach as a specific strategic objective for accelerating the renovation rate.

However, there were some notable outliers among EU Member States such as Belgium, Germany and the Netherlands, which have integrated the mass renovation concept as a more specific objective. The LTRS of Belgium's Wallonia and Brussels regions demonstrate the most advanced approach to mass renovations, as they have an action plan for implementing their goals. Other countries can learn from their overall structure of the action plan. However, it is important to note that the action plan includes only a limited number of activities, which may not be sufficient to achieve a significant increase in renovation delivery.

The Netherlands has established a clear strategy for industrialised renovations, acknowledging the urgent need to enhance construction efficiency significantly. Prefabrication is seen as a promising approach for the future. However, the discussion surrounding the DBR is limited to its role in the shift away from natural gas as an energy source. The energy transition will primarily be driven by local governments, focusing on rational spatial units such as districts.

Despite the LTRS review indicating modest progress, it is crucial to highlight that the lack of concrete action plans among EU Member States suggests that large-scale renovations are not yet recognised as a vital solution for accelerating renovation efforts. Therefore, it is essential to investigate more thoroughly those examples that already demonstrate ambitions for large-scale renovations. While the analysis is based on the LTRS sources, there may be ongoing experimental projects that have yet to be captured in the LTRS.

The second hypothesis (H3.2) of RQ3 states: "*The supply side faces significant challenges in adopting innovations for mass renovation on its own*". Proposing this hypothesis was supported by the content analysis of LTRS, which indicated a rather modest adoption rate of mass renovations in the EU. The hypothesis was confirmed through in-depth interviews with representatives from the supply side.

The Estonian construction industry confronts significant challenges in independently adopting innovations for mass renovation. The barriers to the widespread implementation of prefabricated renovation and district-based renovation (DBR) arise from financial, regulatory, technological, and labour market constraints. These limitations impede the scalability of innovative renovation methods and necessitate external support, whether through policy interventions, financial incentives, or industry-wide coordination.

A principal constraint is the financial burden of prefabrication, which requires substantial upfront investments in production facilities. The interviews indicate that offsite prefabrication is generally more expensive than traditional onsite renovation, particularly when applied on a single-project basis. The absence of economies of scale exacerbates the cost disparity, rendering prefabrication an unviable solution unless demand stabilises and large-scale projects are initiated. Contractors and suppliers are reluctant to invest in prefabrication technologies due to uncertainties regarding returns and the relatively low volume of demand in the Estonian market.

The fragmented and inconsistent demand for renovation further complicates supply-side adaptation. Fluctuations in renovation grants create cycles of high and low demand, discouraging firms from making long-term investments in new technologies. During periods of economic uncertainty, construction firms tend to rely on their existing workforce and technologies rather than commit to innovation. In the absence of a steady pipeline of projects, renovation firms cannot justify the risks associated with transitioning to prefabricated renovation methods, even if these methods promise long-term efficiency gains.

In addition to financial constraints, the lack of quality regulations and procurement standards presents a barrier to the adoption of prefabrication. The current procurement process enables small firms, which lack quality assurance systems, to underbid larger, more experienced renovation companies. This scenario creates a competitive disadvantage for firms that prioritise technological investment and high-quality management practices. Larger construction companies, which could facilitate the adoption of prefabricated renovation, remain hesitant to enter the renovation sector due to these unfavourable procurement conditions. In the absence of stricter quality and safety regulations, the market will continue to favour traditional, lower-cost methods over innovative solutions.

The technological shift necessary for the adoption of prefabrication presents a significant barrier. Contractors and designers are accustomed to conventional on-site construction methods and exhibit resistance to adapting their business models to incorporate prefabrication. The interviews indicate that the supply chain – including architects, engineers, and general contractors – lacks familiarity with prefabrication, resulting in scepticism regarding its efficiency and long-term viability. This transition necessitates extensive re-education, training, and restructuring of workflows, which firms are reluctant or unable to undertake without external incentives or demonstrable success cases.

An additional complication is the shortage of prefabrication suppliers in Estonia. Even if demand for prefabricated renovation were to rise, the supply side lacks the requisite production capacity to fulfil the needs of large-scale projects. Existing suppliers predominantly focus on export markets due to weak domestic demand, indicating that any transition toward mass prefabrication would require a fundamental shift within the industry. Without an established network of local prefabrication manufacturers, general contractors are unlikely to take the risk of engaging in prefabrication on a large scale.

The labour market crisis within the construction industry further constrains the capacity for innovative mass renovation. The report identifies a shortage of skilled workers, as the sector struggles to attract young professionals due to its perceived difficulties and lesser appeal compared to alternative career paths. Even if prefabrication could alleviate on-site labour demands, the industry still requires specialised workers trained in off-site manufacturing and installation. The lack of a well-trained workforce presents an additional obstacle to scaling up prefabricated renovation.

Moreover, renovation projects are often dispersed across various locations, complicating the achievement of necessary economies of scale. In contrast to new-build projects, which can be planned for large developments, renovation projects are frequently undertaken on a case-by-case basis in scattered locations. This geographic dispersion hinders efficient logistical planning for prefabricated solutions and diminishes the cost-effectiveness of implementing mass renovation strategies. A coordinated approach by local authorities or another intermediator could potentially address this issue (Akhatova and Kranzl 2022); however, there is currently no national strategy in place to facilitate such projects.

The governance and leadership structure of renovation projects further complicates supply-side innovation. The interviews highlight a leadership gap between prefabricators and general contractors, with prefabricators aspiring to assume project management roles yet lacking the requisite experience in engaging with residents and subcontractors. This structural challenge inhibits a smooth transition to prefabricated renovations, as there is no clear entity capable of effectively overseeing and driving the process.

Moreover, the absence of landmark projects and demonstration cases hampers knowledge diffusion and undermines industry confidence in mass renovation techniques. The supply chain is reluctant to invest in prefabrication without definitive evidence of its advantages and a proven track record of successful implementations. Public-sector participation in large-scale demonstration projects could help mitigate this scepticism; however, the lack of such initiatives further impedes the industry's capacity to transition towards prefabrication.

In summary, the Estonian construction sector encounters a myriad of challenges in independently adopting mass renovation innovations. Financial constraints, inconsistent demand, insufficient regulatory support, technological resistance, labour shortages, geographic dispersion, and governance issues collectively obstruct the supply-side transition to prefabrication and design-build renovation. Without targeted interventions – such as policy support, financial incentives, workforce training programmes, and demonstration projects – the supply chain will struggle to surmount these obstacles and implement large-scale renovation innovations autonomously.

3.4 Policy practice evaluation against the distribution of subsidies across regions

The fourth and last research question (RQ4) of the thesis asks: "*To what extent do informed changes in energy policy contribute to a more equitable distribution of renovation grants at the regional level in Estonia?*". This question was addressed in Article V by looking more closely at how the distribution of grants has changed after regional targeting was introduced.

The first hypothesis (H4.1) of RQ4 states: "*Regionally targeted renovation subsidy programmes lead to a more equitable distribution of grants between regions.*". This hypothesis was tested by comparing PRI and Regional Development Index (RDI) across regions for three grant allocation waves of 2010–2014 (first wave), 2015–2019 (second wave), and 2019–2024 (third wave). To measure the distribution of subsidies, the Proportionality Index (PRI) is used. A PRI value of one can be considered as perfect equal distribution of subsidies. First, the equality of subsidy distribution is evaluated; next, the result for equitable distribution is presented.

The equality of renovation subsidy distribution

The distance from the PRI value of one in percentage points across the whole subsidy period (2010-2024) illustrates large differences among regions (**Figure 11**). The best performer (LVIR) is +155 per cent from equality, while the worst (IVIR) is -89 per cent below. The coefficient of variation (0.556) indicates high relative variation, with strong differences in PRI values across regions. The mean (1.285) exceeds the median (1.06), highlighting a right-skewed distribution driven by top performers (LVIR, POL, RAP). IVIR (0.11) is well below the mean, reflecting substantial regional disparities in renovation uptake and **indicating for unequal distribution of subsidies among regions.**

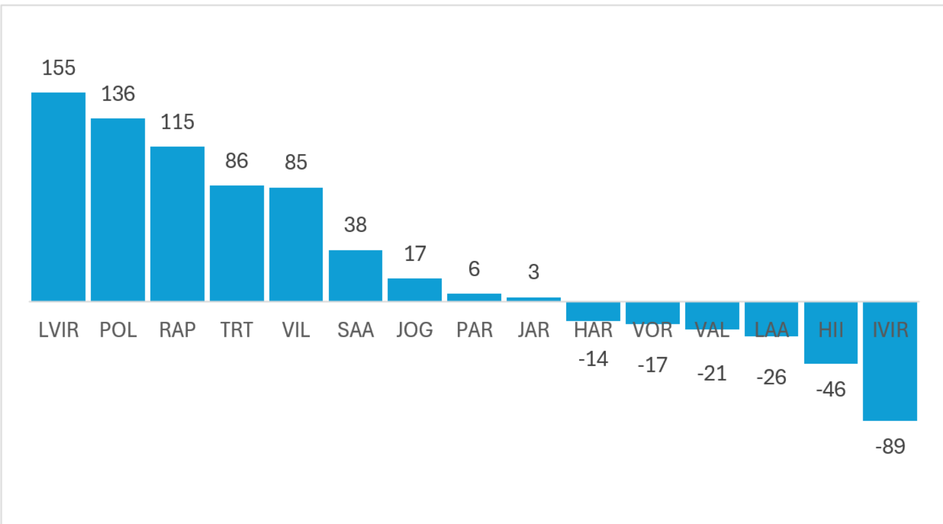

Figure 11 *Distance of average PRI value from Equality in percentage points across regions in 2010–2024. Source: Based on data from Article V.*

The equity of renovation subsidy distribution

The main assumption of fairness evaluations is as follows: if underdeveloped regions receive progressively more support than growing regions, the distribution of renovation subsidies can be considered fair. In terms of PRI, lagging regions should have PRI values above the proportional value of one, while for the leading regions the PRI value should be below one.

The Regional Development Index (RDI) was established to assess the development status of various regions. **Figure 12** presents a scatterplot showing the relationship between the RDI and average PRI value from 2010 to 2024. While this scatterplot provides an overview of the average distribution of subsidies, it does not reveal annual trends, as the average incorporates all PRI values over the specified period. Nevertheless, it serves to evaluate the overall equity of the subsidy programme to date. The data does not exhibit a clear linear correlation between PRI and RDI, largely due to outliers such as Tartumaa (TRT) and Ida-Virumaa (IVIR). Despite this, several significant observations can still be made.

Firstly, Harjumaa (HAR), the most developed capital region, is positioned slightly below the red line of perfect proportionality. This finding contrasts sharply with the results discussed in Article I, indicating that HAR is no longer dominating the subsidy landscape, despite its high level of development. In contrast, Tartumaa (TRT) shows strong performance in both PRI and RDI, suggesting that more developed regions tend to receive higher grant allocations.

Secondly, eight out of the fifteen regions exhibit modest to weak RDI values, yet they have received more grants than their housing stock would imply throughout the subsidy period. Thirdly, five regions (IVIR, VAL, LAA, HII, and VOR) are underperforming in both subsidy acquisition and RDI scores. As a result, the distribution of subsidy grants appears to be more equitable than what the initial non-targeted subsidy programme suggested in Article I. However, this fairness is not uniformly distributed, as there are significant discrepancies in subsidy application rates among the lower-performing regions.

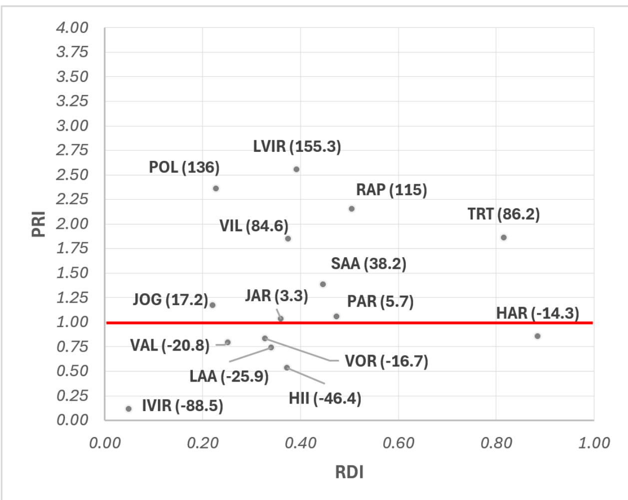

Figure 12 *Relationship between subsidy distribution proportionality (PRI average) and regional development index (RDI) across regions in 2010–2024. The PRI value distance from perfect proportionality (PRI = 1, red line) is shown in percentage points in brackets beside every region acronym. Source: Article V.*

The analysis of subsidy distribution across three application waves illustrates the impact of state intervention on equitable allocation among regions (**Figure 13**). In the initial wave, which lacked a targeted approach, only four regions exceeded the proportionality line. Notably, Harjumaa, the capital region, and Tartumaa secured more than 60 per cent of the total grants due to their high Regional Development Index (RDI).

In the second wave, energy performance ambitions were raised, technical requirements were established for building components, and the focus shifted to indoor climate. There were no low-energy ambition renovations for Tallinn (the regional hub of Harjumaa) and Tartu (the centre of Tartumaa). During this phase, the underperforming region of Ida-Virumaa received a grant that was 10 percentage points higher than expected. This led to significant changes: Harjumaa saw a marked decline in its Proportionality Index (PRI) value, while Tartumaa experienced a notable increase. The PRI value of Ida-Virumaa decreased even more compared to the first wave.

The third wave introduced a targeted subsidy approach, capping funding for Tallinn and Tartu at 30 per cent and offering 40-50 per cent to underperforming regions based on average real estate values. This strategy prompted an increase in grant applications from lower-performing regions. Although only three lagging regions remained below the proportionality line, the disparity between high and low PRI regions widened. Despite a decrease in PRI value for Tartumaa, it remains far from proportionality, particularly given its high RDI. Ida-Virumaa stands out as the most significant outlier, continuing to perform poorly despite the targeted subsidy efforts.

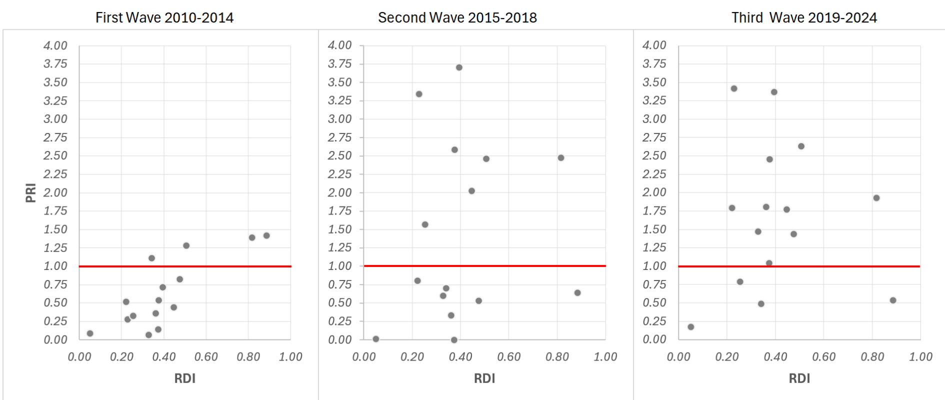

Figure 13 *The dynamics of PRI and RDI relationships within three subsidy application waves among regions (grey dots). Source: Based on Article V.*

The second hypothesis (H4.2) of RQ4 states: "*Policy makers and stakeholders struggle with adopting justice in energy policy due to the difficulties in conceptualisation and monitoring of the justice*". For testing the hypothesis in-depth interviews with energy policy stakeholders were adopted. The list of participants is presented in **Table 2**.

Table 2 Respondents to interviews. Source: Article V.

Acronym	Institution type	No of respondents	Position
KLIM	Ministry	2	Adviser, project manager
AGRI	Ministry	2	Head of department, adviser
EIS	State Agency	1	Project manager
EKYL	Union	2	Board members
ELVL	Union	1	Adviser
EOKK	Union	1	Board member
Technical consultants	Private sector	5	Consultant

The distribution of subsidies among regions was a topic all respondents related to from their experiences. There was general agreement that state assistance should be distributed fairly and rationally. However, a challenge arose when the concepts of equality and justice were perceived differently, leading to numerous questions during the interviews. Respondents understood equality better than justice, as they found more objective ways to measure equality. Another challenge indicated that equality may not be the ideal outcome for policymakers.

For instance, respondents questioned whether regional proportionality for renovations is a reasonable goal. AGRI noted that if regional development is imbalanced, with 60 per cent of gross domestic product (GDP) coming from the capital region, State aid for renovations may need to counterbalance this effect, indicating that unequal grant distribution should have a specific purpose.

Most respondents agreed that achieving a perfect proportional balance of subsidies is debatable, but the PRI could serve as a useful indicator for monitoring subsidy distribution, especially when quantifying policy changes.

The unequal distribution of grants, particularly in the capital region of Harju, surprised stakeholders. For example, ELVL acknowledged they had not previously recognised this impact and are now interested in other metrics that show the effects of State aid on municipalities and regional development. Representing municipalities, ELVL expressed interest in PRI comparisons within and between municipalities.

None of the respondents monitored grant distribution equality specifically, such as tracking the PRI as suggested in the 2018 policy report. EIS and KLIM highlighted time constraints in designing the next phase of the grant programme, which often limit the use of more sophisticated approaches. Instead, leading working groups continuously evaluate past outcomes and make intuitive policy decisions as they assess data and feedback.

The speed required in policy development often leads to superficial engagement of parties and stakeholders. AGRI is dissatisfied with the underutilisation of their spatial expertise. Involvement usually occurs through the coordination of formal policy decrees. AGRI expects more debate on the regional aspects of grant design. Conversely, KLIM acknowledges these limitations but defends the formal approach due to time constraints and the multitude of responsibilities of KLIM officials.

While addressing disparities between short- and long-term priorities in energy policy, policymakers recognised the potential for a comprehensive regional strategy through enhanced cooperation. Though time constraints may not be immediately obvious, other pressing tasks could hinder these goals.

Most stakeholders viewed involvement positively and affirmed that their feedback is anticipated and well-received. ELVL reported satisfaction with the current level of involvement and indicated they lack capacity for deeper engagement in policy design. If municipalities gain more responsibilities in the Renovation Wave, a more inclusive approach would be expected, necessitating an enhanced capacity from the union. EOKL, however, took a more critical stance, claiming their perspectives on the subsidy programme implementation are not well-received.

Interviews with technical consultants who assist apartment associations with subsidy applications highlighted three key factors that explain the distribution of subsidies across different regions. Firstly, a consistent observation is that renovation momentum is primarily driven by proactive intermediaries, such as property managers and renovation consultants, rather than by apartment associations. The spike in renovations observed from 2015 to 2018 was largely attributed to the lobbying and outreach efforts of housing managers and technical consultants, who encouraged deep energy renovations. However, such efforts were not evenly distributed among and within regions. Respondents indicated that the increased adoption of renovations in underperforming regions was also linked to targeted campaigns by the private sector, whose attitudes toward deep energy renovations significantly impact the decisions made by apartment associations. Furthermore, municipal initiatives, such as the SmartenCity pilots in Tartu and the renovation programmes initiated by the Rakvere city government in the LVIR region, have amplified this effect by providing demonstration projects.

Secondly, regional differences encompass more than merely issues related to information asymmetry. In Ida-Virumaa (IVIR), the consultants highlight three significant barriers to subsidy uptake: historically low prices for district heating, gaps in language and information, and a widespread distrust of experts, consultants, the government, and even their own community. Conversely, the recent renovation boom in Tartu (TRTL) can be attributed to smaller, lower-quality properties that have benefited from proactive support from the municipality and intermediaries. In Tallinn, however, a different dynamic emerges, characterised by well-maintained properties, a greater capacity for self-financing, and a reduced tolerance or patience for the bureaucratic processes associated with subsidies.

Thirdly, respondents emphasise that both very small and very large buildings seldom apply for grants, albeit for different reasons. For small associations, even higher support rates do not mitigate the high costs per square metre, and stricter bank requirements impose a heavy loan burden on very small apartment buildings – approximately double that of typical mid-sized blocks. In contrast, large buildings with more than five storeys face increased per-unit costs due to safety and accessibility regulations (e.g., elevators, fire safety), procurement limitations, and complex decision-making processes. Making collective decisions in large communities, such as those with around 200 apartments, is significantly more challenging than in mid-sized buildings with 40–60 apartments. Consequently, the evidence suggests that large multifamily buildings rarely apply for renovation subsidies.

Consultants contend that occupancy rates directly affect renovation decisions. In declining areas, low occupancy often foreshadows future abandonments due to insufficient demand. In such circumstances, the ability to make renovation decisions is compromised, as the apartment association may not function effectively. Underoccupied buildings struggle to secure renovation financing since banks take vacancy rates into account during risk assessments. In Estonia, where the rental market is weak, high vacancy rates frequently signal serious socioeconomic issues within the larger region. Consultants highlight the VAL and IVIR areas, where underoccupied buildings even appear in urban centres.

4 Discussion

This subsection synthesises the findings of the thesis across all four research questions and situates them within broader debates on distributive, energy, and spatial justice, regional development, demographic change, and innovation in the built environment. The results show how renovation subsidies, demographic trajectories, and emerging renovation technologies interact within a complex socio-economic system, and how these interactions can either mitigate or reinforce existing territorial inequalities in Estonia.

The theoretical framework of the thesis combines distributive justice in the Rawlsian tradition (Rawls 1971) with more recent strands of energy justice (Sovacool and Dworkin 2015) and spatial justice (Lefebvre 1997; Soja 2010). This aligns with wider work arguing that the low-carbon transition is not merely a technical shift but a socio-spatial transformation whose legitimacy depends on whether benefits and burdens are allocated fairly (Garvey et al. 2022; Jenkins et al. 2016). The empirical analyses in this thesis contribute to these debates by demonstrating how a seemingly neutral renovation subsidy distribution in Estonia generated negative spatial spillovers, and how these spillovers can be partly corrected once justice and regional development objectives are explicitly recognised in policy design.

4.1 Energy policy, regional disparities and justice

The analyses for RQ1 and RQ4 show that non-targeted renovation subsidies systematically favour economically stronger regions. In the early phase of the programme, the Proportionality Index (PRI) of subsidy distribution revealed a clear concentration of grants in the capital region, while lagging regions received far fewer resources than their share of the multifamily stock would justify. This pattern confirms the "success to the successful" dynamic identified in Systems Theory (Meadows 2011), where regions with stronger economic bases, higher demand and better institutional capacity are best placed to exploit generic subsidy schemes.

Subsequent regional differentiation of subsidy rates partially corrected this imbalance: higher support in weaker counties and reduced rates in stronger ones altered the spatial pattern of State aid and moved it closer to proportionality. This resonates with evidence from other European countries, where subsidy design strongly conditions the spatial uptake of renovation support and can either reinforce or mitigate existing regional inequalities (Frantál and Dvořák 2022; Turcu 2017; Willand et al. 2020). Similar to findings from Romania, Croatia and the Czech Republic, renovation subsidies in Estonia initially tended to accumulate in growing areas, leaving behind regions where both the need and potential for renovation were high but local capacities were weaker (Mikulić, Keček, and Slijepčević 2021; Turcu 2017).

Treating regions as subjects of justice makes these patterns normatively salient. In Rawls's terms, distributive arrangements are just only if inequalities work to the benefit of the least advantaged (Rawls 1971). Translating this to the regional scale, a purely proportional allocation of renovation grants according to housing stock may be insufficient: lagging or shrinking regions may justifiably warrant a higher share of subsidies if this strengthens their long-term prospects. This echoes recent work on spatialising energy justice, which emphasises that energy vulnerability and policy benefits are unevenly distributed across space and that justice claims must therefore be assessed at multiple territorial scales (Bouzarovski and Simcock 2017).

The Estonian case also aligns with empirical studies that explicitly examine the regional equity of renovation support. International reviews warn that tax credits and general renovation incentives often disproportionately benefit middle- and higher-income households and regions, thereby increasing free-riding and undermining both cost-effectiveness and justice (Neef, Egner, and Klöckner 2024; Risch 2020).

From the perspective of Estonian strategic aims, these patterns are normatively problematic. The national aim of balanced regional development ('Estonia 2035' 2021) is further specified in the State Spatial Plan, which emphasises the preservation of the existing settlement structure and the avoidance of excessive polarisation between core and peripheral areas. An energy policy that relies solely on competition between applicants and focuses narrowly on energy efficiency effectively channels renovation grants towards already prosperous and capable communities. While such an outcome may appear acceptable when judged only against climate targets, it conflicts with the declared goal of maintaining a coherent settlement system. As the inequitable distribution of grants reinforces existing disparities, renovation policy must therefore be evaluated not only in terms of saved carbon dioxide but also in terms of its alignment with these wider national development objectives.

At the same time, the findings underline the limits of energy policy as a regional development tool. Renovation grants operate within a broader regional development subsystem shaped by long-term economic restructuring, labour markets, and infrastructure (Heidenreich and Wunder 2007; Kebza, Nováček, and Popjaková 2019). While subsidies can influence the trajectory of individual buildings and neighbourhoods, they cannot in isolation reverse entrenched patterns of divergence between core and peripheral areas. Nevertheless, they should not deepen those divides. From the perspective of energy justice (Jenkins et al. 2016; Sovacool and Dworkin 2015), the key contribution of this thesis is to show empirically that fundamental design changes – such as regionally differentiated grant rates – can significantly alter who benefits from climate-oriented renovation policies.

However, establishing more equitable rules for subsidy applications is not enough to ensure a fair distribution of subsidies among all regions, as this thesis clearly illustrates. While certain underdeveloped regions in Estonia are consistently benefiting from renovation subsidies (e.g. Counties of Lääne-Viru, Rapla), others are struggling to take advantage of these opportunities, despite having favourable conditions (e.g. Counties of Valga, Ida-Viru). Interviews with consultants indicate that policymakers often underestimate the importance of intermediaries in promoting the need for renovations and the available funding options. Evidence shows that the attitudes of these intermediaries towards deep energy renovations significantly affect the progress of apartment associations in pursuing comprehensive renovations and, consequently, applying for subsidies. This influence is particularly noticeable in regions where leading real estate management companies have shifted from a stance of scepticism towards comprehensive renovations, resulting in a sharp increase in PRI values in those areas.

Results from Article I indicate that, in 2010, the Energy Performance of Buildings Directive (EPBD) prioritised energy efficiency but overlooked critical dimensions such as social and spatial justice (EU Directive 2010). Concurrently, Estonian strategic documents emphasised even regional development as a key objective (KEM 2000; MKM 2008; SIM 2005, 2012, 2014). Nonetheless, these intentions did not translate into the initial phases of the deep energy renovation subsidy programme.

The 2012 recast of the Energy Efficiency Directive (EED) sought to establish a binding energy efficiency target of 20 per cent by 2020. While it made general references to the protection of "vulnerable customers," it fell short of providing a robust definition of energy poverty or implementing mandatory measures for this demographic (EU Directive 2012).

In 2018, the recast of the EPBD introduced requirements for Long-term Renovation Strategies to include a monitoring framework aimed at reducing energy poverty and identifying the least efficient buildings (EU Directive 2018).

The 2023 recast of the EED aimed to elevate the EU's energy efficiency ambitions significantly, aligning them with the broader climate objectives of the European Green Deal and the "Fit for 55" package while diminishing reliance on fossil fuel imports, particularly from Russia (EU Directive 2023). This recast marked a pivotal shift from a focus solely on energy metrics to a more integrated approach that includes social policy objectives, acknowledging the necessity of a just and inclusive transition for its success and public acceptance.

The final version of the EPBD in 2024 further enhances the social justice dimensions established in the EED 2023 (EU Directive 2024). Social justice is now a fundamental element of the new directive and its associated Renovation Wave strategy. It mandates that financing measures specifically target vulnerable customers and the least efficient buildings to address energy poverty. Additionally, progress in reducing the number of households experiencing energy poverty will be monitored through the new National Building Renovation Plans (NBRPs), ensuring that the responsibility for renovation lies with building owners, not vulnerable tenants.

Thus, a clear trend emerges in which the EU's previously energy-centric climate mitigation framework has increasingly integrated social considerations into its energy transition strategy. However, spatial justice is not addressed in any of the versions of the EED and EPBD, which permits individual Member States to pursue their own regional development objectives.

4.2 Demography, vacancy and the ethics of "where not to renovate"

The results for the second research question demonstrate that demographic processes and vacancy patterns are central to understanding renovation potential. The distance-based analysis showed that occupancy rates decline with increasing distance from regional centres, reflecting wider trends of shrinkage and suburbanisation observed in many European countries. Projections to 2050 indicate that parts of the existing apartment building stock in strongly shrinking regions are likely to be abandoned, raising fundamental questions about the prudence of large-scale public investment in those buildings.

The building-level analysis further clarifies why vacancy plays such a decisive role. High vacancy signals weak demand for dwellings in a building and often indicates that the wider region is shrinking. Where vacancy rates are high and coincide with low property values, a declining local economy and diminishing services, buildings are likely to face long-term abandonment. In such contexts, there is little rationale for directing renovation grants towards those buildings, as the market is unlikely to respond even when subsidies are available. It is therefore plausible that the probabilities of renovation conditional on vacancy will remain very low, even under redesigned subsidy schemes that formally seek to favour low-occupancy buildings.

Logistic regression revealed a vacancy-related threshold: once more than roughly one quarter of dwellings in a building are unoccupied, the probability of applying for deep renovation grants drops close to zero, whereas highly occupied buildings (95–100% occupancy) have much higher renovation probabilities. Similar approaches in other contexts have demonstrated that utility-based vacancy indicators can reliably identify depopulating or underused housing stocks and inform strategic decisions on renovation versus demolition (Li, Guo, and Lo 2019).

From a justice perspective, this produces a genuine ethical tension. Investing substantial state resources in highly vacant, low-demand buildings in rapidly shrinking areas may be neither economically nor environmentally defensible, particularly when considering embodied emissions and the risk of lock-in to an oversized housing stock (Abbey et al. 2022; Liu et al. 2020; Röck et al. 2020). On the other hand, an exclusive emphasis on energy-efficiency upgrades that appear low-risk and cost-effective (often referred to as “no-regret” measures) can exacerbate spatial inequalities if it results in reduced renovation funding for disadvantaged neighbourhoods (Aurambout et al. 2021).

Scholarship on shrinking cities suggests that, when decline is deep and persistent, strategies of managed decline, consolidation, and selective retreat may be more appropriate than maintaining the entire housing stock (Haase et al. 2014; Hoekstra et al. 2020). However, these approaches must be carefully designed and implemented with strong community participation to avoid exacerbating social exclusion or reinforcing territorial stigma in marginalised areas. Politicians often struggle to label certain regions as hopeless despite the fact that their decline may have already passed the tipping point. Nonetheless, it is unnecessary to impose direct restrictions on subsidies for these areas, as apartment associations in such regions typically lack the ability to apply for funding due to high vacancy rates, limited organisational capacity, and the elevated risk involved for banks. Instead, it would be prudent to exclude these areas from the calculations when determining the total volume of subsidies.

The findings of this thesis, therefore, support a differentiated approach to vacancy in renovation policy. In buildings and neighbourhoods where population decline is moderate, vacancy metrics can be used to prioritise renovations that stabilise communities and preserve viable housing. In areas facing severe or irreversible shrinkage, the same metrics can justify shifting emphasis towards disinvestment, consolidation, and repurposing of stock, provided that affected residents are supported and alternatives are offered. By making these distributional choices explicit, vacancy-sensitive renovation strategies can enhance both economic efficiency and transparency regarding who is and who is not benefiting from the energy transition.

Related inequalities emerge when renovation probabilities are examined by building type. Logistic regression results showed that medium-sized, typical mass-constructed apartment buildings have the highest likelihood of receiving grants, while both larger estates and smaller buildings receive substantially less support. The most disadvantaged are small, non-typical wooden buildings with only a few apartments, for which the probability of obtaining State aid approaches zero. This pattern partly reflects the design of current grant schemes: technical requirements and minimum investment sizes fit standardised buildings in stronger markets more readily than small, heterogeneous stock in weaker regions. Even if future grant rules were adjusted to favour such buildings, their typically higher vacancy rates suggest that effective renovation demand may nevertheless remain very low.

4.3 Innovation, mass renovation and uneven benefits

RQ3 focused on emerging innovations in mass renovation, specifically industrial serial renovation and district-based renovation (DBR), and their potential to accelerate deep energy renovations in typical mass-constructed multifamily buildings. The content analysis of EU Member States' Long-Term Renovation Strategies (LTRS) revealed that, despite the prominence of the Renovation Wave in EU discourse, relatively few Member States explicitly articulate mass renovation as a strategic objective, and even fewer present concrete action plans. This aligns with broader assessments that highlight the importance of industrialised prefabrication and neighbourhood-based approaches, yet note that they remain marginal within national renovation frameworks (Bertoldi et al. 2020; BPIE 2022).

At the same time, the LTRS analysis identified a small group of outliers, most notably Belgium (Wallonia and Brussels), Germany, and the Netherlands, where mass renovation is more explicitly articulated as a strategic objective. In these instances, action plans for industrial prefabrication or district-based approaches provide at least an initial roadmap for scaling up renovations, even if the planned activities remain limited in scope. More broadly, however, the review confirms that large-scale, programme-based renovation is not yet widely recognised as a central solution for accelerating renovation rates in Europe. The absence of detailed mass renovation strategies in most LTRS documents suggests that pilot projects and experimental programmes are progressing in a piecemeal manner, often outside the main policy narratives. This highlights the need for a closer examination of those Member States that have begun to systematise mass renovation and for better integration of such approaches into EU and national renovation frameworks.

Interviews with representatives from the Estonian construction sector confirmed that financial, organisational, regulatory, and technological barriers hinder the supply side's ability to independently adopt serial renovation and Design-Build-Renovate (DBR). These findings align with research on Energiesprong and similar models, which suggests that industrialised deep energy renovation necessitates new business models, long-term performance guarantees, and stable policy support to become economically viable at scale (Brown, Kivimaa, and Sorrell 2019).

Within Estonia, pilot projects demonstrate that serial renovation is most technically and economically feasible in standardised, medium-sized buildings in growing markets. Non-typical wooden buildings are harder to include in industrialised renovation programmes, as such buildings require site-specific solutions (Arumägi and Kalamees 2014) that are not well scalable in a cost-effective manner. As a result, innovation-oriented grants could therefore concentrate on building types and locations that are already relatively attractive, while small, non-typical wooden buildings that are often located in peripheral or shrinking areas and characterised by higher vacancy could be largely excluded.

The absence of regional differentiation in Estonia's serial renovation grant scheme led to a spatial uptake that closely mirrored the trends observed with generic renovation subsidies. Most projects, comprising 68 per cent, were concentrated in Tartu and Tallinn, the two largest and fastest-growing regional centres. Furthermore, the regional distribution of these subsidies shows that they were predominantly accessed by the leading areas (HAR, TRT, RAP, SAA) with the highest levels of regional development.

Industrial serial renovation is currently more expensive than conventional on-site renovation. Although innovation-oriented grants covered around half of the construction costs at the time, poorer regions still faced substantial financial and organisational barriers to participation. Furthermore, acting as an early adopter of an untested technical solution entails significant risks (Rogers 2003). Therefore, it is plausible that communities in growing regions, with stronger balance sheets and better access to expertise, were more willing and able to assume this risk than those in declining areas.

From a justice standpoint, this illustrates how climate-driven innovation can unintentionally deepen existing inequalities in who benefits from the energy transition (Hearn, Sohre, and Burger 2021). Consequently, innovation policies that support industrialised renovation without compensatory measures risk creating a two-tier housing system: one in which well-located, standardised buildings receive high-quality, net-zero ready renovations, while structurally or economically disadvantaged buildings are left with conventional, incremental, or no renovations at all. This concern resonates with critical work on spatially just transitions, which warns that technologically sophisticated decarbonisation pathways can reproduce existing spatial hierarchies unless distributional and recognition dimensions are explicitly addressed (Bouzarovski and Simcock 2017; Garvey et al. 2022).

The results suggest that innovation policies should be combined with targeted interventions that either adapt serial or DBR concepts to more challenging building types or offer alternative pathways – such as incremental renovation packages, demolition and replacement, or social housing programmes – to enhance housing conditions in disadvantaged areas. Otherwise, the Renovation Wave risks becoming a mechanism for upgrading already competitive housing markets rather than a tool for achieving a just transition in the built environment.

4.4 Multi-scalar justice and governance capacities

The thesis demonstrates that justice in renovation policy is intrinsically multi-scalar. At the regional scale, the introduction of targeting and the observed changes in PRI values indicate a move towards a more equitable distribution between counties. Yet within regions, significant inequalities persist between municipalities, neighbourhoods, and individual buildings. Medium-sized, typical mass-constructed buildings exhibit much higher probabilities of receiving grants than small, non-typical wooden buildings, even in the same county. A policy that appears equitable at the regional level can therefore conceal pronounced inequities at finer spatial scales, as already highlighted in the literature on spatialising energy justice (Bouzarovski and Simcock 2017).

Stakeholder interviews revealed that policymakers and practitioners more readily distinguish between equality and proportionality than between equality and justice. Equality is easier to measure, and indicators such as the PRI are seen as useful tools for tracking changes in grant distribution. Justice, by contrast, is viewed as abstract and difficult to operationalise, echoing the broader challenge identified by Jenkins et al. (2016) of translating the distributional, procedural, and recognition dimensions of energy justice into concrete policy metrics. Limited analytical capacity, time pressure in policy design, and competing priorities contribute to a reliance on intuitive decisions rather than a systematic assessment of distributional outcomes.

These findings help explain why regional or social justice monitoring remains rare in renovation policy, despite the growing prominence of justice discourse in EU climate governance (Bulkeley, Edwards, and Fuller 2014; Garvey et al. 2022). They also point towards the importance of building “justice literacy” within institutions responsible for energy policy. Simple, transparent metrics such as proportionality indices, vacancy-based renovation probabilities, or typology-specific grant rates can serve as bridging tools between normative debates and day-to-day policy work. The results of this thesis illustrate how such metrics can be implemented in practice and how they reshape the conversation among stakeholders.

However, better indicators alone are not sufficient. The interviews show that meaningful integration of justice considerations also requires earlier and more substantive involvement of regional actors, better use of spatial expertise, and governance arrangements that allow for deliberation on trade-offs between climate targets, cost-efficiency, and regional equity. This resonates with recent work on just sustainability transitions, which emphasises that justice in transitions is not only about outcomes but also about the politics, power relations, and participatory processes through which decisions are made (Avelino et al. 2024).

4.5 Energy policy as a complex system and the need to anticipate spillovers

Taken together, the findings portray renovation subsidies as part of a complex socio-economic system characterised by feedbacks, spillovers and path dependencies. The thesis builds on General Systems Theory (Bertalanffy 1973), transition studies, and the notion of “wicked problems” in planning (Rittel and Webber 1973), showing that interventions designed to address one policy objective, such as accelerating deep renovations, can have unintended impacts on regional development trajectories and social inequalities.

The Estonian case illustrates both positive and negative spillovers. On the positive side, already renovated buildings can stimulate neighbouring renovations, as demonstrated by Irwin (Irwin 2019) and confirmed by stakeholder perceptions. On the negative side, non-targeted subsidies allowed more capable regions and building types to act as “free-riders” relative to weaker ones, capturing a disproportionate share of public funds and reinforcing existing spatial disparities (Neef, Egner, and Klöckner 2024).

The results show that such spillovers are not inherently inevitable but are challenging to anticipate. When policymakers acknowledge them and adjust rules, for example by differentiating grant rates, recognising vacancy thresholds, or favouring disadvantaged building typologies, they can influence the distributional pattern of renovations without abandoning the climate ambition. This aligns with the broader argument in just transition research that distributional and procedural justice considerations can be embedded into transition policies without fundamentally undermining decarbonisation goals (Moodie 2025; Müller et al. 2024).

Nevertheless, anticipating spillovers requires analytical capacity and time, both of which are often scarce in policy ministries. As the interviews indicate, rapid policy cycles, high workloads, and fragmented responsibilities make it tempting to rely on simple technical or financial criteria and to postpone systematic justice assessments. This reinforces calls in the transition literature for more reflexive, power-aware, and justice-sensitive governance approaches (Avelino et al. 2024; Rotmans, Kemp, and Van Asselt 2001).

4.6 Towards just sustainability transitions in the Renovation Wave

Finally, the findings can be situated within the emerging discourse on just sustainability transitions. Recent scholarship argues that transitions must be evaluated not only by their contribution to climate mitigation, but also by how they redistribute power, risks and benefits across social groups and territories (Avelino et al. 2024; Garvey et al. 2022). This thesis adds empirical depth to these debates by showing, in a single national case, how renovation subsidies, demographic change and innovation policies jointly shape the geography of the transition in the residential building sector.

The Estonian experience suggests three broader lessons for the EU Renovation Wave. First, non-targeted subsidies are unlikely to deliver climate targets along with spatial justice. Without explicit targeting, they tend to concentrate in already successful regions and standardised building types. Second, integrating justice and regional development considerations into renovation policy is possible and can be achieved through relatively straightforward adjustments, such as differentiated grant rates, vacancy-sensitive prioritisation, and typology-specific support schemes. Third, justice in renovation policy is inherently multi-scalar and dynamic: instruments that appear fair at one scale or in one phase may generate new inequalities at other scales or over time.

Overall, the thesis argues that a just transition in the residential building sector requires more than ambitious energy and climate targets. It demands anticipatory governance that recognises the complex interactions between subsidies, regional development, demography and innovation, and that deliberately designs instruments to mitigate rather than amplify existing spatial inequalities. In this sense, the case of Estonia demonstrates both the risks of ignoring justice in renovation policy and the potential for relatively simple design changes to reorient the Renovation Wave towards more equitable and territorially balanced outcomes.

4.7 Beyond regional targeting: social and building-level approaches

The analysis in this thesis has treated regions as the main "subject of justice" in the allocation of renovation subsidies. However, energy justice scholarship reminds us that distributive principles can also be applied directly to social groups, such as low-income or energy-poor households. From an energy justice perspective, the central question is how the benefits (lower bills, comfort, health) and burdens (co-financing, administrative effort, debt) of renovation policies are shared across society (Jenkins et al. 2016). Likewise, a capability-oriented view emphasises that policies should expand people's real freedoms to enjoy adequate housing and energy services, not only deliver cost-effective emission reductions (Robeyns 2005).

Against this backdrop, regional targeting is only one possible route towards a fairer distribution of renovation grants. Alternative targeting logics that focus on income, tenure, building characteristics, or utility bill data can potentially address social inequalities more directly, but they also raise their own practical and normative challenges.

Income- and vulnerability-based targeting of households

A first family of alternatives aims to direct support to low-income or otherwise vulnerable households, irrespective of their region. EU-level work on energy poverty has highlighted that energy-inefficient housing and high energy expenditure are strongly correlated with low incomes, along with other forms of vulnerability, and has explicitly recommended stronger targeting of low-income households in efficiency policies (Ugarte et al. 2016).

Many national schemes therefore use means-tested eligibility (e.g. income thresholds linked to social assistance or poverty lines) or composite energy poverty indicators that combine income, housing quality, and expenditure variables (Kyprianou et al. 2019; Pye 2015). Empirical evaluations suggest that such schemes can effectively reduce high energy burdens, improve thermal comfort, and deliver co-benefits for health, especially when deep energy renovations are funded at very high subsidy rates for eligible households (Xu and Chen 2019).

However, income-based targeting also faces significant implementation challenges. Identifying eligible households requires access to reliable income data, which raises issues of data protection, administrative coordination, and political acceptability. A lack of data and difficulties in identifying target households are among the main bottlenecks for such schemes (Ugarte et al. 2016). In practice, many low-income households fail to take up available programmes because of information gaps, distrust of authorities, complex application procedures, or the need to coordinate with other co-owners and landlords (Asensio et al. 2024; Currie 2004; Xu and Chen 2019).

In owner-occupied multi-apartment buildings, which are typical in Estonia, means-testing at the individual household level is particularly challenging, as renovation decisions and grant applications are made collectively by the apartment association. This creates a tension between targeting the most vulnerable households and maintaining a simple, administratively feasible scheme at the building level. One effective approach could be to sustain differentiated subsidies at the building level to alleviate high renovation costs and offer further assistance to vulnerable households facing challenges with escalating housing expenses, even when building-level subsidies are in place. This strategy would help ensure that economically disadvantaged communities do not oppose renovations solely due to financial constraints. Furthermore, this method simplifies management, as it requires vulnerable communities to initiate their applications for additional support, rather than establishing a nationwide eligibility framework for these households.

Targeting tenure and building types

A second alternative is to target subsidies based on tenure and building type rather than geography. Many energy-poverty oriented renovation programmes in Western Europe prioritise social housing and privately rented dwellings, where low-income and vulnerable households are disproportionately represented (Croon, Hoekstra, and Dubois 2024; Dewilde 2018). Recent work on renovation policies for energy-poor homes in London, for example, shows that combining area-based criteria with indicators of tenure and household vulnerability can enhance both health and distributional outcomes compared to purely area-focused schemes (Georgiadou et al. 2024). In Central and Eastern Europe, initiatives such as the Residential Energy Efficiency for Low-Income Households (REELIH) project have demonstrated that it is possible to combine subsidies and loans in ways that specifically support low-income homeowners in multi-apartment buildings, provided that homeowner associations receive targeted technical and organisational support (European Parliament 2016).

For Estonia, this approach could entail reserving higher grant rates or additional support instruments for: (i) social or municipal housing stock; (ii) apartment buildings where a high proportion of residents receive means-tested social benefits; or (iii) building types that are typically occupied by lower-income groups. This would shift the focus from regions to the socio-economic profile of buildings and their residents. At the same time, international experience warns that non-targeted or weakly targeted renovation subsidies tend to be taken up disproportionately by higher-income households and more affluent neighbourhoods, a phenomenon referred to as "renovation poverty" (Willand et al. 2020). Without specific provisions for low-income households, simply changing the targeting unit from region to building type may not be sufficient to avoid regressive outcomes.

Progressive grant design and "social top-ups"

A third set of instruments aims to improve justice not through eligibility criteria, but by varying the level of support received by different groups. Rather than implementing a single uniform grant rate, subsidy schemes can offer progressive co-financing. For instance, this could involve a basic grant for all eligible buildings, combined with higher rates ("social top-ups") for low-income households, energy-poor buildings, or specific vulnerable groups. Recent reviews of renovation subsidy schemes indicate that more targeted, higher-rate subsidies for low-income households can enhance environmental effectiveness by focusing on the least efficient homes while also improving distributional outcomes, provided that administrative costs remain manageable (Charlier, Risch, and Salmon 2018; Chlond, Gavard, and Jeuck 2023).

Microsimulation work on French renovation subsidies, including a low-income sub-obligation within the energy-efficiency obligation scheme and income-differentiated grants, suggests that such progressive designs increase the leverage of public spending and reduce vulnerability to energy price shocks among low-income households (Giraudet, Bourgeois, and Quirion 2021). At the same time, other studies reveal that generic renovation subsidies often end up being mildly regressive at the population level, as higher-income households are more likely to invest and consequently capture a larger share of public funds (Lekavičius et al. 2020).

In Estonia, a progressive design could be implemented at the level of the apartment association by allowing a higher grant intensity for buildings where a minimum share of owners falls below an income threshold, or by providing additional "social top-ups" that can be used to cover the co-financing share of low-income owners identified through social assistance registers. However, such arrangements would require careful coordination between energy, housing, and social policy administrations to avoid excessive complexity and protect personal data.

Utility-funded and on-bill schemes

A fourth group of alternatives involves changing not only "who gets what", but also "who pays" and "how". Utility-funded energy-efficiency obligations, with explicit sub-targets for low-income or energy-poor customers, are now widespread in several EU Member States and can deliver substantial energy savings for vulnerable groups when well designed and adopted in favourable contexts.

In parallel, on-bill financing and tariff-based on-bill programmes allow households to repay renovation investments through their utility bills, with the repayment structured so that expected monthly bill savings exceed the surcharge ("bill neutrality"), thus improving energy affordability (Bianco and Sonvilla 2021). Such programmes are expected to enhance access to capital for credit-constrained households, including those in multi-apartment buildings, by relying on bill-payment history rather than conventional credit scores.

However, the expenses associated with deep energy renovations, particularly for significantly outdated buildings in cold climates, surpass the energy savings achieved

(Dodoo, Gustavsson, and Tettey 2017). Therefore, such schemes do not mitigate energy poverty, as housing costs after renovations are higher.

From a justice perspective, however, utility-funded and on-bill schemes are ambivalent. If programme costs are passed through to all consumers via tariffs, low-income households that cannot or do not participate may end up cross-subsidising better-off participants.

Moreover, tariffed on-bill schemes targeted at low-income customers can create new risks of indebtedness and may be used politically to justify cuts to grant programmes that are better suited to the needs of the poorest households. In the Estonian context, such instruments might therefore be considered complementary for light renovations rather than primary mechanisms for justice-oriented deep energy renovation policy and would require robust consumer protection and careful assessment of distributional effects.

Implications for targeting low-income households in Estonia

Taken together, regional targeting is only one, and often a rather blunt, way of addressing social inequalities in renovation. Income- and vulnerability-based targeting, tenure- and building-type-focused measures, progressive grant designs, and carefully regulated utility-funded or on-bill schemes all offer alternative routes towards a more just distribution of renovation support. Yet none of these alternatives is straightforward in the specific institutional setting of Estonian multi-apartment buildings, characterised by high owner-occupation, heterogeneous income profiles within buildings, and apartment associations as key decision-making entities.

Experience from initiatives such as REELIH shows that, in such contexts, combining financial instruments with strong technical assistance, capacity-building for homeowner associations, and mediation between low-income owners, municipalities, and banks is critical to ensure that vulnerable households can actually realise deep renovations.

For the purposes of this thesis, these alternative policy logics matter in two ways. First, they show that the normative assessment of regional targeting developed above should not be interpreted as an argument against justice-oriented renovation policy, but rather as a reminder that regions are only one possible proxy for vulnerability. Second, they highlight that a more comprehensive approach to justice in renovation policy would likely require a hybrid design: a basic grant available nationwide, modest regional adjustments, and additional low-income or vulnerability-based top-ups, combined with targeted advisory support. Whether such a layered approach is administratively and politically feasible in Estonia remains an open question, but the international literature indicates that relying solely on regional targeting is unlikely to be sufficient to ensure a just distribution of renovation grants.

5 Conclusions

This chapter summarises the main conclusions of the thesis in relation to its overarching aim and research questions. The aim of the study was **to explain how central government intervention in the renovation of multifamily residential buildings, primarily guided by energy and climate targets, interacts with existing spatial disparities and justice considerations.** The thesis combined quantitative and qualitative methods to examine how renovation subsidies, demographic trends, and innovation policies shape the distribution and feasibility of deep energy renovations in Estonia.

5.1 Main conclusions by research question (RQ)

RQ1: In what ways do non-targeted subsidy policies influence regional disparities in Estonia?

To measure spatial distribution of deep energy renovation subsidies, a proportionality index (PRI) was developed. The PRI considers the potential share of building stock in a region and compares it against the share of applied subsidies in the same region. The thesis concludes that non-targeted renovation subsidies lead to an unequal distribution of grants between regions. The PRI values among regions indicated that, in the initial phases of the Estonian renovation programme, more than half of all grants were concentrated in the capital region, while several lagging regions received significantly fewer grants than their share of the multifamily housing stock would imply. Statistical analyses confirmed that grant acquisition was strongly associated with indicators of regional prosperity, such as higher real estate values and stronger economic performance. In the absence of explicit spatial or social targeting, more capable and economically stronger communities obtained a disproportionate share of state support, and thereby undermining the national strategic aim of balanced regional development.

RQ2: How do population trends at the regional level influence residential vacancy and renovation patterns?

The analyses demonstrated that population trajectories and spatial location are closely connected to housing vacancy and renovation activity. Buildings located further from regional centres exhibited higher vacancy rates, and projections to 2050 indicated that a considerable share of the apartment building stock in shrinking regions is likely to be abandoned. Logistic regression results showed that vacancy acts as a critical threshold variable: once occupancy falls below approximately 77 per cent, the probability of applying for deep renovation subsidies approaches zero. In contrast, buildings with very high occupancy, particularly those that are fully occupied, have the highest likelihood of receiving renovation grants. These findings establish vacancy as a key determinant of renovation potential and underscore the need to consider demographic and settlement dynamics when assessing where renovations are feasible.

RQ3: What hinders the adoption of innovations for accelerating the deep energy renovation rate?

The thesis concludes that innovations aimed at accelerating renovations, such as industrial serial renovation and district-based renovation, face significant barriers at both policy and industry levels. Content analysis of the EU Member States' Long-Term Renovation Strategies revealed that only a few countries explicitly promote mass renovation approaches, and detailed action plans remain rare. In the Estonian construction sector, interviews with supply-side actors identified financial constraints, the need for substantial upfront investment in prefabrication facilities, fragmented and unstable demand, gaps in quality regulation, and resistance to organisational and technological change as major obstacles to the wider adoption of mass renovation. Furthermore, the technical and economic characteristics of serial renovation limit its applicability mainly to standardised, medium-sized, mass-produced apartment buildings, thereby restricting the direct benefits of these innovations to a subset of the housing stock.

RQ4: To what extent do informed changes in energy policy contribute to a more equitable distribution of renovation grants at the regional level in Estonia?

The results showed that informed adjustments in subsidy design can alter the spatial distribution of renovation grants. When regional targeting was introduced, by raising grant rates in weaker regions and reducing them in the strongest ones, several regions moved from under-representation towards, or above, proportionality. This confirms that policy design choices directly affect the geography of State aid. At the same time, interviews with policymakers and stakeholders indicated that concepts such as equality, proportionality, and justice are interpreted differently, and that justice is difficult to conceptualise and monitor in practice. While indicators such as the PRI are regarded as useful tools for tracking distributional changes, the routine use of such measures is limited by time and capacity constraints in policy development.

5.2 Overall contribution of the thesis

Across all four research questions, the thesis demonstrates that energy renovation subsidies and innovation policies are not distributionally neutral. If subsidies are not targeted, either spatially or socially, and all applicants are given formally equal opportunities to apply, these subsidies tend to concentrate in regions and building types that already possess stronger economic and organisational capacities. Demographic trends and vacancy patterns further restrict the set of buildings where deep renovations are practically and financially viable. Innovations in mass renovation have the potential to accelerate progress towards energy and climate targets, but their current design primarily favours typical mass-produced buildings in stronger regions, leaving small and non-standard buildings at a disadvantage.

By empirically linking subsidy distribution, demographic change, vacancy, building typologies, innovation potential, and stakeholder perspectives, this thesis provides a comprehensive picture of how central government interventions in the renovation of multifamily buildings intersect with existing spatial disparities. The findings indicate that adjustments in subsidy rules – such as regional targeting and differentiated grant rates – can improve equity at the regional scale but also underscore the need for further attention to differences within regions and between building types.

Overall, the thesis concludes that achieving national energy and climate objectives in the residential sector requires not only ambitious targets and innovative technical solutions but also careful consideration of the spatial and social distribution of renovation efforts. Incorporating regional development objectives, vacancy information, and building-type characteristics into renovation policies can help ensure that public support for deep energy renovations contributes to, rather than undermines, a more balanced and just spatial development.

6 Future studies

The findings of this study identified significant gaps in knowledge crucial for advancing effective, efficient, and equitable energy policy interventions. Key questions for future research include the following:

1. To what extent do current energy policies support free riders who are able to undertake deep energy renovations independently?

Energy policies often provide financial incentives and subsidies to encourage energy-efficient renovations, but this raises the issue of free riders – those who would have invested in these renovations without any public assistance. In many cases, policies unintentionally support such free riders, diverting resources from homeowners who genuinely need the financial boost to undertake deep renovations. By providing blanket incentives, governments may overextend funding without achieving optimal additionality – the net environmental benefit that occurs when renovations are induced solely due to policy interventions. Effective policy design should distinguish between those who can afford independent renovations and those whose projects hinge on external support, potentially through means-tested programmes or staggered incentives based on energy savings.

2. How do trends in consumption-based vacancy analysis relate to spatial development in general and the distribution of renovations specifically?

Consumption-based vacancy analysis, which assesses unoccupied or underutilised buildings based on utility usage, can reveal broader trends in spatial development and highlight regions where investments in renovations are most needed. Vacant or sparsely used properties often correlate with areas experiencing economic stagnation or population decline, leading to a lag in energy-efficient upgrades. Conversely, high-consumption areas, particularly in urban centres with growing populations, may attract more renovation projects due to higher property values and the increased likelihood of policy-driven renovation initiatives. Understanding these consumption trends allows policymakers to direct renovation efforts where they will have the most impact, potentially revitalising declining areas while ensuring urban development follows sustainable practices.

3. What patterns emerge among renovations that are implemented without the benefit of subsidies?

Renovations carried out independently of subsidies often reflect specific demographic, financial, and motivational patterns. Apartment associations that undertake unsubsidised projects typically belong to higher-income brackets, have greater environmental awareness, or are driven by long-term cost-saving goals. These renovations may also occur in areas with higher property values, where the return on investment is perceived as greater.

4. To what extent are current renovation trends aligned with climate targets and timelines?

While energy renovation initiatives have made significant progress in improving building efficiency, many current trends fall short of meeting climate targets within the prescribed timelines. The pace of renovations often lags behind the urgency of decarbonisation goals, particularly in older building stocks where upgrades are more challenging and costly. Factors such as fragmented implementation, inconsistent policy support, and varying regional priorities contribute to this misalignment. Moreover, some renovation efforts focus on incremental improvements, which may not achieve the deep energy savings needed to meet long-term emission reduction targets. Accelerating progress will require more comprehensive policy frameworks, robust enforcement mechanisms, and the integration of long-term sustainability planning.

5. How are renovations of detached houses distributed spatially, and what variables influence renovation decisions?

The spatial distribution of renovations in detached houses often reflects patterns related to regional income levels, climate conditions, housing stock age, and policy availability. Wealthier regions typically see higher renovation activity due to greater access to private financing, while areas with colder climates may prioritise energy-saving improvements to reduce heating costs. The availability of subsidies or local incentives can also shape the distribution, as regions with proactive policy measures attract more renovation projects. Other influencing variables include proximity to renovation service providers, property market dynamics, and public awareness of energy-saving benefits. In rural or remote areas, logistical challenges and limited contractor availability can slow renovation rates, emphasising the need for tailored interventions.

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Publications

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Intersection of the global climate agenda with regional development: Unequal distribution of energy efficiency-based renovation subsidies for apartment buildings

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ABSTRACT

The residential sector is an important target area for achieving Europe's 2020 energy saving aims. There is virtually no evidence, however, of how incentives for attaining energy efficiency interact with countries' regional development aims. This article presents recent experiences from Estonia, where an energy renovation subsidy programme financed with carbon emission trading funds was carried out between 2010 and 2014. We show that despite equal access to subsidies for residents living in various places, a regionally unequal distribution of subsidies occurred. Empirical analyses confirm that low-performing regions acquire less public subsidy, thus adding another layer of regional inequality to existing socio-economic differences. Findings suggest that renovation subsidy distribution is related to regional socio-economic indicators and that real estate value explains 40% of subsidy distribution variations between regions. Although the energy policy goal of carbon conservation is important, ignoring the location and organisational capacity of local communities results in missed opportunities to mitigate growing regional disparities.

1. Introduction

“Success to the successful” is a systems' trap that Meadows (2008) has vividly described in a study of systems. The phrase suggests that social groups that already enjoy higher “capital” accumulation—due to their greater education, wealth, and social networks—tend to also be far better equipped to seize additional benefits. We argue that this phenomenon can be prevalent in societies, especially when access to certain publicly-available incentives requires more human, social, organisational or other types of capital and distribution of such benefits is competitive.

In Europe, it is important that the ongoing energy transition (Bridge et al., 2013) and cohesion policies support each other. Regional policy is a classical cross-sectoral policy field that can only reach its aims when parallel sectoral policies, including energy policy, embeds regional development in its agenda. In the context of a multi-level governance system, it is also important that the impact of policies at various governmental levels are consistent. For example, EU energy policy aims should be consistent with the policy targets of the EU's economic, social, and regional policies, however each member state also has the responsibility to apply EU targets in a way that ensures balanced development within national borders. The tools and impacts of energy policies are already by nature more global; the strategies at the national level could potentially consider how energy policy measures could alleviate rather than deepen socioeconomic stratification and regional inequalities within countries.

Many attempts have been made to measure and to understand the mechanisms of energy poverty (Bouzarovski et al., 2012; Braubach and Ferrand, 2013; Healy and Clinch, 2004). At the household level, energy poverty is understood as “the inability to secure a socially and materially necessitated level of energy services in the home” (Bouzarovski and Tirado Herrero, 2017, 69). Low-income groups living in energy-inefficient dwellings often pay disproportionately high energy cost; therefore, specific social protection measures or energy policy instruments are needed to alleviate this component of their poverty. Links between spatial inequalities and energy policies are less studied, but due to segregation in cities and disparities in regional development, vulnerable groups inevitably also tend to concentrate in space.

Bouzarovski and Tirado Herrero (2017) emphasise a clear divide between countries according to the core-periphery boundaries in Europe: in Southern European and (formerly socialist) Central and Eastern European (CEE) countries, energy poverty is generally higher,

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and even the middle class is affected by high energy prices. In Northern and Western European countries, energy poverty threatens weaker social groups, who often live in less energy-efficient dwellings. Furthermore, CEE countries typically struggle with the legacy of an inefficient energy sector and low quality housing. A large share of the housing stock in CEE countries originates from the socialist years when energy prices were low and housing construction and maintenance was heavily subsidised. Energy poverty in CEE can be explained by interrelated conditions: privatisation of energy infrastructure; a transition from public to almost fully private ownership of housing; large investment needs in both sectors; in some countries dependence on energy imports; related sharp increases in energy tariffs and other housing costs for households; and, slow progress in social welfare programmes. As such, the housing sector in CEE countries urgently needs investments; consequently, energy poverty is a critical issue in both larger cities as well as in peripheral regions of these countries.

In this study, we explore an energy efficiency housing renovation subsidy programme applied at the national level in Estonia that possesses a built-in component of competition between communities applying for public subsidies. More specifically, we study the first comprehensive public subsidy programme occurring between 2010 and 2014 in Estonia (during the post-socialist period) intended to support energy efficient housing renovation. Our empirical contribution—-which demonstrates **how energy efficient housing renovation grants were distributed in Estonia at the core-periphery scale**—fills a gap in scholarly research in explaining how globally-oriented climate change aims interact with country-level regional development aspirations. This study therefore contributes to discussions about how to avoid the “success to the successful” trap in connecting energy policy with other cohesion aims.

This article first introduces the relations between energy policy and social inequality generally while focusing on regional polarisation. Next, we analyse to what extent the notion of equality is addressed in EU energy directives and member states’ energy efficiency action plans. This is followed by the identification of relevant policy goals in Estonia, providing context for energy subsidy programmes introduced in the subsequent section. We then describe the data employed and techniques used. After presenting the data and results from our empirical analysis, we offer conclusions and identify policy interventions that could improve the coherence between global/European energy and country-level regional policies.

2. Role of equity in energy policy

2.1. The context of regional polarisation

The term 'regional polarisation' suggests that successful regions, compared to lagging regions, provide richer opportunities for economic growth, a more diverse social life, better housing opportunities, and greater possibilities for individual fulfilment. While regional disparities between EU member states are decreasing, the inequalities within member states are increasing (Heidenreich and Wunder, 2008). The reasons for growing disparities are complex. According to Lang (2015), the formation of peripheral regions is a social and economic but also a discursive and political process. Also, sometimes weak regions are not getting weaker per se but stronger regions are developing faster (Nordregio et al., 2007).

Formerly prosperous industrial and agricultural regions are often faced with double deprivation. In former socialist countries, such regions received abundant state infrastructural and housing investments. The volume of housing construction was large in fast-growing major CEE cities; at the same time, many people were attracted to smaller industrial towns (Tammaru, 2001) and to collective agricultural enterprises which dominated rural centres (Marksoo, 1990), where state-regulated salaries were competitive and apartments were generously distributed to arriving specialists. By the beginning of the post-socialist transition, peripheral regions in CEE countries were characterised by relatively good infrastructure and housing stock. Today, investment needs in these places are large and the out-migration of an economically productive population undermines the financial stability of small municipalities even further. The problem is also low return on housing investment. Real estate prices tend to rise only in major urban regions that attract enterprises and new residents. For these reasons, investments in energy efficiency are most likely to offer a return in prosperous regions where the value of improved real estate remains stable or appreciates. This makes co-financing attractive for residents, whereas in peripheral regions such motivation develops more modestly.

The complexity of regional polarisation emergence renders coherent policy intervention difficult to apply and its outcomes challenging to evaluate. It is argued that EU regional policy interventions are a waste of resources as they do not alleviate regional disparities (Boldrin and Canova, 2001). This is only partly true, because interventions for addressing polarisation may not work as intended due to the lack institutional capacity at the level of nation-state (Charron, 2016), or because of differences in social capital within and between communities (Ojamäe and Paadam, 2015; Raiser et al., 2002; Taylor, 2000). This means that intervention policy per se is not useless, but some communities are more capable of utilising EU subsidies while others are not.

Within EU member states, “peripheralisation” and “metropolisation” appears to be a structurally embedded and path-dependent processes (Lang, 2015; Martin and Sunley, 2006). For many peripheral regions in CEE with agricultural or industrial backgrounds, the most prosperous times are in the past. New and competitive economic activities have disproportionately developed in capital cities and other larger centres with diverse economic structures and healthy connections to global economies. This is also reflected in national internal migration patterns: larger metropolitan areas are attractive destinations for those leaving regions with growing unemployment (Leetmaa and Väiko, 2015). While regional polarisation is a Europe-wide trend (Boldrin and Canova, 2001; Gardiner et al., 2004), in CEE countries polarisation together with slow development in social protection and regional policy capacity have produced a severe loss in human capital (Raagmaa, 2001) in lagging regions. Most public subsidy programmes, however, presume local initiative, and in peripheral regions such local partnerships tend to be weaker.

In the 1990s, the housing privatisation process was considerably faster in core regions. The approach of housing privatisation in most CEE countries was to diminish public ownership of housing units (Kährik, 2000) so that residents would assume housing costs. But this approach did not work smoothly even in major cities, because investment needs were beyond households’ capacities to pay, especially during the early post-socialist years. Little by little, (non-governmental) apartment associations in larger apartment buildings assumed various administrative and financial responsibilities, but the capacity of associations varied: in some residential buildings, effective leaders organised gradual improvements while in others, the apartment association staff was only able to accomplish the bare minimum with low communal costs. Even in large cities, it took time to establish the organisational capacity of apartment associations. In peripheral districts, maintenance and renovation of apartment houses is now often overseen by municipal officials rather than by owner communities. At the same time, some energy efficiency renovation strategies presume that a targeted community is able to mobilise its members to acquire available subsidies: an optimal renovation programme for each particular building must be identified considering technical, economical, financial, and procedural aspects. Given these conditions, we argue that disparities in energy poverty—similar to disparities in other regional development concerns—are deeply and institutionally rooted, and communities in peripheral regions may lack organisational capacity (e.g. social and financial capital) to compete for public subsidies.

We stress the importance of the polarisation phenomenon on a regional level because we assume that energy policy applications (e.g.

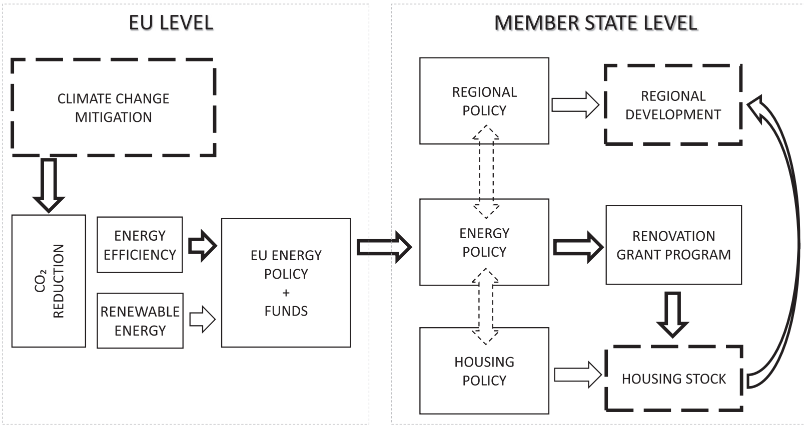

Fig. 1. Influence of global climate change agenda on local regional development.

housing renovation programmes) may unintentionally foster the growth of regional disparities (Bouzarovski and Tirado Herrero, 2017). Fig. 1 illustrates how the global climate agenda could shape regional development by implicitly influencing housing conditions through the requirement to conserve energy use in buildings. As the literature suggests, subsidised residential renovation projects may not distribute equally in space (Turcu, 2017).

2.2. Equity aspects of EU directives and member states' renovation strategies

The current climate agenda for buildings is operationalised through Energy Efficiency Directive (EED) (Council Directive 2012/27/EU, 2012). The main aim of the EED is to establish a set of binding measures to meet climate change mitigation targets in EU. Although EED is oriented to solve energy problems, we expect it to address social aspects for two reasons: (1) the application of any regulation can produce social and territorial impacts which might result in unexpected externalities and should therefore be mitigated in advance (this is the main rationale for the introduction of impact assessment procedures); and (2) disparate outcomes and uneven development cannot be addressed in separate specific regulations because of the complex nature and national variations in underlying conditions. Instead, these issues should be integrated with other sectoral regulations to achieve the aims of social and regional policy.

We observe that EED refers briefly to social aspects only in its introduction. In article 7/7 (a) there is a more concrete suggestion that member states may include funding scheme requirements with a social aim, but only in the "Saving Obligation Scheme", which is not relevant to housing renovation. Consequently, there are no direct requirements that energy efficiency measures at the national level (including renovation programmes) should directly address member states' social or regional policy challenges.

Although there are official impact assessment procedures available and in use (European Commission, 2015a) for European initiatives (e.g. directives), no significant contribution for social and regional equality was suggested to EED using this tool (European Commission, 2011). Furthermore, energy poverty is mentioned only once in the impact assessment report of the EED, when it is pointed out that EED supports a social agenda by reducing energy poverty. This is a general and normative statement which is not elaborated further in the assessment report. Therefore we argue that impact assessment of EED failed in impact assessment's core principle to answer the essential question of what are the economic, social and environmental impacts and who will be affected (European Commission, 2009). Moreover, this shortcoming was not recognised by the EU Impact Assessment Board whose explicit task is to analyse and submit opinions on the draft of impact assessment report. This is probably because impact assessments of EU initiatives do not anticipate territorial impacts that are also commonly absent from other initiatives (Fischer et al., 2015, 2011).

The Building Performance Institute Europe (BPIE) has made an important contribution in delivering EED article 4 by introducing guidelines for long-term housing renovation strategy (BPIE, 2013). However, this document does not address social equity, energy poverty or regional aspects related to building renovations. BPIE's subsequent document (BPIE, 2014) focuses on fuel poverty. This is an important emphasis, but unfortunately this report is too recent to have substantial impacts on the EU energy policy that has shaped current discourse. Furthermore, such single reports have generally little influence at the national level because of information overload and time stress on decisions by the government officials.

Indeed, it is quite surprising that despite various impact assessment procedures and a vast amount of literature on energy poverty, there is still no explicit emphasis of inequality in EU directives and guidelines. But this situation is likely about to change. A recent report prepared by the European Commission (2015b) for the European Parliament and Council states explicitly—for the first time—the need to address fuel poverty in building renovation strategies. The commission also emphasises a new preference for European Structural and Investment Funds to be used in grant programmes to fill the financing gap (for low income groups, social housing, and energy-poor households). To achieve these aims, the national government effort should certainly effect a mediating role. Next, we shall examine to what extent this opportunity has been utilised by European countries so far.

Under the EED, member states must prepare a National Energy Efficiency Action Plan (NEEAP); in addition, national governments must publish annual reports that quantify the national energy efficiency target and outline in detail how various programmes have been (or will be) implemented to meet the goals. In 2014, when each country was required to submit its third NEEAP report, a national building renovation strategy—designed to be evaluated on an ongoing basis—was required. Since the recent Science for Policy report by the Joint Research Centre on the assessment of the renovation strategies has not addressed social nor spatial aspects in its evaluation (Castellazzi et al., 2016), we present a brief overview of NEEAP reports in Table 1.

There are 12 member states that have not implemented nor planned any equality measures in their energy efficiency action plan. Although EED does not explicitly state the importance of equality aspects, there are 16 member states that have considered or will apply equality in their energy programmes in the future. The forerunner is the Czech Republic; although it has the lowest risk of poverty compared to other

Table 1
Risk of poverty and equality statements in National Energy Efficiency Action Plans.
Source: Eurostat; Member states' NEEAP reports 2014.

EU member state	Risk of poverty rate 2014	Equality statements in NEEAP reports
Czech Republic	14.8	JESSICA programme can be used by non-profit association specialized in social housing. Future measure in social housing
Netherlands	16.5	Special fund for social housing
Sweden	16.9	None
Finland	17.3	None
Denmark	17.9	None
Slovakia	18.4	Objective of decreasing energy poverty will be designed
France	18.5	Zero-interests loan for social housing Property tax reduction Future initiatives reducing fuel poverty
Luxembourg	19.0	Free interest loan has been considered
Austria	19.2	Styria region: renovation finances for social housing
Slovenia	20.4	Special scheme for low income household
Germany	20.6	None
Belgium	21.2	National level: tax credit for low-rent dwellings Wallonia: advice and grants for low-income households Brussels: free advice and differenced grants for low income households Flemish: incentives to social housing companies
Malta	23.8	None
UK	24.1	Special funding for low income households
Poland	24.7	None
Estonia	26.0	None
Lithuania	27.3	Programme that includes social housing
Cyprus	27.4	Programme focused on low income households
Portugal	27.5	None
Ireland	27.6	Programme for low income households
Italy	28.3	None
Spain	29.2	None
Croatia	29.3	Special financing will be established for low and mid income households in the future
Hungary	31.8	None
Latvia	32.7	Special measure for social housing Strategy for 2030: establishment of measure against energy poverty
Greece	36.0	Grants depending on the income
Romania	39.5	Special initiative for low income households
Bulgaria	40.1	None

countries, certain equality measures have been implemented there. Furthermore, the Czech Republic has a high quality building renovation strategy (Castellazzi et al., 2016). We stress that half of CEE countries that have higher-than-average risk of poverty have not implemented equality measures. The worst case is Bulgaria, with 40% of risk of poverty, no quality measures, and a renovation strategy is failing EED requirements. The same applies to Portugal and Poland, however, their risks of poverty are lower than that of Bulgaria (27.5% and 24.7% respectively).

National energy initiatives for addressing social and spatial aspects are rather scattered, and there is no evidence of a systemic approach on the subject within the EU and its member states. The concept of equality is explicitly missing in reports, even when general phrases like "energy poverty" can be found in the documents. Clearly more research is needed to understand how and to what extent equality is addressed in specific energy programmes of the member states, especially in CEE with its large share of deteriorating housing estates. Lastly, we emphasise that some attempts to assess the possible impacts of national energy policy using alternative tools of impact assessment have failed to anticipate social impacts because of a lack of consideration of social objectives by policy makers (Golobic and Marot, 2011). This suggests that the impact assessment tools per se are not a panacea for addressing social equality and that human factors must be emphasised to better define socially significant goals in impact assessment tools.

3. National policy goals and energy renovation in Estonia

3.1. Policy goals in Estonia

Every intervention programme is designed within the framework of relevant strategies. Several strategic policy documents guide regional, housing and energy policy in Estonia and, in theory, shape intervention proposals. We review documents most relevant to our empirical data and observed time period (2010–2014). The major spatial development principles of the country are reflected in the National Spatial Plan (Spatial Plan 2030) (Estonian Ministry of the Interior, 2013). One of the aims is to preserve the country's existing settlement system and maintain permanent settlement in peripheral regions (empty territories are not expected to emerge). Spatial Plan 2030 proposes to achieve this by maintaining physical and social infrastructure. There is no reference, however, to how and to what extent deteriorating housing should be addressed within this broad goal. Still, because housing stock can be addressed as part of physical infrastructure, it is clear that quality housing is needed and renovation subsidy programmes can help to achieve goals of the Spatial Plan 2030.

The Estonian Regional Development Strategy (Regional Strategy) (Estonian Ministry of the Interior, 2005) states broad goals for 2005–2015. Equality is emphasised by framing the vision of equal opportunities irrespective of spatial location. In respect to energy efficiency subsidy programmes, this means that communities on the periphery should have equal possibilities to apply for renovation grants. It also follows that if subsidies are limited, we should expect equal distributions of such finances between and within regions. Furthermore, in order to achieve equal opportunities, weaker regions like peripheries should have better starting points and advantages compared to more advanced regions that could finance energy renovations without major subsidies (Grösche and Vance, 2009). Another goal of Regional Strategy that supports our previous argument is that of limiting the disparities between capital region and other regions. This goal suggests that a concentration of housing renovation subsidy in the capital region is unwanted. In other words, energy programmes should not construct another layer of poverty in the already existing core-periphery spatial order.

So far, all Estonian governments throughout the post-socialist period have maintained a neo-liberal position and have avoided interventions in the housing sector (Liepa-Zemeša and Hess, 2016). This is somewhat justified in consideration of the generous contribution of the former Soviet state to the housing sector, but current welfare regimes in post-socialist countries do not support taking comparable responsibility. The Housing Management Strategy 2008–2013 (Housing Strategy) (Ministry of Economic Affairs and Communication, 2008) that was relevant at the time of the observed subsidy programme does not explicitly address regional or energy aspects. However, there are some support mechanism designed to aid large families. Energy poverty as a challenge is not mentioned.

Energy policy that should regard the housing–regional development nexus is addressed in the National Energy Management Strategy through 2020 (Energy Strategy) (Ministry of Economic Affairs and Communication, 2009). Although we could presume that in this more specific national strategy links between energy and other policies are more clearly expressed, there are unfortunately no connections built into this document between national energy, housingpolicy, regional policy, nor social equity.

The updated version of the Regional Strategy for 2015–2020 (Estonian Ministry of the Interior, 2014) is more conservative about

Table 2
Grant application criteria.
Source: Prepared by authors using information from Fund KredEx.

Requested grant amount	Energy conservation rate	Energy performance class	Threshold
15%	20–30%	E	No criteria
25%	40%	D	Façade and roof insulation, new windows, renovated heating system
35%	50%	C	All previous criteria, plus heat recovery ventilation system

spatial notions of balanced development and has softened the strict comprehensive goal of ubiquitous equal opportunities. Instead, regional differences should be connected to varying opportunities. This, however, should not legitimise grant applications only for the regions and social groups that are more capable or have higher financial capacity. While all versions of Regional Strategy have direct policies about energy sector development, there are no references to housing development strategy. This is a lost opportunity, as housing quality affects the quality of life in all regions, which is strongly emphasised throughout all versions of Regional Strategy. Moreover, it is evident that housing has not been considered to be a part of EU regional policy (Tosics, 2008).

In the early 2010s, the central government attempted to reduce the number of sectoral strategies in order to have a better general overview of goals and the means of achieving them; this aim, however, has mostly been renounced but the impact still remains. For example, after the evaluation of the Housing Strategy's progress and despite the fact that a new version was already prepared, the central government decided to abandon the new Housing Strategy for the following period. Instead, it was suggested that the Housing Strategy should be part of a broader effort. Interestingly, this wider view was the new version of the Energy Strategy.

The main reason to abandon the Housing Strategy and to integrate it with energy policy was not related to the aim to reduce sectoral strategies, although it was a significant argument at the time, but the very idea that housing policy was mostly regarded as a panacea for inefficient energy use in the residential sector. We suggest that the EU2020 energy goals, along with the strong involvement of energy specialists in policy design, reduced the importance of energy efficiency to the level that a comprehensive Housing Strategy was regarded as irrelevant.

The new version of the Energy Strategy, which has recently been officially adopted (10.2017), is a significant improvement of the previous version and considers the existence of all related sectoral strategies including the Spatial Plan 2030 and the Regional Strategy. However, it is still a techno-economic view that constricts housing policy into a narrow energy-efficiency framework and addresses broad regional policy goals like energy supply, energy transmission, and energy security. The fundamental failure of the new strategy is that housing and energy renovation is addressed regardless of location.

It has been declared that the strength and extent of state-level regional policy have decreased since Estonia joined the EU (Raagmaa et al., 2014); we argue that this is also the reason why connections between regional, energy and housing policies are weak (Fig. 1). No region of Estonia is declared to be hopeless, and energy-efficient housing renovation is consequently expected to happen everywhere.

3.2. Renovation subsidy programme in Estonia

In order to foster renovation activities and meet EU carbon goals, member states have designed incentive programmes. Next, against the policy backdrop in the previous section, we introduce the energy efficiency subsidy programme and the applications criteria which is the basis of our empirical study.

Prior to 2009 (almost 20 years after socialist housing construction programmes were terminated), only a small number of residential buildings in Estonia were renovated using contemporary techniques. Mostly urgent repairs like roof replacement were undertaken; sometimes the buildings walls (usually windowless sides) were insulated or windows were replaced. Energy efficiency developed as an important agenda in Estonia in 2009 after ambitious CO_2 emissions reduction goals were established in a renewable energy directive (Council Directive 2009/28/EC, 2009) and elaborated in a recast of energy performance buildings directive (Council Directive 2010/31/EU, 2010).

A more comprehensive housing renovation subsidy programme (known as KredEx scheme) was established in 2010 with a budget of 37.7 million euros for grants. This programme was financed with CO_2 emissions trading funds (a mechanism of the Green Investment Scheme that allows sale of Assigned Amount Units (AAU) to Kyoto protocol parties possessing a deficit in carbon emissions allowances), while the funds raised may be spent only on projects that further reduce carbon emissions

Apartment buildings with more than two apartments were eligible for grants. A grant could be used for all energy conservation work and applied to the total cost of the project. The grant amount depended on three criteria: 1) the estimated energy reduction (which was required to be calculated by certified energy auditors); 2) the class of energy performance certificate (EPC); 3) threshold criteria was required to achieve in order to apply for a larger grant amount (Table 2).

The subsidy was handled centrally by Fund KredEx. Although apartment associations were encouraged to apply for subsidy, the complexity of technical, financial and economic burden of renovations was left to community members to address. Local authorities had no influence over the subsidy handling. The first subsidy period concluded in September 2014 with the end of the subsidy budget. During that time, the programme granted renovation subsidies for 661 unique apartment buildings. While the grants covered on average of 25% of the overall expenses (total investment for energy renovation was 151 million euros), apartment associations had to acquire the remaining finances from commercial banks. Even at the beginning of the subsidy programme, when Fund KredEx also provided soft loans (before commercial interest rates lowered), the large role of commercial banks made this subsidy scheme competitive.

The subsidy programme had no specific objectives intended to aid low-income and energy-poor families or regions where the proportion of these families is high. The programme was considered an equal access opportunity, suggesting that everyone has an equal starting position to apply for a grant. The programme was considered a success mainly due to certain techno-economical dimensions which provided high-quality design and construction and follow-up monitoring based on scientific (technological) knowledge (Kurnitski et al., 2014; Kuusk and Kalamees, 2016a, 2016b).

4. Empirical study

4.1. Estonia's regional development and housing context

Estonia provides a compelling case for investigating renovation distributions for two key reasons. First, the form of ownership and occupation of apartment dwellings is remarkably homogenous: the private home ownership rate is 96%, the owner occupied rate is 82%, and rental market is small (7.3% market and 1.7% social (Pittini et al., 2017). Second, the energy renovation programme establishes equal conditions for applicants, and the sole responsibility for the renovation initiative belongs to the apartment owner associations. These conditions exclude many uncertainties that must be otherwise carefully addressed, making our analysis framework rather robust.

In 2014, Estonia's 15 counties were divided into 215 municipalities including 30 cities. There were 21,401 apartment buildings containing more than two flats built before 1990 (90% of all apartment buildings) (2011 Census). Over half of those buildings (64%) are in cities and 36% are in rural municipalities. The first large socialist residential estate projects were launched in the 1950s and the final projects were terminated in the early 1990s. Due to the technologies applied during their construction, all these apartment buildings are now targets for energy efficiency renovation programmes; urgent renovation is necessary regardless of energy improvements. Every community of residents or owners in an apartment building can form a non-profit apartment association to collectively manage the building. There were 10,181 registered apartment associations in 2014. In fact, the potential for applying public subsidies and applying commercial loans could not have been comparable in different regions because the frequency of apartment association formation has varied. In lagging regions in particular, where people have lower incomes and fewer resources, the motivation of community members for cooperating in housing maintenance and renovation has been more limited. In many peripheral settlements, viable apartment associations were missing until recently (the formation of an apartment association was made compulsory in Estonia by law in January 2018).

4.2. Data and analysis methods

Our analysis unit is an apartment building that includes more than two apartments and was built before 1993 (N = 21,401). We used the same criteria that Kredex has established in its eligibility rules. The main problem with this analysis unit is the uncertainty of abandoned or soon-to-be abandoned buildings. As the renovation grants distribution is compared against the total housing stock in apartment buildings, it is critical to use the actual number of occupied buildings, otherwise we might overestimate the potential capacity of renovations. Unfortunately, there are only estimates of abandoned buildings (DTZ, 2013). To overcome this uncertainty we use 2011 census data and exclude all buildings which were classified empty or more than half vacant. This step in our research reduces the analysis units by about 10%, resulting in 19,720 apartment buildings in the dataset. The number of municipalities we use is 208; we exclude seven municipalities (mostly small islands) from our analysis because there are no such apartment buildings that can be renovated.

Our data originates from a renovation grants database and the national statistical database. Renovation subsidy data is extracted from the Fund KredEx database. There were 661 unique buildings in the KredEx database which were subsidised during the 2010–2014 grant period for energy renovations. Using the buildings registry, we estimate approximately 10% of all major renovations of apartment buildings were carried out outside of the subsidy programme within that time.

We first estimate the grants distribution as the share of renovation grants [*SH_REN*] in a region in this way:

$$SH\_REN = \frac{Number\ of\ Renovations\ in\ Region}{Number\ of\ Total\ Renovations} \times 100$$

However, the apartment housing stock in Estonia is not distributed equally in regions. There are more apartment buildings in cities and in rural areas where industrial labour was required. Therefore, we next analyse the distribution of renovation grants considering the number of apartment buildings in a region. Doing so allows us to compare the potential for renovation with renovation in practice. We estimate the relative share of renovations [*REL_SH_REN*] in a region as follows:

$$REL\_SH\_REN = \frac{Number\ of\ Renovated\ Apartment\ Buildings\ in\ Region}{Number\ of\ Apartment\ Buildings\ in\ Region} \times 100$$

The relative share of renovations in some regions can be small and therefore difficult to interpret. Furthermore, it is not a practical measure for showing the distribution and illustrate possible inequalities between regions. To overcome this limitation, we devise a renovation proportionality index [PRI] which can be employed on a regional (county or municipality) level:

$$PRI = \frac{Share\ of\ Renovated\ Apartment\ Buildings\ in\ Region}{Share\ of\ Apartment\ Buildings\ in\ Region}$$

The [*PRI*] is mathematically the same construct as [*REL_SH_REN*] but it has no unit. Values of [*PRI*] higher than 1.0 suggest that there are proportionally more renovated apartment buildings considering the total stock of apartment buildings in a corresponding region.

We first test our assumption of inequality at the county level using the proportionality index. Our main analysis in explaining renovation inequalities is based at the level of municipalities. The data for this originates mostly from the Estonian Statistical Bureau. We select variables that can illustrate the level of regional development of the municipalities. Absolute values of the variables are adjusted to reflect the relation to the municipality size using population size to obtain per capita values. Descriptive statistics of the variables are presented in Table 3. Variables 1–5 illustrate the number of renovations in different ways. Variables 6–32 are socio-economic indicators of the municipalities. The Demographic Workforce Dynamics Index [*DEM_WDI*] expresses the ratio between two population groups: 5–14 year olds and 55–65 years old. If the ratio is greater than 1.0 there will be more workers in the next decade than workers who are potentially leaving the job market because of their age. The variable [*RE_VALUE*] represents the median price per square meter of real estate transactions (only for apartment buildings) between 2010 and 2014 and it is acquired from the public database of the Estonian Land Board. Dummy variables are used to distinguish between municipality types (urban = 1; rural = 0, variable [*CITY*]) and to identify the three largest towns [*BIG_CITY*]. Data for apartment associations [*SH_APARTASS*] is obtained from the Estonian Business Registry.

Next, we investigate relationships—between the proportionality index and socio-economic variables of the municipalities—using canonical correlation analysis (CCA), which determines correlations between two sets of data (Hotelling, 1936). For both datasets, CCA is used to identify linear combinations of variables that have maximal correlation with another dataset. The number of such linear combinations depends on the smallest number of variables in either dataset. We use CCA unconventionally as we have only one variable [*PRI*] in the first dataset. The second dataset consists of socio-economic variables for municipalities. Therefore, we can obtain only one linear combination. CCA is useful because it provides more insights about the relationships between dependent and independent variables than conventional bivariate correlation could extract. CCA can calculate the correlation and its importance in the canonical model, allowing us to exclude insignificant variables in further analysis. Furthermore, we can calculate the canonical variable—a ‘super-variable’—that captures the essence of all variables in set two. CCA is applied using IBM SPSS v23 built-in function.

As an extension of CCA, we specify a multiple linear regression model to understand how and to what extent socio-economic variables can explain the distribution of renovation subsides in municipalities. We use CCA to determine the significance of variables applied in the regression analysis. To conduct the analysis, we use IBM SPSS Statistics v23 and MS Excel 2013. Geographical analysis and illustrations are created with ArcGIS 10.2.2.

Table 3
Descriptive statistics (N = 208).
Source: Prepared by authors using information from Fund KredEx, Building registry, Business registry, National census database, and Estonian Land-Board.

Variable	No	Coding	Min	Max	Mean	SD
Share of multiapartment buildings form building stock	1	SH_MAB	0%	27.4%	0.5%	2.0%
Any number of renovations = 1; no renovations = 0	2	REN_binary	0	1		
Share of renovated buildings from all renovations	3	SH_REN	0.00	0.47	0.00	0.03
Relative share of renovated buildings	4	REL_SH_REN	0.00	0.22	0.02	0.04
Renovation proportionality index	5	PRI	0.00	6.53	0.58	1.13
Share of apartment associations	6	SH_APARTASS	0.00	2.00	0.40	0.29
Percentage of Estonian speakers	7	LANG_EST	2.18	99.66	87.54	20.78
Percentage of Russian speakers	8	LANG_RUS	0	96	11	20
Real-estate transaction price (EUR/m2, median, 2010–14)	9	RE_VALUE	0	1133	195	236
Relative poverty	10	REL_POVERTY	5.90	40.40	21.38	6.42
Gini coefficient of income inequalities	11	GINI	0.23	0.27	0.24	0.01
Share of unemployed	12	UNEMPLYMNT	1.60	9.20	3.93	1.45
No. of active companies per capita by annual report	13	COMPANYS_Pcap	9.51	119.13	41.68	16.10
Companies' sale income per capita (EUR)	14	COMP_SALES_Pcap	0.78	389.50	16.32	29.59
Demographic workforce dynamics index	15	DEM_WDI	0.23	2.07	0.75	0.28
Population size, 2015	16	POPUL	277	413,782	6275	29,785
Population change percentage (2011–2015)	17	POP_CH_11_15	− 48.76	156.80	− 3.15	16.96
Dummy variable - municipality type (city = 1; rural = 0)	18	CITY	0	1		
Dummy variable - three biggest cities (big city = 1; other = 0	19	BIG_CITY	0	1		
No. of real-estate transactions per capita	20	RE_TRANS_Pcap	0.00	163.72	32.04	24.82
No. of workplaces per capita of 15–65 year olds	21	WORKPLACES	0.21	1.87	0.55	0.24
Economic diversity: No. of business areas	22	ECON_DIV	12	265	71	41
Percentage of voters in local elections	23	VOTERS	0.48	0.82	0.60	0.06
Municipality's capital assets per capita (EUR)	24	CAPIT_ASSETS_Pcap	300	6435	1859	861
Costs for education per capita (up to 19 year olds) (EUR)	25	COST_EDU_Pcap	968	6407	2582	689
Costs for social security per capita (EUR)	26	COST_SOCI_Pcap	22.03	618.96	85.15	70.48
Costs for leisure activities per capita (EUR)	27	COST_LEISUR_Pcap	43	752	132	78
Costs for economy and environment per capita (EUR)	28	COST_ECON_Pcap	47	1090	208	144
Salaries and pensions (EUR per capita)	29	SALARIES	2899	7658	4658	727
Income support (EUR per capita)	30	INCOME_SUP_Pcap	0.53	72.33	16.66	13.22
Municipality budget income per capita (EUR)	31	BUDG_INC_Pcap	0.78	3.99	1.21	0.38
No. of pupils per capita	32	PUPIL_Pcap	0	330	91	37

4.3. Research limitations

Since our aim is to provide a regional-level overview of grant distribution and explain renovation activities on a macro-level, we focus on general socio-economic indicators. We acknowledge that there are several community-dependent factors (internal barriers for renovation) which contribute to the speed and success of renovations. For example, poor organisational capacity, general scepticism, a lack of trust, and divergent values are barriers which describe a community. We assume that internal barriers, such as investment resistance, are present in every building. Although we have no clear evidence how such barriers are geographically distributed, our field experience suggests that internal barriers are more prominent in peripheral regions where residents predominate from lower socio-economic groups. Furthermore, the rate of apartment association formation is lower in peripheral regions compared to core regions. Therefore, we assume that overall resistance and willingness to renovate has little significant impact on our results.

5. Results and discussion

5.1. Distribution of renovation grants

Our first empirical task is to analyse the distribution of renovation grants regionally and test our inequality assumption. Table 4 shows the distribution of renovations and number of apartment buildings that are eligible for the subsidy programme. The largest number of apartment buildings (38%) and renovations (60%) are in Harjumaa County (HAR) which includes the capital city of Tallinn. Tartu County (TAR) and Ida-Viru County (IVIR) both have about 10% of the apartment building stock, however there is a large gap between the distributions of grants in those counties: 16% and 1.5%, respectively. Hiiu County (HII) is an island that has a small number of apartment buildings and only one was renovated using the subsidy programme.

We also observe that the grant distribution during the period of our study does not follow a normal mathematical curve as might be expected (cf. Rogers, 2003). The renovation applications submission rate was relatively high within the first 12 months of the start of the grant scheme (32% of the total number of applications were received during this time period). The number of applications peaked in 2012, two years after the grant scheme announcement. By that time, 82% of subsidy applications were already submitted. There was no significant difference between regions and the grants' distribution dynamics—it followed a comparable pattern in every region.

Table 4 is ordered by renovation proportionality index (PRI), the ratio of renovation distribution of apartment housing stock in each county. A value of 1.0 suggests that the subsidy distribution and the number of apartment buildings in that county are proportional. There are two counties that have acquired more grants relative to the apartment building stock, Harju County (HAR, *PRI* = 1.72) and Tartu County (TAR, *PRI* = 1.25), where the country's two largest cities are located. Rapla County (RAP) has a [*PRI*] slightly less than 1.0 (*PRI* = 0.91) but all the others have acquired renovation subsidies significantly less than the potential of apartment building stock would suggest. Fig. 2 illustrates renovation subsidy distribution geographically.

It is clear that renovation subsidies are not distributed equally among counties. Between municipalities the contrast is even higher. The [*PRI*] value varies between 0 and 6.53 (mean = 0.582; SD = 1.12; n = 208). There are 127 municipalities which have not acquired any grants and 42 municipalities have [*PRI*] value over 1.0. Therefore, our assumption of unequal distribution of grants is confirmed.

5.2. Explaining the distribution of renovation grants

Our second aim is to identify characteristics that explain the distribution of grants. Our data includes geographical locations of

Table 4
Regional distribution of renovation grants.
Source: Prepared by authors.

County	Code	Number of apartment buildings	Share of apartment buildings (SH_AB)	Number of renovations	Share of renovations (SH_REN)	Renovation proportionality index (PRI)
Harju	HAR	6950	35.2%	400	60.5%	1.72
Tartu	TAR	2560	13.0%	107	16.2%	1.25
Rapla	RAP	621	3.1%	19	2.9%	0.91
Pärnu	PÄR	1580	8.0%	41	6.2%	0.77
Lääne-Viru	LVIR	1158	5.9%	27	4.1%	0.70
Valga	VAL	557	2.8%	9	1.4%	0.48
Lääne	LÄÄ	449	2.3%	7	1.1%	0.47
Põlva	PÕL	432	2.2%	6	0.9%	0.41
Jõgeva	JÕG	578	2.9%	8	1.2%	0.41
Viljandi	VIL	1110	5.6%	14	2.1%	0.38
Saare	SAA	403	2.0%	5	0.8%	0.37
Hiiu	HIIU	153	0.8%	1	0.2%	0.19
Järva	JÄR	641	3.3%	4	0.6%	0.19
Võru	VÕR	546	2.8%	3	0.5%	0.16
Ida-Viru	IVIR	1982	10.1%	10	1.5%	0.15
	TOTAL	19,720	100.0%	661	100.0%	

renovated buildings and descriptive data for the municipalities, permitting us to extend and elaborate the investigation. Using national statistical data, we gathered 27 socio-economic indicators that describe the municipalities' regional differences (variables 6–32 in Table 3). Our dependent variable is the value of the proportionality index [*PRI*].

We define two datasets for CCA. The first dataset consists of one dependent variable [*PRI*] and the second dataset includes 27 independent variables (socio-economic indicators and share of apartment buildings [*SH_AB*]). The canonical correlation between the two datasets is 0.694 ($p < 0.01$). The square of canonical correlation value is 0.482, suggesting that 48.2% of the variation in the first dataset is explained by the variables in the second dataset. Standardised correlation coefficients (weights for linear combination) for the second dataset express the contribution of each variable to the canonical variable (Table 5). There is no standard test for the significance of canonical correlation coefficients. However, the canonical loadings can be used to determine such significance manually. If the value of the canonical loading is greater than 0.3, the canonical correlation coefficient for each variable can be regarded as significant. CCA extracts four significant variables that explain the variation of renovation proportionality index [*PRI*]. The most influential is [*RE_VALUE*] which shows positive correlation (0.664) and the second is [*UNEMPLYMENT*] which is negatively correlated (− 0.329). The third and fourth influential variables, [*SH_APARTASS*] and [*DMI_WDI*] are both positively correlated [(0.231) and (0.681), respectively] against the first dataset (dependent variable). For testing purposes, we performed CCA a second time for these four

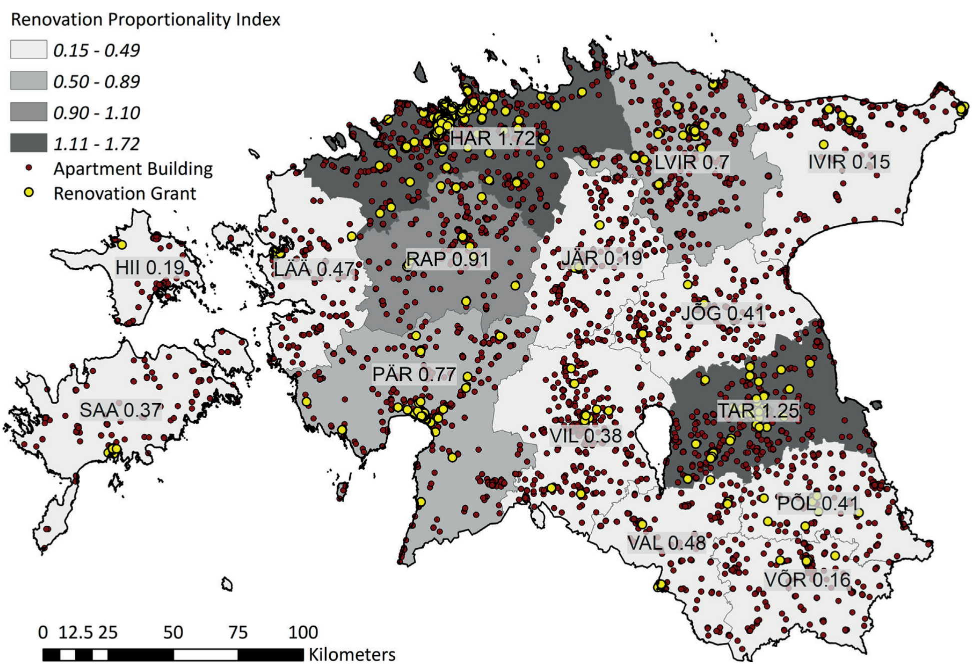

Fig. 2. Renovation grant distribution within regions of Estonia, Source: Prepared by the authors using information from Fund Kredex, Estonian Land-Board, and Buildings Registry.

Table 5
Canonical correlation coefficients and canonical loadings.
Source: Prepared by authors.

No.	Variable	Standardized coefficient	Canonical loadings
1	SH_AB	− 0.608	0.128
6	SH_HOUSASS	0.231**	0.532*
7	LANG_EST	− 0.980	0.063
8	LANG_RUS	− 1.159	− 0.065
9	RE_VALUE	0.664**	0.892*
10	REL_POVERTY	0.098	− 0.663*
11	GINI	0.022	0.238
12	UNEMPLYMNT	− 0.329**	− 0.543*
13	COMPANYS_Pcap	0.019	0.632*
14	COMP_SALES_Pcap	0.138	0.262
15	DEM_WDI	0.168**	0.795*
16	POPUL	0.557	0.166
17	POP_CH_11_15	− 0.007	0.195
18	CITY	0.049	0.103
19	BIG_CITY	− 0.120	0.092
20	RE_TRANS_Pcap	− 0.052	0.222
21	WORKPLACES	− 0.063	0.496*
22	ECON_DIV	0.093	0.622*
23	VOTERS	− 0.021	0.053
24	CAPIT_ASSETS_Pcap	− 0.002	− 0.070
25	COST_EDU_Pcap	0.227	− 0.145
26	COST_SOCI_Pcap	0.040	− 0.161
27	COST_LESUIR_Pcap	− 0.028	− 0.067
28	COST_ECON_Pcap	− 0.025	− 0.100
29	SALARIES	0.051	0.701*
30	INCOME_SUP_Pcap	0.184	− 0.281
31	BUDG_INC_Pcap	− 0.098	− 0.176
32	PUPIL_Pcap	− 0.093	0.198

* Significant loadings (value over 0.3).

** Important variables in linear combination based on absolute value over 0.1 and on loadings significance.

influential variables in the second dataset. The resulting explanation of canonical correlation dropped only 4 percentage points compared to the first CCA attempt ($r = 0.668$; $r^2 = 0.447$, $p < 0.01$), suggesting that these four variables capture the essence of variations in our dependent variable and it is rational to include these variables in further multiple variable analyses.

Next, we specify a multiple linear regression to predict dependent variable [*PRI*] using four socioeconomic variables [*RE_VALUE*], [*UNEMPLYMENT*], [*SH_APARTASS*] and [*DMI_WDI*] that were selected using our CCA process. A statistically significant regression relationship is found ($p < 0.01$), with R^2 of 0.441. Regression coefficients are presented in Table 6. As in CCA, the most influential variable is [*RE_VALUE*] and the only negative effect occurs from [*UNEMPLYMENT*].

Additionally, we specify a second regression model with the same conditions as the first but removing nine outliers that had standardised residual value higher than 2.0. Doing so, the regression model improved significantly with an R^2 value of 0.601 ($p < 0.01$). Nine outliners included municipalities which scored low in regional development but still had acquired renovation grants. This means that in reality there can be exceptions to the general rule that low socio-economic variables indicate no renovations. This phenomenon calls for further elaborated investigations to understand the capacity and motivation of those associations that managed to acquire renovation grant despite unfavourable conditions.

Table 6
Regression results.
Source: Prepared by authors.

	Unstandardized coefficients		Standardized coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	− 0.087	0.302		− 0.287	0.774
SH_HOUSASS	0.557	0.236	0.142	2.362	0.019
RE_VALUE	0.002	0.000	0.355	4.392	0.000
UNEMPLYMNT	− 0.124	0.046	− 0.160	− 2.717	0.007
DEM_WDI	0.803	0.305	0.197	2.630	0.009

5.3. Discussion

Results show that competition-based renovation subsidies are distributed unequally within Estonian regions. This finding is significant, as there are regions that differ in acquiring subsidies by a factor of 10 while their housing stock is approximately the same size. This result is consistent with a recent study in which unequal subsidy distributions were identified within the capital region of Bucharest (Turcu, 2017). However, the subsidy distribution mechanism is different in Romania compared to Estonia. Estonia has established a central distribution system using Fund KredEx as a distributor and subsidies upon request of apartment associations. In Bucharest, state subsidy funds are distributed by municipalities that decide which buildings will be renovated, and apartment associations have little influence over the renovation process. Interestingly, both subsidy distribution mechanisms result in unequal distributions of grants.

Subsidy distribution differences in Estonia are strongly related to regional development indicators, such as real estate value and unemployment rate. Higher real estate value and lower unemployment rates increase the probability of acquiring renovation grants. In other words, successful regions are more capable of acquiring public finances, thus exacerbating existing differences. This trend works against regional aims to decrease regional and societal polarisation. Interestingly, the post-impact assessment report of the 2010-2014 KredEx housing renovation programme acknowledges the regional differences of grant distributions, however it fails to identify and address this phenomenon as a regional development concern (Lauri, 2014).

The empirical analysis shows that most influential indicator that relates to unequal subsidy distribution is the value of local real estate, which alone explains about 40% of total variation in renovation distribution between regions. We interpret the influence of real estate value on renovation likelihood in three ways: (1) low real estate values reflect a depressed local economy (poverty) which prevents investments in housing; (2) low real estate values reduce the likelihood of loan acquisition for renovations in depressed places; (3) low real estate values suggest a feeling of hopelessness, and shrinking peripheral regions may engender a lack of motivation for change among community members.

Unemployment rates indicate the overall economic climate of a region. A lack of adequate income prevents investment in housing renovation. Our results confirm this through negative correlations between renovation likelihood and unemployment.

We observe that the existence of apartment associations is positively correlated with housing renovation. Although associations were not mandatory in Estonia during the subsidy programme, there were associations established in about half of the apartment building stock in 2014. As a rule, only apartment associations could apply for grant funds for renovation. Therefore, some communities were in a better starting position if they had an active association already established at the time of subsidy programme announcement. Experienced associations reflect the social co-operational capacity of community members of an apartment building. An experienced association can work more efficiently regarding decision-making about a potential apartment building renovation because of accumulated social capital that is considered a significant factor in collective action generally (Putnam, 1995) and in renovation action specifically (Cirman et al., 2013). This in turn may have a positive neighbourhood effect: comprehensively renovated apartment buildings in a neighbourhood serve as visual advertisement for renovation programmes and can demonstrate to community members that capacity is present locally for success in the application process.

The demographic workforce dynamics index is a future-oriented indicator and reflects potential prosperity of a region by forecasting growth or shrinkage of the labour market. Its positive correlation with renovation activity is not surprising. However, this indicator is the least influential among statistically significant variables in our analysis.

The grant distribution rate within the four-year subsidy period demonstrates two important insights. Firstly, the early adopters, who in theory should reflect a slow start (Rogers, 2003) were quick in their decisions and thus conquered a surprising two thirds of the total amount of applications within the first year. However, to reduce the complexity of the decision-making process, early adopters were not very ambitious about their energy conservation goals. Secondly, majority of grant applications (82%) were submitted within the first 24 months. This fact emphasises the competition effect of the renovation programme and indicates that more competitive communities (i.e. apartment associations with greater administrative capacity and being in favourable location) can take immediate advantage of subsidised investment opportunities. Interestingly, the speed of renovation decision by apartment associations' is not correlated with the factors that indicate socio-economic status of the community and technical properties of a building (Lihtmaa, 2014). The spatial correlation between adoption speed and building locations is yet to be determined.

6. Conclusions and policy implications

The distribution of grants in an energy programme can produce important social consequences and critical effects on regional development. In examining outcomes from a state-funded energy programme in Estonia dictated by market mechanisms and lacking social criteria and regional balancing in the disbursement of subsidies, we find clear evidence that the distribution of grants for energy-efficient housing renovation subsidies is unequal both within counties and within municipalities. The relative share of renovations relying on KredEx subsidies in a region is related to the socio-economic indicators of the region. Real-estate transaction prices explain approximately 44% of the variation in relative share of renovations. Thus, real estate value is a reasonable basis for further research for example on the role of commercial banks in financing renovation projects.

Clearly, residents in economically stronger and diverse regions are better equipped to acquire subsidies and improve the quality of housing, leaving residents in weaker regions behind in unrenovated dwellings with lesser potential for enhancing their property value. This systems' trap amplifies urbanisation, energy poverty, segregation and, most importantly, societal polarisation.

An important task of the climate change agenda is to reduce carbon emissions, which can be achieved by emphasising energy efficiency and introducing renewable energy. Both of these practices are consistent with core objectives of the EU energy policy. This goal is important, measurable and even financed by the EU, rendering it a strong driving force of member states' individual energy policies. However, while shaping this policy there are additional aspects besides carbon targets that should be addressed. For example, energy efficiency incentive programmes can shape regional development by affecting the quality of housing stock in certain locations. Our analysis demonstrates that in Estonia, despite formally equal opportunities to access the programme, renovation grants are unequally distributed between regions. A confirmed relation between the relative volume of grants distributed and economic prosperity suggests that, without social considerations and lacking a regional strategy in grant distribution, the outcomes deepen pre-existing regional inequality. This energy programme outcome is in direct opposition to regional development policy. Consequently, we argue that it is a missed opportunity to address regional disparities with policy instruments made available in energy efficiency measures.

We might ask why Estonia—along with Bulgaria, Hungary, Spain, and Italy, four countries possessing higher poverty risks than the EU average—failed to integrate social goals or criteria, which could mitigate regional inequalities, into building renovation policy. We suggest that a lack of cross-policy co-operation limited the emergence of such problems and challenges in the first place, since energy-efficient apartment building renovation is usually considered a strictly technical and financial practice. Furthermore, the EU Energy Efficiency Directive does not explicitly state that member states must address inequality and social asymmetries while shaping energy incentive programmes. A failure to perform ex-ante assessment for renovation grants programme in Estonia—although there are readily-available tools such as Strategic Environmental Assessment, Policy Impact Assessment and Social Impact Assessment—ensured that the failure of national energy policy to address regional disparities remained masked.

In addition to incompatible aims between energy policy and regional policy, we can also argue that the climate change agenda could have an effect on other sectoral policies too. Findings from our analysis of various Estonian strategic policy documents suggests how national housing policy has been marginalised within the context of carbon conservation aims. Addressing energy efficiency simply as a techno-economic exercise, the already powerless neoliberal housing policy was reduced to the extent that a distinct strategy was considered irrelevant and housing policy was integrated with the energy strategy. The final formulation of the housing policy, as it is presented in the energy strategy, provides a clear indication that energy policy (with the effective influence of energy specialists) has overpowered the social aims of housing policy. This insight presents us with a lesson about the strength and influence of the climate change agenda (and its generous financial support system).

We acknowledge that the main goal of EED is to mitigate climate change while regional and social disparities are generally addressed in other sectoral policies (e.g. cohesion policy) which are not regulative like directives but rather disseminate awareness and provide financial motivation to foster mitigation of disparities in member states. However, as it is evident form our case study, such indicative polices have not influenced the development of the renovation programme in Estonia.

To improve equity in disbursement of subsidies for housing renovation, we might suggest several broad policy recommendations—including cross-policy co-operation and ex-ante assessments of intervention programmes—however, we recognise that it is not straightforward to universally introduce this practice for all member states of the EU directly. It takes time for policy-making practice to adapt to the energy transition concept and to consider the subtle externalities of the intervention programmes. We therefore focus on two key recommendations at the EU level which in turn could foster the change in member states' practice.

First, the EU Commission should articulate an aim to address social equality and balanced regional development in EU energy-related polices. Our analysis confirms a lack of explicit equality statements in EU energy policy. This could be why some member states have not introduced territorial nor social aims in renovation strategies. We suggest that it is necessary for the Commission to build awareness within its own organisation for articulating relationships between energy and regional policy. Next, the EU legislation should convincingly convey the importance of equality in energy policy of member states. And finally, the Commission should take full advantage of specific spatially-driven ex-ante evaluation tools to design more inclusive regulation and effective communication. We note a recent advance in impact assessment, known as Territorial Impact Assessment (Fischer et al., 2015), which is designed specifically to evaluate policy initiatives on a higher governmental level (such as EU directives) to improve the territorial considerations of those initiatives. We believe that as the Commission's rhetoric changes and the emphasis shifts towards social and regional aspects in energy policy, member states will comply.

Second, there is an urgent need to raise awareness about the territorial impacts of national policy-making generally and in

energy policy specifically. As EU-level legislation development, and especially the recast of directives, is a time-consuming process, more effective immediate actions are required to influence national policy making. Our empirical study suggests that overlooked spatial factors and the current general atmosphere of techno-economic discourse in Estonia has rendered carbon reduction aims one-sided. As local energy policy experts and programme developers are becoming more aware of the consequences of disparities and how inequality affects general development, they might also be able to design effective measures. As a broad approach to build awareness of territorial impacts, we therefore suggest the Commission include explicit equality statements in communications with member states. More specifically, we propose to focus direct communications toward such member possessing higher poverty risk rates, undeveloped renovation strategies, or growing regional disparities.

Additionally, we suggest that the EU Commission require member states to address equality and spatial aspects within the reports of mandatory energy efficiency action plans and also provide targeted guidelines to fulfil this task. We recognise that additional requirements from the Commission are generally not welcomed by member states, however, this could be one of the most effective measures for creating awareness of social and territorial impacts that are not obvious in current policy development discourse. In turn, this requirement could foster co-operation between various governmental bodies and motivate the application of novel ex-ante assessment tools to anticipate the externalities of intervention programmes. Finally, it could be useful to introduce additional assessment criteria to evaluate the quality of equality measures in energy efficiency action plans in order to establish a useful feedback loop.

Regarding the approach taken by individual countries, we suggest that policy makers consider abandoning market-based competition-driven renovation programmes and establish demand-based approaches instead. For more equal distribution of public finances, regional priorities should be articulated and vulnerable groups should be prioritised. Several strategies can help mitigate disparities, including establishing regional quotas, differential subsidy rates for growing and shrinking regions, additional finances for vulnerable groups, and inclusion of local authorities in grant distribution decisions. We recommend providing free professional advice and consultation for apartment associations, especially for those who are developing their capabilities. Also, dissemination of information about best practices can reduce investment resistance and prepare community members for meaningful discussion.

We conclude that, on the one hand, regional socio-demographic characteristics and economic performance explain a regionally unequal distribution of renovation grants. On the other hand, the availability of subsidies can affect the trajectory of a community and its housing stock (reflected in socio-demographic and economic measures). We observe a reinforcing feedback loop of deprivation of human capital in certain regions, an outcome which is contrary to regional development strategy. As Energy Efficiency Directives force compliance with EU carbon targets, there will be greater pressure to increase the pace of housing renovation, regardless of the beneficiaries and location. For Estonia and other similar countries, it is not too late to improve regulations to better address inequality in housing renovation policy, because a majority of apartment buildings await renovation.

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Article II

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Preliminary assessment of preconditions to deliver carbon neutrality in apartment buildings by 2050

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Abstract. Member states of European Union have large stock of residential buildings that require urgent renovation in order to reach carbon neutrality by 2050. In our paper we provide a preliminary evaluation of preconditions of such goal within the context of shrinking regions. Our data originates form renovation subsidy database of large renovation programme managed by state fund and form Nation Statistical Bureau. First we estimate the potential of apartment buildings occupation within the next 30 years. We exclude buildings that are going to be abandoned due to the demographical and migration reasons. Next we calculate the potential of construction sector to deliver required amount of renovations. We observe that the in our case current renovation rate must at least be increased by factor of three in order to comply with the carbon neutrality goal. This, however, is very challenging because supply of renovations' construction is limited and overstimulated demand could increase construction prices significantly while rendering the effect of state incentives inefficient. Therefore an urgent technological change in renovation delivery is required to reach carbon neutrality goals.

1 Introduction

Carbon neutrality is one of the big challenges within the energy sector. To mitigate climate change it is necessary to transform energy consumption form fossil fuels to renewables and also conserve energy. As buildings require about 40% total energy produced in Europe (50% in Estonia), it is obvious that there is a great potential for reducing energy demand. Energy performance of building directive (EPBD) [1] requires all new buildings to be nearly Zero Energy Buildings (nZEB) from 2020. However, in most of European countries, the majority of buildings stock was built after World War II mainly during the period with low requirements on energy performance. Therefore existing buildings include a large potential for energy performance improvement [2–6], especially in cold climate.

As reductions in CO_2 emissions are generally proportional to the energy saving potentials [7] EPBD requires EU member states to renovate almost all buildings by 2050 in order to achieve carbon neutral economy. This significant challenge is addressed in long term energy efficiency strategies that are prepared by member states and presented to European Commission. In order to set renovation milestones for next decades we need to know which buildings and where to involve in renovation strategy.

In their literature review on energy performance of buildings during the operational stage Geraldi and Ghisi [8] showed that buildings' stock-level analysis has extensive potential to improve building performance analysis. Nägeli et al. [9] developed bottom-up building stock model of Switzerland and Sandberg et al. [10] modelled building stock in 11 European countries while showing that models can effectively reproduce the past development, current stock size and composition and the long-term dynamics in the system in an acceptable way.

It is clear that some buildings that are currently in use, will be left out of service by 2050. On one hand this happens naturally by the buildings stock renewing process which speed is estimated about 1% per year and modern carbon neutral buildings will be built instead. However, there are important reasons why buildings could be abandoned before the end of their life cycle.

There are two major trends that affect the demand for buildings in the future. Firstly, we point out the urbanisation which leads to major restructuring of the location of population. Larger and economically diverse centres are growing (supported by erecting of new nZEB buildings) as the periphery shrinks. The growth of the stronger regions is fuelled at expense of weaker regions [11]. This trend amplifies the regional divide between core-periphery lines [12]. Secondly, European population is getting older and shrinks [13].

As the population declines there is less demand for buildings, especially in peripheral regions. It is evident that there is no rationale to include such buildings in renovation plan.

Current calculations of the amount of buildings that require renovation are done rather simply. For example the previous renovation reports in Estonia are based on total amount of surface area recorded in building registry

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[14,15]. Furthermore, building stock modelling has mostly applied in the context and expectation of population growth [10,16]. Those approaches ignore the effect of abandoned buildings in the future. More importantly, the calculations of carbon conservations targets are also based on this data which in turn could result in overestimated potential of energy and carbon reduction targets. However, abandoned buildings are not consuming energy and thus are not emitting carbon dioxide. This in turn renders the carbon goal more obtainable.

We would also like to point out that EPBD does not explicitly state that energy policy must address regional and social aspects. However, there are evidence that ignoring such aspects in policy application can have negative externalities which further exacerbates the social polarisation. For example recent studies show that renovation grants tend to distribute unequally between and within regions [17,18].

Therefore we can argue that long term renovation strategies must also address migration and demographical trends in order to address carbon neutrality in cohesion with regional development.

The requirement of EPBD to renovate most of the building stock is such an ambitious goal that we can even question to what extent it is achievable. On one hand, boosting renovation activities require incentives and information dissemination. However, if the demand for engineers and builders grow, the prices also tend to rise, which in turn renders the incentives and grants inefficient. This could seriously hinder the achievement of carbon neutrality goal. Thus, the growth capacity of the building sector is of paramount importance and must be analysed while designing a renovation strategy.

The objective of this study is to assess how the buildings' renovation goal can be achieved in the context of urbanisation and population decline taking account the growth limits of construction sector. We employ the example of residential sector in Estonia and focus on the apartment buildings.

2 Methodology

In order to predict building stock for the preliminary assessment of the goal of climate neutrality of buildings by 2050, we use the migration and demographic projections for forecasting the occupancy of existing buildings within the next 30 years, Fig 1. We analyse what kind of preconditions are needed to deliver the renovations by building sector. Specifically we look into the dynamics of renovation demand and construction prices.

To give an estimation of apartment buildings renovation potential, we start by describing the current residential stock that is built before the year of 2000 (*n=22597*). This is due to the reason that newer buildings are considered sufficiently energy efficient and we can use data form census of 2000 to compare with the data form building registry.

We use regional population forecast form National Statistical Bureau to estimate population change in counties (*n=15*) in order to calculate future occupation of apartment buildings. There are five scenarios for population forecast [19] in Estonia for 2050. We use the base scenario which is considered the most probable. For comparison reasons we also make rough estimations with more positive and more pessimistic scenario. As official population forecast is only addressing years till 2045, we used linear extrapolation to fit the forecast for EU carbon neutrality target of 2050.

To further specify the effects of regional population migration we use the results form commuting studies also prepared by National Statistical Bureau. We assume that if a region is shrinking, population is moving from smaller and economically weaker places to larger centres. This assumption is compliant with urbanisation and migration trends [20,21].

Next, we analyse the amount and regional distribution of new builds by utilising building permits form national buildings registry. Doing so we are able to assess the demand for new apartments and evaluate the capacity of construction sector in different regions.

Next, we look to what extent construction prices for renovations have changed during the period of 2010 and 2019. This period is selected because at that time Estonia has introduced an comprehensive subsidy programme to accelerate renovation activities [22]. Therefore, there is an exhaustive database readily available to analyse technical, economic and spatial dynamics of energy renovations. We only include buildings that have implemented deep energy renovations (*n=609*).

Next, we compare renovation cost dynamics against apartment buildings' construction price index in order to understand if the role of stimulated renovation demand has caused renovation costs to increase more than natural growth. Informal interviews with representatives of construction companies (*n=3*) are used to interpret the results.

We use MS Excel for statistical analysis and ArcGis software for spatial analysis.

We would like to point out that this study is a preliminary assessment and therefore we are yet unable to forecast which types of apartment building are going to be abandoned. At the time our contribution is sufficient for broader energy renovation strategy. However, for the regional application more specific analysis is required.

We acknowledge that renovation volume has been hindered also by renovation barriers such as mistrust, lack of social and financial capital, lack of motivation, information asymmetry. which have been addressed in numerous papers previously [23–27]. Instead we focus on the renovations delivery.

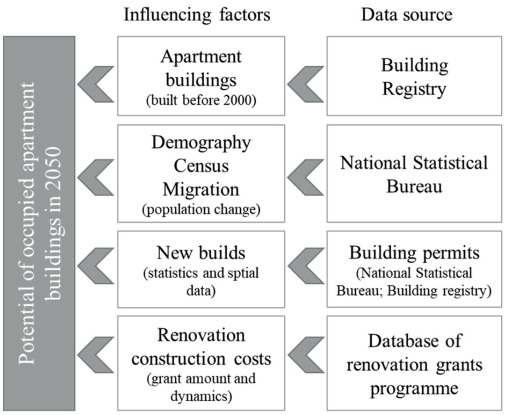

Fig 1. Influencing factors and data source to determine potential of renovations by 2050.

3 Results and discussion

3.1. Apartment buildings according to existing database

Apartment buildings account for 51% (34 282×10^3 m^2) of the total net area of dwellings in Estonia. According to the 2000 census, 70% of people (i.e. 931,000 persons) lived in apartments. The most active construction period was 1961 – 1990, when about 79% apartment buildings were construed [28]. Dominating construction types for apartment buildings are brick and concrete (Fig 2). In total, there are about 22.6 thousand apartment buildings in building registry that are built before 2000. As a rule, dwellings in peripheral areas are older. Today the designed service life of older apartment buildings is close to the end which could lead to hazardous situations and therefore urgent intervention is needed.

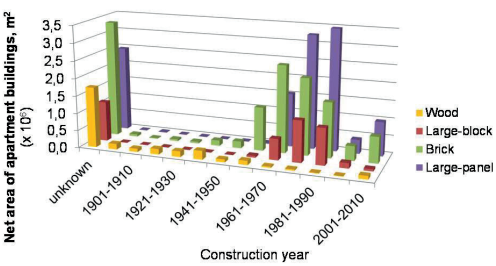

Fig 2. Distribution of apartment buildings by the net area and by the construction types in Estonia [29].

3.2. Occupation of apartment buildings in 2050

The apartment building forecast depends on construction of new buildings and decline of existing buildings. Both parameters are influenced by demand which in turn depend strongly on population change.

Within last decade the average rate of new apartment buildings is 150 per year. New apartment buildings have mostly concentrated in capital region of Harju County and in southern centre of Tartu County. Those are the regions, which grow and also have gained most renovation subsidies form state's renovation programme during the last decade [30].

The main scenario of population forecast for 2050 estimates 3.5 percent decrease of residents. However, inner state migration shows that only two counties grow at the expense of others (Table 2). This means that a significant amount of apartment buildings are going to be abandoned within next decades. Our calculations show that 5322 apartment buildings which makes 17.1 percent of current total surface area, will be left out of service by 2050 (Table 2).

National Statistical Bureau's population forecast also includes more positive and pessimistic scenario which results about 4000 and 6000 of abandoned apartment buildings respectively. We can observe that those scenarios have little effect on the occupation change of apartment buildings compared to main scenario. This is because the impact of overall population decline is marginal compared to inner state migration which bases on the urbanisation and regional change principles.

In conclusion, the amount of apartment buildings that require extensive renovation is about 14.5 thousand which includes 64% of current apartment buildings stock (Table 1).

Table 1. Renovation potential forecast by 2050

	No of buildigs
Apartment buildings (built before 2000)	22 600
Renovated using subsidy programme (2010-2019)	1 100
Renovated without of any subsidy (2000-2019)	2 000
Building abandonment by 2050	5 000
Total renovation need by 2050	**14 500**

Table 2. Forecast of population and occupation change in apartment buildings by 2050.

Region	Population change (%)	Current stock of apartment buildings (built before 2000)		Abandondment of apartment buildings (by 2050)	
		No of buildings	*Net area (thousand m²)*	*No of buildings*	*Net area (thousand m²)*
Harju county	22.4	8 055	12 956	-56	-47
Hiiu county	-22.2	159	114	-82	-59
Ida-Viru county	-43.4	2 140	4 230	-1 068	-1 672
Jõgeva county	-39.2	688	559	-374	-269
Järva county	-40.6	764	715	-453	-365
Lääne county	-32.9	521	489	-185	-165
Lääne-Viru county	-33.9	1 486	1 361	-599	-499
Põlva county	-33.6	458	428	-221	-167
Pärnu county	-18.5	2 111	1 605	-540	-376
Rapla county	-22.9	651	564	-284	-237
Saare county	-20.3	540	454	-193	-134
Tartu county	5.8	2 476	2 803	-126	-83
Valga county	-39.7	596	582	-262	-208
Viljandi county	-32.8	1 265	881	-575	-356
Võru county	-29.9	687	638	-304	-224
Grand Total		**22 597**	**28 378**	**-5 322**	**-4 861**

3.3. Capacity of construction sector

Typical energy renovation includes additional thermal insulation (typically onsite construction) of walls (15 – 20cm) and roof (30 – 40cm), replacing windows, installing new heating system and mechanical ventilation system with heat recovery [31–33]. In Estonia there are about 200 deep energy renovations per year. Continuous motivation of apartment associations to renovate their buildings combined with renovation grant [22] has resulted increased demand for construction works year by year.

National Statistics show that the construction price index has increased 15 percent during the years of 2011-2019. At the same time our analysis of renovation subsidy programme shows that renovation costs have increased 59 percent. While the average renovation cost in 2015 was 247 €/m², it has increased to 297 €/m² in 2017[34].

Table 3. Renovation cost dynamics in 2010-2019

Year	Count of subsidised renovations	Renovation cost chage in year (%)	Construction price index change in year (%)
2010	1	-	-
2011	21	16.4	3.3
2012	89	11.2	4.2
2013	65	11.2	4.4
2014	22	16.6	0.3
2015	16	2.5	-0.8
2016	79	10.1	-0.6
2017	139	13.9	1.0
2018	106	6.2	2.7
2019	71	11.0	1.8

This shows that state stimulations are increasing the demand for renovations faster than construction sector is able to grow. Yearly change of construction index and renovation costs are illustrated in table 3.

Our results do not consider that carbon neutrality goal also includes the renovation of other types of buildings such as commercial, education and administrative buildings. This means that the demand for construction delivery is even higher, thus rendering the challenge of climate change combat more difficult to achieve.

Construction companies have testified that using current laborious technics they are unable to double the renovation delivery. Our calculations show that in average the renovation delivery must be increased by threefold. Therefore, we can argue that using current technology, construction sector is unable to deliver renovations in significantly increased rate in the future.

3.4. Preconditions for carbon neutrality

Combining the previously given results with informal interviews with the stakeholders of construction sector, we can conclude next preconditions for carbon neutrality goal for apartment buildings

Firstly, it is clear that current pace and the capacity of growth of construction sector in insufficient to deliver carbon goals. Virtually all renovations are bulky handcraft which is slow and expensive due to the labour costs. Therefore technological change form manual built to prefabricated renovation is required.

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Secondly, in order to increase the productivity of designers, standardised solutions especially for large building estates should be used. This in turn raises the productivity of offsite renovation and production companies.

Third precondition is sufficient and consistent financial support for carbon neutrality renovation. State support is required to start pilot projects of prefabricated panels and to encourage early adopters to choose new solutions. Although first pilots of prefabrication are tested, we suggest to continue with this practice in order to develop engineering and construction skills as well to introduce the solution for customers. Support can be reduced when prefabrication has mainstreamed and the costs have reached desired equilibrium.

Prefabrication requires constant demand in order for the sector to be sustainable. Therefore, state support should be readily available in order to stimulate the demand within recessions of economic cycles. Prefabrication technology can also be applied for export as there are similar buildings especially in other post-soviet member states. However, for the smaller, custom and heritage apartment buildings prefabrication possibilities are limited and thus we need further research on how productivity can be increased in such cases.

Fourth precondition addresses the context of regional disparities. Communities in growing centres are more capable to renovate than in smaller places and especially in shrinking regions and periphery [17]. Therefore, limited state support for renovations should be distributed between regions differently. Larger centres where market-based development prevails, state support should be used for project management and consultations to ensure the quality of renovations. Novel solutions that promote productivity can also be eligible for support. Although there is no rationale for carbon neutral renovations in shrinking regions, those buildings also require some renovations. State support should be used in cases which present unsafe building usage and show dangers for occupants' health.

The major target group for renovation support are regional and local centres which are key importance in settlement structure. If those places have market barriers for energy renovations, it is reasonable for the state to stimulate renovation demand and support also direct construction costs.

Current study concentrates on apartment buildings. The second large dwelling type, detached house, should not be overlooked. Those buildings are also significant, both in their ubiquity and energy consumption. Csoknyai showed that detached houses are responsible for 50-80% of the total primary energy demand of the housing stock, depending on the country [35].

4 Conclusions

Achieving carbon neutrality in buildings is an important and difficult challenge within next three decades. On the one hand, shrinking regions cause the reduction of residential buildings that are occupied in next decades, thus reducing the overall renovation demand. However, our study shows that current renovation rate is still insufficient and needs to be increased by several times to deliver the required amount of renovations by 2050.

Clearly, government incentives such as grants and tax rebates are effective measures to boost renovation activities within communities. Such stimulations in turn could cause the significant construction price growth due to the rising demand and thus render the incentives inefficient while also hindering the renovations in vulnerable regions. Our case study shows that renovation demand has increased construction costs at least by factor of two.

We also note, that non-residential buildings must be also upgraded to meet carbon goals. Furthermore, overall construction demand increases also due to the urbanisation and regional migration which causes the increased demand for new builds. Therefore, as our case shows, carbon goals could only be achieved by technological change that results of significant increase in engineering and construction productivity.

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Article III

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Emerging renovation strategies and technical solutions for mass-construction of residential districts built after World War II in Europe

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ABSTRACT

While deep energy renovations of buildings have been implemented for over a decade, the pace and volume of building upgrades are still insufficient to achieve carbon neutrality by 2050. Therefore, it is urgent to adopt technological and management innovations to significantly improve renovation performance. A significant portion of Europe's building stock was constructed after World War II using industrial methods, often in concentrated districts. It is reasonable to consider mass-renovating these dwellings that require urgent structural and energy performance upgrades. This paper aims to assess the extent to which EU member states are planning to implement mass-renovations and identify the main barriers to initiating and mainstreaming mass-renovation approaches. We conducted a content analysis of EU member states' long-term renovation strategies (n = 29) and used in-depth interviews (n = 16) with representatives of the renovation supply side in Estonia. Our findings reveal that the recent iteration of national long-term renovation strategies demonstrates a weak approach to mass-renovations. Only the regions of Wallonia and Brussels in Belgium have provided specific action plans. While one third of states have mentioned the theoretical benefits of mass-renovations, most countries have not addressed this approach at all. The interviews revealed that maintaining consistent demand, involving large new builders, and adopting offsite prefabrication of renovation components are key factors for initiating or mainstreaming mass-renovations. First, we propose that EU member states include mass-renovation goals and action plans in the next version of strategic documents that determine the financing of energy efficiency. Second, central governments should empower local governments with the necessary skills and resources to lead district-based renovation adoption. Third, we suggest that countries make significant investments in industrializing current resource-consuming onsite renovation practices to transition towards off-site prefab serial renovation.

1. Introduction

The Energy Performance of Buildings Directive (EPBD) [1] clearly sets the target of achieving zero-emission buildings and a carbon-neutral building stock by 2050. This means that also existing buildings must achieve significantly higher energy performance than current standards. It is evident that energy renovation activity needs to at least double in order for 35 million building units to be renovated by 2030 [2]. While public buildings will be renovated according to EU and national regulations, there is uncertainty regarding the renovation of residential and privately owned commercial buildings. The latter will primarily be renovated based on profitability [3,4], which can be incentivized through carbon taxes or binding operational licenses with carbon emissions limits. However, implementing carbon taxes on existing residential buildings may not be politically or socially acceptable due to existing energy poverty. Therefore, additional supportive measures, as well as new technical and economic solutions, are necessary to meet stricter energy performance and emissions requirements.

The need to increase the pace of renovations has been acknowledged in the literature [5–7]. However, much of the existing research focuses on stimulating demand and assumes that the market will deliver the necessary renovations. While this assumption is generally valid, especially in normal market conditions, it is also important to stimulate the supply side of renovation by supporting innovations and productivity in the planning, design, and construction sectors. The research on supporting the supply side of renovations, particularly in terms of speeding up the pace and volume of renovations, is scarce compared to studies that primarily address demand side factors. This discrepancy may be a reflection of the current renovation policy, which seems to be biased towards stimulating demand.

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Conci and Schneider criticize renovation strategies that only incrementally increase energy renovations and propose that local renewable energy production within districts can result in a reduction of at least 30 % in primary energy consumption [8]. While local carbon-neutral energy production is crucial for achieving a carbon-neutral future, deep renovations of buildings at the necessary pace are essential for a sustainable building stock.

Energy performance is just one of the seven essential requirements [9] set for buildings and building products. Older buildings constructed during the post-World War II construction boom have reached the end of their designed service life. Therefore, building renovation is necessary not only to improve energy performance and minimize emissions but also to ensure good living quality and working conditions. Simultaneously improving energy performance makes the renovation process more economically viable and reduces the use of natural resources.

The literature suggests two major supply-based strategies to increase the speed and volume of energy renovations. The first strategy involves replacing time-consuming on-site renovations with off-site renovations using prefabricated insulation elements [10–13]. The second strategy involves moving beyond individual building projects and implementing serial renovations by aggregating several buildings within the same time frame and proximity [8,14–17]. In this paper, we will refer to both strategies collectively as **mass-renovation**.

The initial report on the renovation strategies of EU member states does not include the concept of mass renovation when assessing strategies among selected EU countries [18]. However, this does not imply that members have not addressed this issue. BPIE's second report [19], which evaluates the first iteration of national long-term renovation strategies (LTRS), also does not specifically focus on mass renovations. Nevertheless, some LTRS documents do mention the concept of mass renovation. This raises the question of how EU member states have tackled emerging technological and strategic challenges.

Although several methods of mass renovation have already been tested and piloted, there is still a lack of knowledge regarding the challenges and incentives for the supply side to simultaneously adopt prefabrication and district-based renovations.

Therefore, our main aim is to study how EU member states have addressed emerging technologies and strategies to increase the pace of renovations, which are crucial for achieving a carbon-neutral economy. Our second aim is to explain the necessary preconditions for adopting and scaling up mass renovations for residential multi-family buildings, particularly in large housing districts.

To address these research questions, we analyse the barriers, triggers, and enablers within the supply side of renovations, with a focus on construction companies, designers, and consultants. We use Estonia as a case study to illustrate the challenges and review existing literature to demonstrate how these challenges have been addressed in renovation policy among EU member states.

The article is organized as follows: Chapter 2 provides an overview of the state of prefabrication and district-based renovation in Europe. Chapter 3 explains the methodology of our empirical study. The results are then presented in Chapter 4, followed by a discussion of the findings in Chapter 5. Finally, Chapter 6 presents our conclusions.

2. From mass-construction to mass-renovation

2.1. Prefabrication in renovation

Using prefabrication in residential renovations has already been recognised [20] and several pilot projects are already implemented. One of the first largest collaboration in the field of prefabricated renovation was in the frame of International Energy Agency's Energy in Buildings and Communities Programme (IEA-EBC) Annex 50 'Prefabricated Systems for Low Energy Renovation of Residential Buildings' in 2006–2011 [21]. The project was concentrated on typical apartment buildings and was focused on energy efficiency and comfort in buildings, optimisation of construction and cost efficiency of prefabrication.

In 2008–2009, Finnish researchers worked together with German and Norwegian partners on a research project entitled "Wood-based element systems for improving the energy efficiency of building exteriors (TES energy facade)" [22]. In Sweden, " Technology Procurement of Rational Insulation of External Walls and Facades of Existing Apartment Buildings" project was started because there was a need for the development of rational solutions for improved energy performance of the building envelope, primarily walls, designed for energy efficiency of existing buildings [23]. The EU Horizon2020 project E2ReBuild in 2011–2014 aimed to enhance energy-efficient retrofit strategies that add value to existing apartment buildings and that minimises technical and social disturbance for tenants and facilitates energy efficient operation and use of the buildings including encouraging energy efficient behaviour [24]. The EU Horizon2020 project 'MORE-CONNECT' was realised in 2015–2019 to develop energy efficiency, hygrothermal performance and aesthetics of buildings and demonstrate technologies of prefabricated modular renovation elements, including the prefab integration of multifunctional components, e.g. for climate control [25]. The DRIVE 0 concept is based on the development of circular deep renovation solutions, where prefabrication and demountability are key factors for success [26]. In oPEN Lab project the assembly of prefabricated façade elements will be developed for high-rise buildings in city of Tartu, Estonia [27].

The largest innovation initiative in Europe must be Energiesprong which has delivered almost 6000 net-zero energy houses by industrialised renovation in Netherlands (5700), UK (130), Germany (68), France (26) and Italy (5) [28]. According to Energiesprong website, majority of project have been so far smaller terraced houses. Arguably Netherlands has some larger multi-family buildings also in pilot phases.

Despite several ambitious and successful projects, prefabrication is still within first phases of innovation adoption. According to the theory of innovation diffusion [29], we can argue that even Energiesprong countries are just passing the phase of innovators (Fig. 1). This means that demand is mostly unaware of the prefabrication method and early adopters take risks in technological failures which are partly mitigated by incentive programmes. Fig. 1also illustrates how prefab market phases relate to product life-cycles. This means that Netherlands is the only country currently which is closing fast to niche market phase and belongs also to growth phase in product development scale.

2.2. District-based renovation (DBR)

The idea of revitalising built environment based on one or several neighbourhoods is not new [30]. In fact, it is a fundamental principle of urban planning and development to address a district as a unified system and plan accordingly. However, it appears that **energy policy, which influences the investments for buildings today more than ever before, is mostly missing such district concept**. This ignorance might be due to the fact that energy specialists and spatial planners traditionally have different backgrounds, and energy experts have had little desire to influence planners and designers. However, this stance has changed in light of the goals of climate change, as well as the opportunity presented by aging housing stock in need of energy conservation [31,32].

While the potential for energy conservation in residential buildings is significant [33] and policy demands tangible results [1], energy policy experts have primarily focused on large-scale market interventions to promote building renovations. Their pragmatic approach prioritizes the energy performance of individual buildings, rather than considering the revitalisation of entire neighbourhoods.

Consequently, the market intervention system, which is largely based on such assumptions, provides incentives for individual buildings that meet their energy conservation targets, regardless of their location within a neighbourhood or the overall neighbourhood context [34].

This market intervention policy has resulted in more energy-efficient

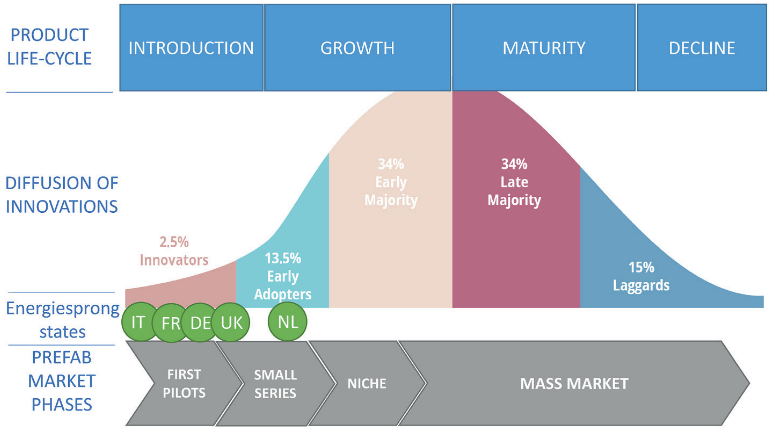

Fig. 1. Renovation market development phases and adoption of demand in Energiesprong initiative. *Figure based on* [28,29].

buildings compared to a scenario without intervention [35]. However, building-based approach could also result in spatially scattered renovations of such buildings which have demonstrated larger financial capacity and leadership to overcome renovation complexities.

This means that between single lighthouses there could be many deteriorating buildings. While the goals of energy performance and building modernisations have been met in those individual buildings, the neighbourhood still needs revitalisation.

Recently the idea of district-based renovation has been gathering momentum. For example, IEA-EBC has produced analysis of DBR within their project of Annex-75 [36]. The value of Annex-75 project is the development of cost-based approach and presentations of international case studies [15].

The second similar but more specific development that includes the concept of DBR is the framework for Positive Energy Districts (PED). This concept has myriad of terminologies used throughout scientific literature and research projects [37]. It is also referred to as Positive Energy Blocks (PEB) and Positive Energy Districts (PED). Despite the existence of several conceptual frameworks of PED [38], the main idea is to view a district as an integrated energy system that emphasizes the distribution of renewable energy among highly energy-efficient buildings the main idea is to view a district as an integrated energy system that emphasizes the distribution of renewable energy among highly energy-efficient buildings.

Therefore, PEN is currently considered the most effective framework for promoting flexibility in energy efficiency goals among buildings within a district. This means that certain buildings, especially those with cultural or heritage value, may have less ambitious energy efficiency targets, while others strive for higher levels of efficiency, ultimately resulting in a carbon-neutral district as a whole.

In conclusion, DBR offers several significant advantages over the traditional approach of focusing on individual buildings. For instance, the concentration of energy demands in a specific area presents opportunities for wholesale principles and reduced costs. Neighbourhood-level renovation projects can also address the enhancement of public spaces between upgraded buildings. Additionally, the increased volume of construction turnover may generate interest in renovations among large general contractors, who have primarily focused on new builds until now.

Therefore, it is reasonable to suggest that DBR can contribute to an accelerated pace of much-needed renovations [17], a higher volume of renovations, and the addition of spatial quality [39], all while maintaining affordable construction prices.

3. Methodology

3.1. Methodological framework

To answer proposed research questions, we apply two distinctive research methods of data collection and analysis:

(1) Content analysis of documents prepared by EU member states regarding renovation strategies and action plans;
(2) In-depth interviews with the key representatives of the renovation supply side.

The variety of methods is needed to capture more insights about the nature and solutions to mass-renovation development. We apply the triangulation of methods which will lead us to observe the phenomenon form several sides and confirm results which are difficult to measure otherwise [39].

3.2. Research method: content analysis

The first method used in our study is content analysis of documents prepared by EU member states regarding their renovation strategies. The main objective of this method is to determine how the concept of mass-construction is addressed in key plans that will play a significant role in achieving carbon neutrality. Additionally, we aim to identify the experiences that member states already possess in this area.

To achieve this goal, we focus on reviewing national long-term renovation strategies (LTRS), which were first mandated by the Energy Efficiency Directive in 2012 [32]. Specifically, we analyse the most recent (third) iteration of these strategies, which were prepared in 2020 by EU member states and regions ($n = 29$). These LTRS documents in English can be accessed on the European Commission's website [40].

We apply contextual extraction of content to all the documents in the sample. Since mass renovation is not yet widely adopted, the specific semantics and terminology used to describe the idea, plans, and experience may not be explicitly stated in LTRS. Therefore, we search for different markers that could indicate concepts, policies, or practices related to mass renovation. The keywords we use include: mass (-construction, -retrofit, -renovation); scale up; cluster; aggregation; neighbourhood; district; prefabrication; offsite; serial; module; component.

Next, we proceed to classify the documents based on the content they contain. We categorize them according to the level of ambition and implementation of mass renovation. We propose five classes:

(1) Mass-renovation is unmarked or irrelevant – there are no references to mass-renovations such as offsite prefabrications and concepts of district approach or the keywords are irrelevant to renovation scale-up and mass-renovation.
(2) Concepts of mass-renovations are recognised superficially.
(3) Concepts of mass-renovation are recognised as a solution for scale up and theoretical benefits are introduced.
(4) Mass-renovation is addressed explicitly as a general aim in LTRS to boost the volume and speed of renovations.
(5) Specific action plan for adopting mass-renovation is described in LTRS.

After quantifying and classifying the documents, we closely examine all the documents belonging to classes three to five to gain a comprehensive understanding of current approaches to mass renovation. We extract relevant content, describe it, and make comparisons.

3.3. Research method: in-depth interviews

We conduct in-depth interviews with the key representatives of the renovation supply side. With this method, the main aim of is to understand how mass-renovation is addressed and experienced among stakeholders that deliver new builds and renovations. We use purposive criterion sampling to include most relevant stakeholders.

The sample includes general construction contractors (n = 5), technical designers (n = 2), consultants for renovations (n = 5), prefabricators (n = 2). Additionally, we have group interviews with Association of Construction Entrepreneurs (E.A.C.E) (n = 1) and Association of Architectural and Consulting Engineering Companies (EAACEC) (n = 1) in Estonia to sense the collective interpretation of statements by service providers.

All the interviews are prepared as in-depth interviews and performed using semi structured interview base. The interviews are based on the structure presented in Appendix A.

All the talks were conducted via virtual meetings. Interviews were recorded, and data processing were disclosed to all participants prior to any interview. Small sample is compensated by comprehensiveness of the one-on-one interviews that lasted about 2 h each.

Next, we prepared full transcriptions of interviews using automatic speech recognition software [41].

Transcripts were used with thematic analysis method to extract themes that are related to research questions and provide new knowledge.

For the interpretation of the main results, we additionally relied on insights gathered from the ongoing Horizon2020 project "oPEN Lab" (see openlabproject. eu and [27] for more information). This project aims to pilot DBR with the ambition to achieving a positive energy balance in multi-family buildings on an annual basis.

Our participant observation techniques provided additional confidence in interpreting the transcripts of the interviews. Our observational targets were (1) residents in organized events like general meetings, workshops and information briefings; and (2) representatives of local government in work meetings. We used personal notes for storing observational data. In addition, we had access of unpublished survey of the residents in pilot area of oPEN Lab project. The purpose of the survey was to evaluate the perception towards renovations including also DBR. Survey data collection was concluded in January 2022. The incorporation of supplementary data sources, alongside the interviews, facilitated our interpretation of the findings and the formulation of recommendations.

3.4. Case of Estonia

Estonia serves as a useful case study for analysing mass-renovation due to its significant stock of mass-produced multi-family buildings, which currently house approximately 70 % of the population. These apartment buildings were primarily built between 1950 and 1995, similar to the building stock in other European countries. During this time, the use of wood in constructing residential multi-family buildings ceased as industrialised construction methods became more prevalent. The main types of construction during this period were concrete large panel, brick, and lightweight large block.

Another Soviet legacy was the creation of large housing estates (areas of several dozens of mass-constructed apartment buildings) which were planned as neighbourhoods or "micro-regions" as they were called at the time. Today, these neighbourhoods could serve as testbeds for district-based renovations, where multiple multi-family buildings could be renovated simultaneously.

After regaining independence in 1992, Estonia soon abandoned state-based mass-construction practices, and the private sector began employing modern approaches in residential construction. Nonetheless, some unfinished projects were completed after the collapse of the Soviet Union. The construction of apartment buildings transitioned from a neighbourhood scale to a single-building scale. Minimum energy performance requirements for buildings were implemented in 2007 and have become more stringent every five years. Therefore, buildings constructed between 1990 and 2010 also need to be renovated to meet current energy performance and emission production standards.

The governance of residential renovations in Estonia operates through a simple and robust system (see Fig. 2). The central government's role is to incentivize demand by providing grants and mitigating market barriers in weaker regions through guarantees and loans. Local governments issue construction permits but have limited influence over the renovation of residential buildings.

Most of the intervention in the renovation supply comes through regulation and compliance checks. The supply is not stimulated to the same extent as the demand, although there are still opportunities for innovation.

Demand is also stimulated by local governments through initiatives such as offering grants for the renovation of heritage buildings. However, it is important to note that the impact of these local government programs is relatively small when compared to the programs implemented by the central government.

3.5. Research limitations

There are three significant limitations that we can identify. Firstly, qualitative data is not as generalizable as quantitative studies. However, the key stakeholders in our sample are representative of the Estonian

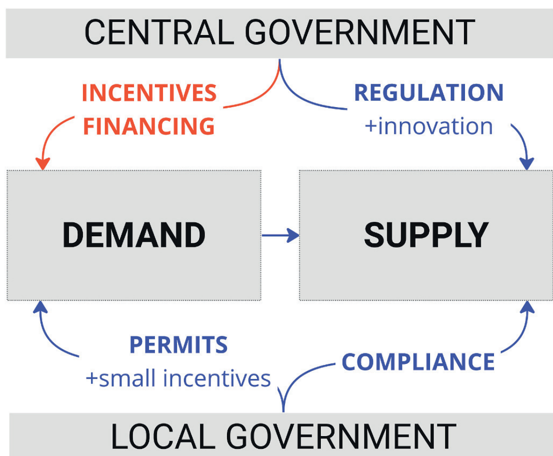

Fig. 2. Governing residential renovation demand and supply in Estonia.

case and provide significant value at both the local and international levels. Our methodology can be applied elsewhere to examine the local themes that different contexts present.

Secondly, relying solely on LTRS analysis might give us a somewhat biased view of mass-renovation adoption in the EU. We acknowledge that while mass-renovation may not be explicitly mentioned in the LRTS of a specific country, there might still be ongoing pilots and testbeds. Although this is a valid point, we believe that only a specific strategic action plan will lead to effective and efficient results in systemic climate change mitigation.

Thirdly, our approach, which focuses on the supply side of renovations, has excluded formal data from the demand side and local governments. This may have resulted in less comprehensive study results. However, the mass-renovation approach is relatively new for all participants and market regulators. While prefab construction is slowly gaining momentum in Estonia, DBR is still being debated and conceptualized as an innovation. On the other hand, prefabricators have been producing building elements for export markets for a decade. Therefore, the supply side possesses the most comprehensive experience with mass-renovation adoption and can provide insights from the perspectives of regulators and demand as well.

By drawing on our extensive experience of working with governments and communities, we can confirm that interviews with the supply side adequately reflect the perceptions of the demand side and the government. Considering the innovative nature of mass-renovation concepts, we can argue that sampling and data collection from residents and governments would not have added extra value to the proposed research objectives.

4. Results

4.1. Evidence of mass-renovation plans among EU member states

During the literature review and interviews, we identified three main factors for increasing the speed and volume of renovations:

(1) Initiatives to scale up renovations from individual buildings to district or neighbourhood level.
(2) Technological change and the adoption of construction innovations, particularly prefabrication and automation.
(3) Research and development priorities and investment plans for advancing mass renovations.

The 2020 edition of national long-term renovation strategies (LTRS) among EU member states reveals few examples of mass renovation initiatives or future plans. Table 1 shows how EU member states address mass renovation in terms of five categories that represent the ambition and implementation of mass renovation concepts.

Although most countries have not included relevant mass renovation concepts in their long-term renovation strategies, there are some positive exceptions, such as Germany, the Netherlands, and two regions of Belgium.

Flanders, Croatia, Finland, Hungary, and Latvia have discussed the theoretical benefits of deep building renovation (DBR), but they lack a clear purpose statement and specific action plan.

The LTRS of Belgium's Wallonia and Brussels region demonstrate the most advanced approach to mass renovations, as they have an action plan for implementing their goals. Other countries can learn from their overall structure of the action plan. However, it is important to note that the action plan includes only a limited number of activities, which may not be sufficient to achieve a significant increase in renovation delivery.

The emphasis on prefabrication and industrialisation of renovations, in general, is less pronounced than DBR concepts. Good examples in this area come from Germany and the Netherlands, although both countries still lack a specific action plan for industrialisation in their LTRS.

While Estonia has already implemented some initial pilots and has ongoing small-series prefab pilots, their national LTRS only describes the theoretical benefits of mass renovations and lacks clear goals for the industrialisation of renovation methods.

The Netherlands has clearly outlined a path towards industrialised renovations, recognizing the need to significantly increase the efficiency of construction methods. Prefabrication is considered a viable method for the future. However, DBR is only mentioned in relation to transitioning away from natural gas as an energy source. The energy transition will be led by local governments and based on rational spatial units, such as districts.

Table 2
Opportunities to significantly conserve time for several large-scale works using prefabrication.

Time savings	No change in time usage
Insulation works	Restore internal finishing
Installation of windows	Renewal of staircase and basement
Finishing the facade	Installation of new heating system
Installation of ventilation ducts	Renewal of electricity system

Table 1
Mass-renovation statements in national long-term renovation strategies among EU member states.

	Mass-renovation levels	Concept	AT	BE-B	BE-W	BE-F	BG	HR	CY	CZ	DK	EE	FI	FR	DE	EL	HU	IE	IT	LV	LT	LU	MT	NL	PL	PT	RO	SK	SL	ES	SE
1	Related keywords to mass-renovation are unmarked or are irrelevant to scale up	PREFAB		○		○	○	○	○	○	○		○	○		○	○	○	○		○	○	○			○	○	○	○	○	○
		DBR					□		□	□	□	□		□	□	□		□	□	□	□	□	□		□	□	□	□	□	□	□
2	Mass-renovation is recognised superficially	PREFAB	○		○																				○						
		DBR	□																					□							
3	Mass-renovation is recognised as a solution for scale up and theoretical benefits are introduced	PREFAB																													
		DBR				□		□					□				□			□											
4	Mass-renovation is addressed explicitly as one aim in LTRS	PREFAB													○									○							
		DBR																													
5	Specific action plan for adopting mass-renovation is described	PREFAB																													
		DBR		□	□																										

○ Prefabrication ; □ District based renovation ; BE-B Brussels region; BE-W Wallonia region; BE-F Flanders region

While it appears that the LTRS review has shown modest results, we would like to emphasize that the absence of concrete action plans among EU members strongly suggests that large-scale renovations are not yet acknowledged as significant means to accelerate the pace of renovation. However, this implies that we need to examine more closely those examples that are already displaying ambitions in large-scale renovations. Although our findings are based on the sources of LTRS, it is possible that there may be ongoing experimental projects that have not yet been reported by the LTRS.

4.2. Reflections for upscaling renovations by local supply chain stakeholders in Estonia

4.2.1. Towards prefabricated renovation of apartment buildings

Currently, the renovation supply in Estonia is primarily controlled by a few companies. Approximately 20% of renovation firms are responsible for 80% of all renovations. Interestingly, the larger construction companies are not involved in the residential building renovation market. Instead, they focus exclusively on new builds.

Interviews have identified eight key factors that hinder the growth of renovation volume:

(1) Inconsistent demand due to fluctuating renovation grant calls. Major deep energy renovations are costly, and state grants are the only viable means to reduce prices and stimulate demand.
(2) Contractors who specialise in new builds find renovations to be technically complex in comparison. Renovations are seen as uncertain, whereas new builds can be meticulously planned. Furthermore, contractors who focus on new builds are not enthusiastic about working in occupied dwellings during the construction process. Managing residents can be complicated and troublesome due to their lack of experience in renovations.
(3) “Bad players” who undercut prices during renovation bidding. The regulations and quality requirements for renovations are not as strict as those for new builds. Consequently, opportunistic bidders are more inclined to take chances. This behaviour is disliked by both larger renovation firms and contractors specializing in new builds.
(4) Low productivity within the supply chain. Despite mass construction, the variation in demand requirements and the small market have prevented a concentrated focus on a few typical buildings.
(5) Onsite construction technology is time-consuming and relies heavily on expensive handcraft. Therefore, increasing production volume requires a corresponding increase in the workforce, which may not be a feasible solution for all types of renovation works.
(6) There is an insufficient number of qualified workers entering the construction sector labor market.
(7) Compared to other sectors, the construction industry is not attractive enough for young people considering careers as builders or engineers. Moreover, engineering studies are often perceived as challenging.
(8) Renovation demand is dispersed geographically. Concentrated demand within specific city districts or neighborhoods could significantly boost construction productivity, particularly for general contractors. Small settlements struggle to attract contractors for individual buildings, rendering their efforts in preparing for renovations futile. The use of DBR could help mitigate such market barriers.

4.2.2. Renovation volume growth: practitioners explain

Three major themes which are considered most significant by supply side practitioners are discussed next.

First and foremost, the most significant theme is the inconsistent demand for renovation due to the fluctuating availability of renovation grants. In times of economic uncertainty, designers and contractors are reluctant to expand their workforce or invest in new innovative technologies to enhance design productivity or construction output. Instead, they prefer to manage the increasing demand using their existing resources.

Contractors are practical and believe in market-based solutions, even in the context of renovation. This means that if demand steadily grows, supply will catch up and offer new solutions to improve productivity. Contractors are also confident that renovation prices will not surpass the general inflation rate. Their past experiences have shown that as demand increases significantly, competition grows rapidly. This leads to higher margins for subcontractors and lower margins for general contractors. Consequently, overall renovation expenses will not increase proportionally to the growth in demand.

The market principle also applies to Estonian material producers, who primarily focus on exporting their goods today. These producers highlight the weak demand in the Estonian market, which restricts them from redirecting their products for local consumption, as they are legally obligated to fulfill export contracts.

However, if the market demonstrates a consistent and new demand for building materials, producers are willing to adapt and provide their products for the local market instead.

The second emphasized theme examines the shortage of larger contractors in the renovation market. Interviews indicate that bigger companies are not enthusiastic about undertaking renovation projects due to their complexity and reputation. Instead, they prefer to focus on new builds. While it is true that renovations are more complex than new builds, it is possible that construction managers are also hesitant due to their lack of direct experience in renovations. Large companies argue that the volume of average renovation projects is not sufficient in terms of turnover, and instead propose large-scale renovation campaigns that encompass entire neighbourhoods.

Large companies are also hindered by smaller renovation firms that do not implement high-quality management systems. As a result, these smaller companies succeed in winning contracts by offering the lowest bid. This issue extends beyond simply offering low prices; it also affects the reputation of renovation works.

There are currently few quality and safety requirements for companies to participate in renovation procurement. This has allowed small companies to win contracts even though they have not implemented any safety assurance systems. It is possible for a company to gain the legitimate right to operate in the construction industry by purchasing it from another company, without having the necessary systems and staff directly responsible for safety or quality. Larger construction companies find this situation unacceptable, as quality is something they value and advocate for.

If renovation procurements do not include the same quality and safety standards for contractors as new builds do, larger companies will not be interested in competing with so-called one-man companies. Therefore, if there is sufficient demand for new builds and if quality management is not required in renovation procurements, larger construction companies will refrain from entering the renovation market.

The third theme is technological. Currently, the method of renovation being used is onsite construction, which is a time-consuming and resource-intensive process. Contractors believe that it may be possible to speed up onsite construction by adding more lifting mechanisms, but this would also increase the overall costs of renovation. Given the constraint of relying solely on onsite technology, the only solution to increase the volume of renovation is to increase the workforce in proportion. However, this is not a feasible solution for a small country like Estonia, especially in the context of the EU Green Deal, which could result in labor shortages throughout Europe. Therefore, it is clear that there is an urgent need for technological change towards the prefabrication of renovation elements in order to improve the efficiency of current resource utilisation.

4.2.3. Prefab mainstreaming barriers

One specific topic discussed in the interviews was how to integrate prefabrication into the mainstream. Although there have been various successful prefab pilots implemented in Europe [21,42,43], the pace of renovation will only gain momentum if offsite methods become more prevalent. The following are significant factors identified by supply-side prefabrication that contribute to mainstreaming:

(1) Prefab technology requires more initial investment for the factory and is generally more expensive when done on a single-project basis compared to its onsite counterpart. This is mainly due to the early market stage and lack of economies of scale. As a result, solutions need to be tailored for each new project, and there is a lack of automation in offsite production.
(2) There is low demand and a lack of knowledge on the client side, primarily because they are unaware of alternative methods to traditional onsite construction. Clients are naturally hesitant to be early adopters of technology that has not yet demonstrated long-term performance.
(3) The supply chain is accustomed to traditional methods, and designers are comfortable working within the confines of traditional onsite construction. The business models and workflows of general contractors have also been developed for onsite construction.
(4) There is a lack of significant public landmark projects and promotion of novel methods, which could help reduce uncertainty surrounding these unfamiliar approaches.
(5) The complexity of new methods is a challenge. More precision is required in designing and installing prefabricated elements. While existing buildings are often mass-produced, there are considerable variations between buildings of the same type. In fact, even within a single building, there can be variations between staircases.
(6) The shortage of prefab suppliers hinders the adoption process and slows down progress.
(7) There is a contradiction in the leadership of renovation projects between general contractors and prefabricators. While prefabricators aspire to become general contractors, they often lack the knowledge and experience in managing residents and subcontractors who carry out onsite work.

4.2.4. District-based renovation barriers

Renovation of multiple buildings, and even entire districts, seems like a logical course of action in areas where large-scale construction of residential buildings took place after WWII and now require urgent revitalisation. However, respondents to our survey have identified several obstacles that hinder the wider implementation of district-based renovations (DBR):

(1) Lack of a national strategy for DBR. While there are ideas and even test projects for DBR in Estonia, there is no general strategy or specific plan to prioritize DBR.
(2) The state government still relies on individual financial grants to support individual renovation projects in order to achieve carbon neutrality. This approach has been convenient and efficient for resource management. Furthermore, a clear central policy is seen as just and corruption-free.
(3) Lack of a practical local action plan for DBR. For example, the Municipality of Tartu has the ambition for DBR but lacks a specific written action plan on how to put this ambition into practice. There is also no common understanding of the appropriate district size for DBR.
(4) The municipality has not allocated significant resources to initiate DBR. This is mainly due to a lack of understanding about the multiple benefits of DBR.
(5) Unclear and indirect benefits that would encourage demand for DBR. DBR requires a significant effort from the local community to initiate the process. However, such efforts are rare, and we cannot expect much grassroots support until there are more success stories about DBR.
(6) Unclear evidence on whether residents benefit from lower "wholesale" prices of DBR. While there is a theoretical financial benefit to bulk demand, it is difficult to measure actual cost savings for investments.
(7) Increased complexity and challenges for demand in organizing DBR with cooperation among neighbourhood houses. Leaders of housing associations already face difficulties in changing the mindset of residents and initiating renovations in their own buildings.

4.2.5. Multi-benefits and risks of mass-renovations

While DBR and prefabrication can be considered individually, the greatest impact on renovation productivity and quality is achieved when both concepts are adopted simultaneously. While there are multiple benefits for the local community and broader opportunities for society, we must also take into account potential risks and barriers. Based on our empirical findings, we have presented these topics collectively in Fig. 3 to provide a more comprehensive overview.

Although the specific economic aspects of mass renovation were not our original empirical intention, we still gained some valuable insights from the interviews. The most intriguing insight was the idea that higher prefab renovation costs could be offset by lower unit costs resulting from concurrent renovation of several buildings within a neighbourhood. This idea combines prefab and DBR, two distinctive concepts that are usually addressed separately, and empowers them with economic incentive. We therefore call for a detailed economic analysis of concurrent prefab renovations to establish cost-effective levels in terms of floorspace volume within a neighbourhood.

In terms of gaining momentum in much-needed renovation volume and pace, prefab has the potential to make a significant contribution. Our prefab respondents described time savings on the building site as the most significant changes in the renovation process compared to onsite counterparts. However, there is a knowledge gap between understanding the rational time savings and conducting a detailed analysis of how the conserved time influences the renovation supply capacity. Table 2 presents an example list of works related to time conservation in prefab. The list is compiled from the answers of the respondents and is not conclusive. Evidently, some works still take the usual amount of time regardless of the innovation of prefabricaton. Therefore, we call for a detailed analysis of time conservation in prefab compared to traditional onsite renovations. Such an analysis could indicate the potential growth of renovation volume without a significant increase in the workforce.

5. Discussion and policy implications

The Estonian renovation support system is robust and efficient in managing single renovations (Fig. 2). However, the adoption of mass renovation may not align well with this system, as the role of municipalities are limited. This is particularly true for DBR, which requires significant initiation and influence from municipalities. On the other hand, prefab can be effectively adopted within the current support system.

We observe that district-based urban developments need a coordinator who can bring together all the stakeholders within the district. However, privately owned buildings in residential neighborhoods have not had such a catalyst to encourage collaboration towards a common goal. This is especially evident in large housing estates, which encompass a diverse community that lacks a unified interest and mainly focuses on their own private space within the larger building complex. This finding supports what was reported in Ref. [44].

The most suitable candidate for this coordinating role would be the local municipality, which has authority over spatial planning (Fig. 4). Municipalities should also possess the necessary expertise to govern

	PREFABRICATION (PREFAB)	DISTRICT BASED RENOV. (DBR)
MULTI-BENEFITS FOR LOCAL COMMUNITY	Lower energy consumption. Higher quality of construction. More comprehensive and well-thought-out design Muck quicker renovation process lower disturbances Higer construction site safety level. Better integration of technical systems	Lower unit costs for renovation. Added functional public space and mobility Holistically designed neighbourhood. Potential to offset higher cost of prefab. Contribution to community development. Increased safety and property value.
OPORTUNITIES FOR SOCIETY	Lower carbon emissions. Increased pace and volume of renovations. Opportunities for exporting the products. Wider adoption brings costs down. Lower rate of industrial accidents. Circularity promotes environmental sustainability.	Interest for larger contractors and architects. Good examples promote next projects. Improved public spaces and mobility. Renders old residential districts more desirable. Involvement of other parties within the district. Reason to initiate of advanced one-stop-shops.
RISKS OF ADOPTION	Prefabrication has limitations in design and could also promote boring aesthetics. Possible shortcomings might not have emerged. Low demand due to fluctuating incentives	More complex projects entail the risk of failure. Materialized risk influences many buildings. Overall design failure is more eminent. Superficial governance leads to dissatisfaction.
BARRIERS OF ADOPTION	Higher costs compared to onsite renovation now Early adopters phase has too few examples. Low volume of prefab lacks automation	Local authority lacks experience in DBR. Difficult to find early adopters. Local community has low capacity to initiate DBR Mobilising local community is challenging. Higher investments costs due to outdoor facilities. Difficult to adopt if some buildings are renovated

Fig. 3. Multi-benefits, opportunities, risks, and barriers of adopting mass-renovation strategies.

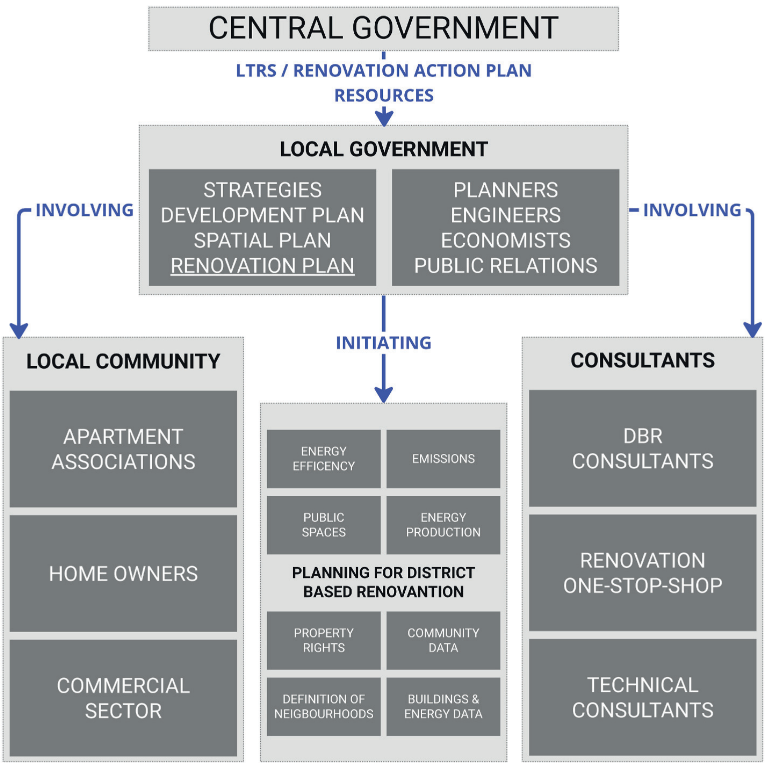

Fig. 4. Implementing DBR – top-down approach.

DBR. Unfortunately, this may not be the case in smaller and remote municipalities, where tasks are fragmented among a few municipality officials.

Following the top-down model shown in Fig. 4, it becomes evident that even well-equipped municipalities require empowerment from the central government. This means that the local DBR planning and implementation process necessitates the provision of necessary authority, instructions, and resources from the central government.

Without additional resources form central government, more capable municipalities can take the initiative and utilize the expertise and experience of their spatial planning divisions to initiate DBR projects. The first notion we point out is the fact that DBR is just another real estate development project which has no significant business case and is located in district of low public interest. Both characteristics indicate that such projects are unlikely to be interesting for municipality architects or planners. This means that DBR requires specific pressure, objective, plan, and effort to reach the priority agenda. Based on in the experience of participant observation in oPEN Lab project [27], we suggest municipalities to start defining and mapping neighbourhoods which are the planning units of DBR. This in turn determines the list of local community members that need to be involved (see Fig. 4left column).

Involving private consultants for DPR could lead to the initiation of DBR by the private sector in the future. One of the best candidates for such private leadership could be one-stop-shops (OSS) for renovations. It is argued that this is because OSSs inherently have the ability to offer integrated solutions [45]. However, adoption of DBR requires many other skills which traditional renovations OSSs are unlikely to possess. Much of the skillset is related to spatial planning and governance which are core properties of a municipality. So close cooperation between OSS and local municipality is expected. Future initiations of DBR could also emerge from local community assuming the DBR has been implemented and practiced with success already. Unlikely, but the best chance to initiate DBR form grassroot level have local settlement societies that focus on the development of their home district.

While Estonia has relied on central governing model for residential renovations, other EU states have already established a much stronger influence of municipalities. For example, in Bucharest, Romania, the municipality strongly influences renovation by providing additional grants in addition to those offered by the central government (up to 90 % of total renovation costs) in exchange for selecting the buildings to be renovated [46]. We must stress again that adoption of DBR requires significant effort from municipalities. We therefore suggest for states that have similar governance model like in Estonia to invest renovation capacity building of municipalities.

It is evident that DBR enables more flexible planning for carbon neutrality. For example, within one neighbourhood, some buildings could prioritize energy efficiency at the expense of others. This approach could help address the challenge of renovating heritage buildings, which may not be renovated in an overly ambitious manner or where the solutions are too expensive.

When considering the workforce needed to renovate all the remaining buildings in Estonia, we obtained mixed results. On one hand, most respondents emphasized the need for larger contractors to enter the renovation market. However, large contractors are not interested in competing in an uncertain market where they lack experience.

Clearly, there are limits to increasing the skilled workforce in order to enhance the pace and scale of renovation. The viable alternative is to make substantial investments in industrializing the renovation of buildings and compensate for the shortage of workforce by improved efficiency of the prefabrication. Despite the lack of specific evidence now, we already observe that industrialised renovations' higher costs could be offset by the volume of DBR.

Regarding future work, we can stress that the uncertainty regarding material availability and restrictions on labour movement due to the Corona pandemic has escalated to a new level as a result of the Russian invasion of Ukraine. Disrupted supply chains may lead to even more severe shortages of construction materials, which could particularly hinder building renovations.

Furthermore, the potential implications of the war crisis could also impede financing for renovations, given the likely progression of inflation that may peak during the next financial crisis. Both scenarios disrupt the much-needed consistent demand for mass-renovation and setback the progress being made in innovation diffusion.

Evidently majority of EU member states have not addressed mass-renovation in their strategies. However, this finding is significant and indicates that mass-renovation has not yet been recognised as a useful tool for addressing the volume and pace of renovations. Therefore, we strongly recommend that future versions of renovation strategies include specific action plans for implementing mass-renovation approaches. These action plans should also incorporate an analysis of building typology and locations. Prefabrication can be effectively applied to buildings that are mass-produced and have relatively simple designs. Location analysis can further identify areas where similar building typologies are constructed in close proximity. This makes the calculations of mass-construction potential possible.

6. Conclusions

The starting point of this article was the observation that mass-constructed residential buildings are most suitable for mass-renovations. These renovations, which involve offsite prefabricated serial renovation on a district or neighbourhood level, have the potential to greatly increase the pace of much-needed renovations. Additionally, mass-renovations can provide consistent quality assurance and reliable energy conservation targets, contributing to the goal of achieving carbon neutrality.

Our study reveals that mass-renovations are adding complexity to existing renovation barriers. It is clear that areas already struggling with renovation difficulties using onsite construction models for single buildings may not fully realize the benefits of mass-renovation. Mass-renovation is a relatively new practice, and even housing associations with fewer renovation barriers approach it with caution.

Unsurprisingly, the supply side often attributes the difficulties in adopting mass-renovation to a lack of consistent demand for such solutions and services. While this argument has some validity, consistent demand can only emerge when there is a supply, positive examples, and performance validations. Furthermore, the benefits of new technology must be easily understood to facilitate adoption. Otherwise, the adoption of change will be limited to innovation projects, unnecessarily prolonging the phase of early adopters.

We observe that the industry needs more standardized technical solutions, practices, and delivery chains to scale up prefabrication and reduce costs. Currently, the demand is low and unaware, while the industry remains cautious. Smaller contractors struggle to manage multiple concurrent renovations within a neighbourhood, and larger contractors do not see collective demand.

The results indicate that the majority of EU member states have not addressed mass-renovation in their strategies. Therefore, to facilitate energy policy development, we suggest incorporating mass-renovation conceptualizations and specific action plans into national renovation strategies or action plans. This approach will empower market participants and regulators with clear objectives needed to accelerate the pace of residential renovations.

The adoption of mass-renovations in practice requires municipalities to adapt the objective of mass-renovations also into the local renovation action plan. If such a plan is missing, it must be established.

While prefabrication aligns with current renovation governance models, this is not the case with DBR, which requires a significant shift towards empowering municipalities that are best suited to initiate and lead the DBR. Evidently, the empowerment of municipalities for mass renovations is a priority that central governments must seriously consider. The establishment of one-stop-shops should also be considered. This could transfer some of the burden of mass renovations from municipalities to the private sector or NGOs.

Although we recommend using both methods of mass renovation to maximize benefits, we acknowledge that each method has specific requirements. For instance, DBR can only be applied when multiple buildings are in close proximity to each other. On the other hand, prefabrications necessitate large, simple, standardized buildings. Consequently, it is essential to evaluate in advance the quantity and locations of buildings and neighborhoods that meet these prerequisites as part of renovation strategies. We particularly stress the significance of considering regions that are experiencing population decline and the abandonment of buildings when conducting these evaluations.

Credit author statement

Lauri Lihtmaa: Conceptualization, Methodology, Data collection, Formal analysis, Writing-Original draft. Targo Kalamees: Original draft preparation, Writing-Reviewing and Editing, Funding acquisition, Supervision.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Large Language Model of ChatGPT version 3.5 in order to improve the clarity and spelling in revision stage of the article. After using this tool, the authors carefully reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

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Data availability

The data that has been used is confidential.

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Appendix A

Coding in content analysis

Prefabrication.

- Prefab
- Serial
- industrial
- offsite/onsite
- Element
- Module
- Component
- Mass
- standardized

District-based renovation.

- District level
- District-oriented
- Neighbourhood
- Grouped renovation
- Collective
- Joint
- Serial renovation
- Aggregation
- Mass
- Group project
- Groupe procurement
- comprehensive neighbourhood regeneration
- Community
- Standardized

Increasing renovation volume.

- Speed
- Volume
- Rate
- Scale up
- Market uptake
- Mainstream
- OSS one-stop-shop
- Mass

Appendix B

Interview structure for construction contractors and prefabricators

Part A. Increasing renovation volume.

What prevents company to increase renovation volumes if there would be significant growth in demand?

To what extent could renovation process be faster if the building was unoccupied?

Why do larger construction companies avoid competing in renovation market?

What is the capacity of construction companies to increase their production volumes?

How and to what extend it is possible to increase productivity of construction company?

What are the most significant renovation barriers in Estonia?

How do significantly increase renovation activities within detached buildings?

How to increase the awareness of apartment associations about the benefits of renovations?

How to mainstream prefabrication in renovations?

Part B. Quality assurance.

How more strict quality criteria in procurement would affect the construction companies access to the renovation market?

If and to what extent it is possible to use professional certificates and prove the qualification of the builders?

How do you evaluate skills if a worked does not have professional certificate?

What kind of quality assurance system you have adopted in case the subcontractors have no certified workers?

What kind of feedback loops there are if the designed solution turns out to ineffective?

Part C. Preventing unwanted outcomes.

Do you see any possible unwanted outcomes that could emerge within the extensive renovation wave?

How would the renovation prices change if the demand for renovations would grow significantly?

Appendix C

Interview structure for construction consultants and designers

Part A. Increasing renovation volume.

What are the significant barriers for increasing the renovations of the apartment buildings?

How to overcome such barriers?

What is your opinion of differentiated renovation grants?

Are there any renovation products that should be banned because of low quality and energy performance?

Have you any experience in consulting homeowners of detached buildings? Why?

How do significantly increase renovation activities?

How likely it is that all the buildings will be energy renovated within next 30 years? Do we have such capacity? What to do?

How to mainstream prefabrication in renovations?

Part B. Quality assurance.

What are the most significant challenges and troublesome activities in your consultation/design work?

What kind of knowledge gaps you would like to fill?

If and to what extent it is possible to increase the productivity of consultants/designer?

What prevents such advancements in productivity?

What kind of digital tools you would need to be more effective and efficient?

What kind public services are needed to be more effective and efficient?

Part C. Preventing unwanted outcomes

Do you see any possible unwanted outcomes that could emerge within the extensive renovation wave?

How would the renovation prices change if the demand for renovations would grow significantly?

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Article IV

Lihtmaa, L., Kalamees, T. 2025. How vacancy of dwellings influences renovation strategies of multifamily buildings. Energies, 18, 603. https://doi.org/10.3390/en18030603

energies

Article

How Vacancy of Dwellings Influences Energy Renovations of Multifamily Buildings

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Abstract: The European climate change mitigation agenda aims to decarbonise all buildings by 2050. However, many existing buildings may not remain operational by this time due to rapid urbanisation and population decline in various regions of Europe, potentially leading to the abandonment of residential properties. The current EU renovation strategies often overlook the future of legacy buildings. The challenge lies in identifying which buildings are likely to become unserviceable and, therefore, unsuitable for significant energy efficiency upgrades. This study proposes the use of domestic consumption metering as a universal vacancy indicator to determine the actual underused dwellings in multifamily buildings. Our case study demonstrates that population registry-based datasets consistently overestimate vacancy rates when compared to the evidence provided by consumption metering data. Consumption-based vacancy rates exceeding 20 percent are associated with an unlikelihood of energy renovations, thereby impeding the aims of the energy efficiency transition. Spatial analysis reveals that vacancy rates increase as the distance from the regional centre to the building grows. This correlation indicates the presence of shrinking hinterlands and highlights the need to consider to what extent such regions should be targeted by incentives for energy renovations. We recommend utilising this vacancy indicator to estimate energy renovation scenarios in policymaking.

Keywords: energy efficiency; electricity consumption; housing vacancy rate; renovation strategy; multifamily buildings

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1. Introduction

The climate change mitigation agenda in the European Union calls for decarbonising all buildings by 2050 [1]. This requires abandoning fossil energy and undertaking deep energy renovations. While commercial renovations can be driven by regulations and public sector commitments, the residential sector poses the biggest challenge. Most residential buildings in Europe were constructed after the post-WWII housing crisis [2], resulting in poor energy performance and urgent renovation needs due to their nearing end of service life.

The current demographic and migration trends accelerate urbanisation and population decline in many European regions [3]. This is particularly evident in Eastern Europe, transitioning from a Soviet-planned agricultural economy. Consequently, residential housing in shrinking regions will likely be abandoned in the coming decades, indicating that such buildings should not be strategic targets for deep energy renovations, as investments would be wasted.

Typically, the market does not support renovations in areas with uncertain futures. Homeowners in declining regions often lack the financial, social, and organisational capacity for significant renovations, and financing from commercial banks in these areas is considered high risk. However, central governments, committed to EU climate goals [4], are expected to intervene in the market to facilitate deep energy renovations. Therefore, targeted intervention, especially for shrinking regions, is crucial in energy policy.

Long-term renovation strategies among EU member states rarely consider the future of legacy buildings. The challenge lies in identifying which buildings are likely to be out of service and thus not suited for major energy efficiency upgrades. Estonia, a small Eastern European country, has attempted to account for building decline in its long-term renovation strategy [5]. However, the method is based on population trajectories but does not consider the actual usage of buildings at the time.

Consequently, there exists a pressing need to evaluate alternative methodologies for vacancy determination to effectively distinguish potential and reasonable energy renovation targets within the building sector.

Residential vacancy can be directly observed by noting signs of neglect or disrepair [6]. This method is particularly applicable to small cases and is more suited to detached houses, which often exhibit clear signs of abandonment. Field surveys may be complemented by analysing photographs of building façades [7], which can also be employed to identify partial vacancy in multifamily buildings. Recent machine learning tool tools can significantly enhance the classification of these images [8]. However, the efficacy of façade image analysis is constrained by the availability and quality of the images. The prediction accuracy of such experiments is also variable; for example, Von Platten et al. report that the accuracy of their algorithm is about 70–90 percent [9]. Furthermore, the variability in the timestamps of the images complicates the comparison of different image capture cycles.

Remote sensing methods, such as measuring nighttime light usage [10], can be valuable in situations where other data sources are unavailable. Combining façade imagery and remote sensing can improve prediction accuracy [11]. However, this approach is still relatively broad and cannot identify the vacancy of individual dwellings within an apartment building.

Ubiquitous occupancy rates of buildings can be derived from population registries, although some alternative attempts have been made also, for example, using tax records for vacancy analysis [12,13]. The data on vacancy for population registries is typically collected in the form of self-declarations by residents. Estonia, along with other EU member states such as Germany, Italy, Spain, and the Netherlands, has made residency registration mandatory. In Estonia, the declaration of residency is strongly encouraged for electoral purposes, among other reasons. Additionally, amenities such as transit subsidies and access to kindergarten placements also necessitate the declaration of a permanent address. However, this requirement may lead individuals to declare an address that differs from their actual residence, thereby skewing the occupancy data of buildings.

Recently, domestic consumption has been adopted as a proxy for observing residential vacancy. Smart metering of water and electricity has enabled non-intrusive occupancy monitoring by offering big data in a variety of resolutions [14–16].

Despite the several methods for evaluating vacancy that have already been described in the literature, there is still little evidence regarding how these methodologies compare to one another, and more importantly, how the actual long-term vacancy influences the energy efficiency aspirations in buildings [17]. This study seeks to address this gap by evaluating consumption-based vacancy against registry-based vacancy patterns, with explicit implications for national energy renovation plans.

To address the aim, we first define consumption-based vacancy indication using the domestic electricity metering data of multifamily buildings, taking into account the consumption in each dwelling unit. The novelty of this study lies in the application of a nationwide dataset in contrast to previous studies that primarily focus on specific geographical regions and sampling [14,18]. Additionally, we possess a comparable vacancy dataset derived from the population registry. This enables us to assert that the method and implementation of domestic consumption smart metering can serve as a universal statewide vacancy indicator that does not yield false positives. Our main observation is that the vacancy rate calculated using the population registry dataset significantly overestimates the vacancy rate when compared to consumption-based data. Regarding climate targets, we demonstrate the relationship between vacancy and deep energy renovations.

The article is organised as follows: Section 2 explains the methodology framework and addresses the complexity of building stock typology along with challenges about consumption-based datasets. The results are then presented in Section 3, followed by a discussion of the findings in Section 4. Finally, Section 5 presents our conclusions.

2. Materials and Methods

2.1. Data Collection, Sampling, and Analysis

2.1.1. Residential Occupational Data and Multifamily Buildings

The main analysis unit is a multifamily building, which is hereafter also referred to as just a building. By the general definition, a multifamily building consists of at least three residential units in Estonia. Hereafter, we use the term apartments and dwellings to refer to residential units. Most of the apartments in Estonia units are owned by residents and therefore are similar to the concept of condominiums in other countries. In every multifamily building, an apartment association is formed to collectively manage a building. The members of the association are the owners of the dwellings or owners of non-residential units if such units are present in a building.

As the occupational data were sourced from Statistics Estonia, the raw dataset was formed by the principle of at least three dwellings in one building. This means that the data also included buildings whose primary use was not residential, but which could have at least three residential units.

For each multifamily building, the following information was available: the total electricity consumption of the building, number of residential units (dwelling), and number of vacant and occupied dwellings according to both electricity usage and the population registry. The total electricity consumption of the building included consumption in dwellings and for building's general electricity consumption as well.

A vacant dwelling is defined as one where the electricity consumption for one year (2019) was less than 100 kWh or if there was no electricity contract associated with the dwelling. In both cases, it can be assumed that no electricity was consumed and therefore, permanent residency is missing in that dwelling. We based our analysis on vacancy data from 2019, as we did not have access to more recent data. However, given the slow nature of vacancy processes, we are confident that the insights remain relevant today. Future studies could aim to collect data from both before and after 2019 to assess trends in vacancies.

The consumption threshold for vacant dwellings has been chosen without the direct involvement of the authors of this study. The raw data were prepared by the National Statistical Office and the vacancy criteria were established earlier by a task force of the ministry that commissioned a nationwide shrinkage report in 2022 [19]. The criteria were established in a way to allow some consumption like security systems but exclude daily refrigerator operation. The threshold of 100 kWh for an average-sized apartment (50 m^2)

within one year means only 2 kWh/(m²·a). The average electricity consumption for a dwelling varies between 22 and 43 43 kWh/(m²·a) [20] and this value is not significantly affected by deep energy renovations if no heat pump is adopted [21]. The increasing local solar energy production in multifamily buildings could reach the equilibrium of consumption on a year-to-year basis [22]; however, the low self-consumption rate of local solar production means that the delivered energy is still prevalent and recorded. Our consumption threshold is the same as the one Flas et al. were using in their studies [14] but differs from the study by Li et al. as they researched detached houses in rural China and defined vacant houses by a consumption threshold of 30 kWh per year based on extensive survey [15]. Another contribution from China set the vacancy threshold to 10 kWh per month, but without further elaborating the rationale [23].

According to the population registry, a residential unit was considered vacant if there were no permanent residents registered at the end of 2019. It is unknown to us whether the situation was different during the year.

We calculate the housing occupancy rate (HOR) with Equation (1):

$$HOR = DW\_occupied/DW\_total, \quad (1)$$

where HOR is the housing occupancy rate, DW_occupied is the number of occupied dwellings, and DW_total is the total number of dwellings in a building. In the following sections, we show the occupancy rate in percentage by multiplying HOR with 100. We also use the concept of vacancy rate, which is mathematically inversely proportional to occupancy rate.

The raw database of occupation consists of a total of 26,708 records for multifamily buildings, which include 501,757 dwelling units. The quality of the occupancy data has been divided between categories and is presented in Table 1.

Table 1. Overview of raw data for analysing occupation of buildings. Source: authors' calculations.

	No. of Buildings	No. of Dwellings	Electricity Consumption Data		Population Registry Data	
			No. of Vacant Dwellings	Occupation Rate	No. of Vacant Dwellings	Occupation Rate
Consumption data link successful						
Apartment buildings	20,666	404,097	31,069	92%	86,563	79%
Non-residential buildings	67	783	145	81%	305	61%
Electricity measuring points missing						
Apartment buildings	4534	80,155	n/a	n/a	23,861	70%
Non-residential buildings	183	2675	n/a	n/a	1409	47%
Consumption data link unsuccessful						
Apartment buildings	1196	13,159	n/a	n/a	5 881	55%
Non-residential buildings	62	706	n/a	n/a	463	34%
Total	26,708	501,575	31,214		118,482	

Source: building registry, Statistic Estonia, and authors' calculations.

Electricity data were available for most of the buildings of the total building stock (n = 20,733); however, 4717 buildings did not have electricity measuring points in dwellings on the building scale, thus occupation data are missing. Such dwellings might be vacant, or the residents buy electricity collectively from the apartment association or similar entity. In the latter case, the consumption of dwellings cannot be recorded by electricity grid providers. About 5 percent of the buildings (n = 1258) could not be linked with the central electricity grid database. Such buildings demonstrate a very low occupancy rate (55 percent) based on registry data and therefore, there is a high likelihood that those are vacant. Consequently, we are missing consumption data for 22 percent of the buildings (n = 5975). However, population data are readily available for every building in our dataset. We test whether population data could be used to substitute consumption data in the results section of 3.5.

For formal analysis, we skipped the buildings that are not defined primarily as residential buildings (n = 312). Such cases present buildings that are predominantly of commercial or public use and the occupation rates for dwellings do not show how such a building is used for non-residential purposes. Therefore, our final analysis consists of a total of 20,666 buildings that include 404,097 dwelling units in total.

Despite the assumed robustness against false positives of the consumption-based vacancy criteria, we sought to ascertain whether the buildings classified as unused by the data are, in fact, empty. We were unable to assess partial usage, as single vacant dwellings cannot be identified through observation or expert knowledge. The validation of consumption-based vacancy data comprised three methods. The first method involved a random check of 10 percent of the vacant buildings using Google Street View to visually confirm any signs of occupation. Secondly, we visited six settlements across different regions to observe the actual state of the underused buildings. Thirdly, we conducted meetings with officials from the local authorities of six municipalities to validate the vacancy results.

2.1.2. Typology of Buildings

The typology of multifamily buildings can be constructed using building size, age, style, construction method, or materials. While the combination of those variables could render a more comprehensive typology, the official buildings registry in Estonia cannot provide reliable data for the entire building stock. Therefore, we only use the number of dwellings as the basis for typology.

The number of dwellings is reliable as the data are cross-referenced by official real estate ownership records in the Estonian Land Registry, also with the official address system, and census. The typology for multifamily buildings is shown in Table 2. Other metrics like construction period and construction method are highly correlated to size. For example, small and very small buildings are predominantly wooden and erected before World War II or later during the early years of Soviet occupation. Large multifamily buildings belonging to the era 1960–1990s are mostly mass-constructed using concrete or brick. This means that a simple metric of a building size describes also other variables and can, therefore, be used for our purposes.

Table 2. The typology of multifamily buildings in Estonia. Data describes all the multifamily buildings, regardless of the availability of electricity consumption data.

Designation	Size Type	No. of Dwellings	Main Construction Type	Main Time Period	Share of Buildings, %	Share of Dwellings, %
XS	Very small	3 to 4	Wooden	1924–1970	26	5
S	Small	5 to 17	Wooden and brick	1900–1995	47	23
M	Medium	18 to 39	Prefab and brick	1960–1990	14	18
L	Large	40 to 71	Prefab	1960–1980	9	26
XL	Very large	72 and more	Prefab	1970–1995	5	28

Source: building registry, Statistic Estonia, and authors' calculations.

For analysing the relationships between occupation rate and renovation trends, we need to distinguish between buildings that are the target of major energy renovations and those that are relatively new. The last buildings that belong to the era of the Soviet legacy were finished in the middle of the 1990s. The first modern multifamily buildings started to emerge close to the millennia. Although the efficiency and quality of those buildings were not on par with today's standards, the location of those houses and room layouts were determined and delivered by the free market. Therefore, we can assume that the occupancy rate of the new-era buildings is not affected by outdated room planning or design. Millenia is also a useful distinction of buildings because of the building registry's data reliability in general and for buildings age specifically—age data are significantly better from the 2000s. We assume that if the construction date is not known, the building has been erected before millennia.

2.1.3. Typology of Settlement Structure

Non-existent electricity consumption indicates underused dwellings which can be aggregated together to calculate the occupancy rate for a multifamily building. A low occupancy rate for several buildings in space could indicate a pattern. Patterns can be observed on different levels: urban district level, settlement level, core-periphery level, formal administrative divisions, and regional level. Our aim was to explain the housing occupancy on a level that could capture the statewide understanding of residential occupancy dynamics. Therefore, the regional approach which included the settlement structure as a base framework was useful to apply.

In Figure 1, the formal administrative units along with significant settlements are shown. Estonia is divided into counties (n = 15, shown with white borders) which are also addressed as regions in policy practice. Every county is divided on average into 5–7 municipalities (total n = 79). In every county, there are four types of settlement units. The first three are urban settlements. The strongest are county centres (n = 15, in violet colour) which are followed by regional centres (n = 47, in blue colour) and lastly other small urban settlements (n = 190). The fourth type is rural settlement (n = 4435). For further analysis, we address county and regional centres as equally significant nodes for settlement structure and thereby refer to both as regional centres; the capital settlement of Tallinn is furthermore divided into 8 districts for better size comparison between other centres. This results formally in 22 regional centres in our study.

Every county is further classified by its development status. Based on the long-term population projections for Estonia [24], we adopt three classes: (1) growing regions where the population grows, (2) low shrinkage regions where the population decreases less than 20 percent, and (3) high shrinkage regions that project over 20% of the population decline by 2050. The locations and prosperity of the regions are also visualised in Figure 1. The values in brackets in Figure 1 show the multiplier of population growth based on long-term population projections.

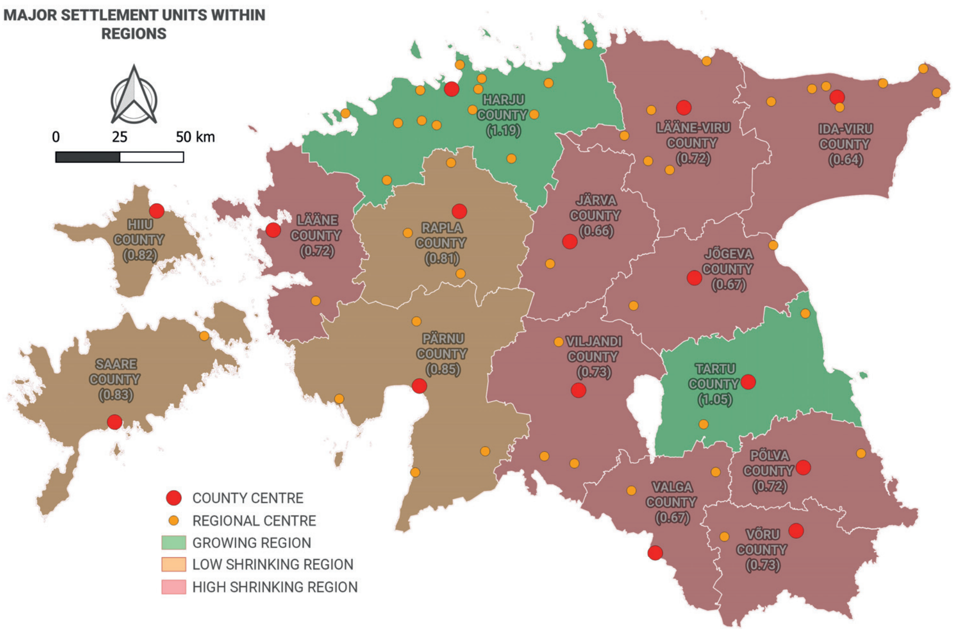


Figure 1. The map of Estonian settlement structure in relation to regional demographic projections for 2024. Source: Statistic Estonia, authors' calculations, and visualisation.

For analysing the relationships between occupancy rate and location of the building, we measure the distance of all the multifamily buildings to the nearest regional centre. To account for the proportionality of housing stock in different locations, every multifamily building is classified by the distance zone (Figure 2). We use 10-step distance zone classifications using distance from a central place (geographical city centre): less than 1 km; 1–2 km; 2–3 km; 3–4 km; 4–5 km; 5–10 km; 10–15 km; 15–20 km; 20–25 km; 25–30 km; >30 km

For distinguishing regional settlements, we used population projections for counties by 2045 (illustrated in Figure 1). We define three types of regions: (1) growing counties that will gain population at the expense of others; (2) low-shrinking counties; and (3) high-shrinking counties. The distribution of buildings in distance zones and regions is presented in the following sources: building registry, Statistic Estonia, authors' calculations, and visualisation.

Table 3 growing regions (Harju County and Tartu County) include 49% of all the multifamily building stock and 57% of the dwellings.

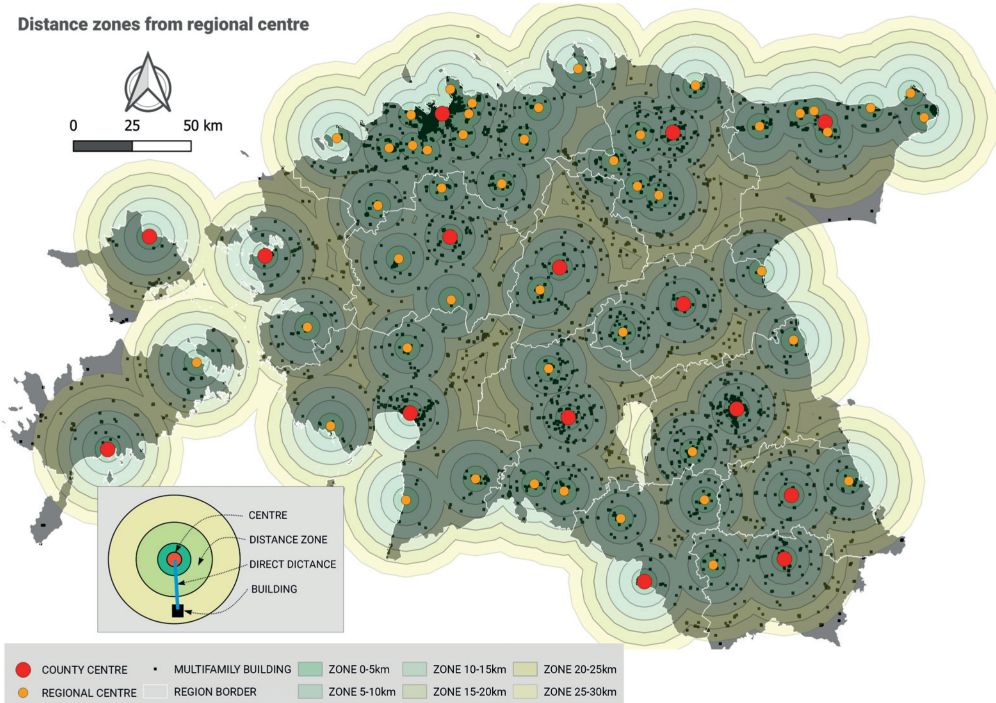


Figure 2. Illustration of distance zones from regional centres. Zones below a radius of 5 km are not shown. Source: building registry, Statistic Estonia, authors' calculations, and visualisation.

Table 3. Distribution of building types in respective distance zones and regions.

Distance	Growing Regions		Low-Shrinking Regions		High-Shrinking Regions	
Zone	Buildings	Dwellings	Buildings	Dwellings	Buildings	Dwellings
<1 km	2372	62,662	891	9969	1979	34,648
1–2 km	4002	98,819	565	9822	1601	29,336
2–3 km	1764	44,136	189	2856	620	17,355
3–4 km	460	8483	124	1529	161	2440
4–5 km	277	3195	46	499	357	13,738
5–10 km	682	7658	388	4424	1130	20,776
10–15 km	397	4618	305	2935	788	8871
15–20 km	145	1268	308	2965	492	5054
20–25 km	68	781	105	1012	294	2863
25–30 km	4	29	44	416	82	750
>30 km			16	127	10	63
Total	10,171	231,649	2981	36,554	7514	135,894

Source: building registry, Statistic Estonia, and authors' calculations.

Considering different aggregation levels, there are three possibilities to present the relationships between the distance of the buildings from the regional centre and the occupancy rate. The first is to focus on the relationships between the exact distance and the specific occupancy rate of a building. This approach renders uncorrelated results as within the long and short distances from regional centres, significant amount of low occupancy buildings can be observed. Testing single buildings fails to account for the housing stock within that particular distance.

The second method is to aggregate all the dwellings within the distance zone and compare this value against the vacant dwellings. This approach is useful as it takes into account the proportionality of housing stock in specific distance zones. The weakness of the approach is that the total aggregation does not reflect the reality of how dwellings are distributed into different buildings.

The third method is to calculate the mean or median occupation rate for all the buildings within a certain distance zone. For regional comparison, this method seems the most appropriate as it accounts for the pattern for individual buildings but also considers the proportionality of building stock in a zone. We use the median values as it is a better metric for analysing the skewed distribution of the occupancy rate. The mean values would have been influenced by single extreme values of low occupancy rate and therefore overestimating the overall occupancy in a zone. We apply the same method for all the occupation datasets regardless of the source (consumption-based or registry-based).

2.1.4. Renovation Database

The renovation dataset originates from a government-controlled entity called Enterprise and Innovation Foundation EISA (formerly Fund Kredex) that processes national renovation grant applications. The dataset includes renovations of multifamily buildings (n = 1695) that have received state grants. Renovations that are adopted outside of state grant programmes are poorly mapped and thus impossible to analyse today. The variables for the renovation dataset include the date, the grant rate, and the indication for major or partial renovations. We only use major renovations (n = 1103) which contribute significantly to the decarbonisation of building stock (including insulation, triple glazing windows, and retrofit of ventilation and heating system) and skip those that are partial renovations like retrofitting only the heating system.

Estonia is a useful case for illustrating the importance of regional demographic dynamics in planning residential renovations. According to Eurostat, the baseline population projection between 2022 and 2050 in Estonia is quite modest within 1 percent of increase and there are much worse performing nations in the EU such as Bulgaria (−17%), Latvia (−28%), and Greece (−17%) [25]. However, Eurostat falls short of delivering the shrinkage metrics for the smaller regions. Therefore, the Estonian case demonstrates that large differences in regional migration projections result in the severe decline and shrinkage of some regions (−36% in IDAVR county) that could end up with significant housing abandonment despite modest population change in the country on average.

2.2. Limitations of the Study

The study is based on the total electricity consumption data in dwellings within the year 2019; therefore, we cannot distinguish between the seasonal use of dwellings, nor can we present electricity usage trends and therefore vacancy trends as well. However, long-term vacancy within one year is a significant and useful indicator for comparing buildings and regions.

The off-grid buildings that are producing and consuming all the electricity on-site are not accounted for in national statistics. Consequently, an electricity-based vacancy rate is also not available. Currently, we do not have any examples of fully autonomous multifamily buildings. However, this will eventually change as local energy production and storage gain momentum and technology advances.

If residents of multifamily buildings buy electricity collectively from their housing association as their contractor for accessing the grid, the consumption of each dwelling cannot be recorded by the grid operators. For such buildings, we cannot have data on vacancy. However, we have the total consumption of buildings, and therefore, we might distinguish significantly underused buildings. The case of whether it is possible to estimate the occupation rate by analysing the total consumption of a building is presented in Section 3.5.

Information about the vacancy or energy consumption for single dwelling units in a building was not disclosed to us. Regardless of the size of the building, if there were one or two vacant residential units in a residence, the calculated number of vacant units would be 1.5. This means that very small buildings are very sensitive and could show a very low occupancy rate even with single vacant dwellings. To overcome this limitation, we used median values instead of average values for vacancy analysis.

The renovation analysis is only based on such buildings that have received state grants and are, therefore, well documented. Therefore, our results do not reflect the occupancy of buildings that are renovated outside of the grant programme. Based on expert estimations, we assume that the majority of such buildings are only renovated partially, and therefore should not affect our goals of analysing major deep energy renovations.

3. Results

3.1. Relations Between Settlement Structures and Occupancy Rate

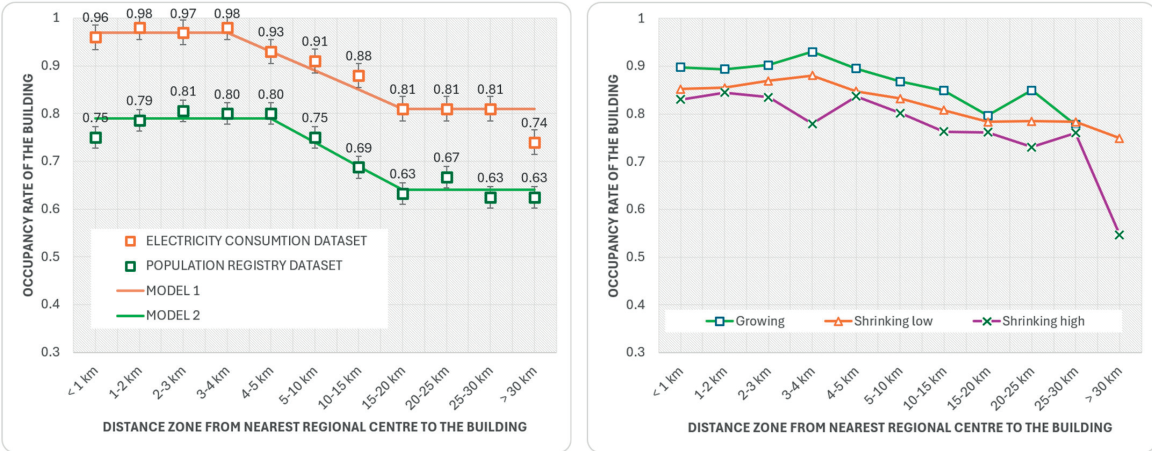
We identified 162 multifamily buildings that have no occupied units, as indicated by the electricity consumption data. All the validation methods corroborated this data-based classification. Additionally, to assess partial occupations, we sought insights from the local authority officials. They confirmed that if a building was at least 50 percent vacant, it was readily apparent from public space. Low vacancies are mostly hidden and public officials only become aware of such cases by chance.

The data on electricity consumption indicates that out of the total of 404,880 dwellings, a significant number of 31,204 remained unoccupied in the year 2019. This means that the median occupancy rate for all the multifamily buildings regardless of type and location is 86 percent.

The overall pattern shows that the occupancy rate declines as the building distance increases from the nearest regional settlement unit (Figure 3a). Within the distance of 3–4 km from the centre of the settlement, we observe relatively stable occupation rates. This distance represents the average physical size of the settlements. After that zone, the occupation starts to decrease constantly and reaches another stable level after 20 km resulting in a rate of 80 percent.

The dataset from the population registry shows a similar trend as electricity usage. However, the occupation rate is constantly much lower compared to the consumption-based rate. The comparison of the population registry dataset against electricity consumption data is further elaborated in Section 3.4. and evaluated in Section 4.1.

The overall downward trend of the occupancy rate persists when considering settlements in expanding (e.g., Tallinn County) and contracting regions (e.g., Valga County). Nevertheless, there is an additional anticipated pattern: as the contraction of the entire region intensifies, the number of vacant dwellings also rises (Figure 3b). Even when buildings are located near regional centres, the influence of regional development status becomes apparent. This is evident in the lower occupancy rates of buildings, which in turn can be attributed to pessimistic long-term population projections.



(**a**) (**b**)

Figure 3. The dependence of occupancy rate on distance from the nearest regional centre. The figure on the left (**a**) illustrates the overall occupancy rate while on the right (**b**), the growth type of settlement is shown. Source: building registry, Statistic Estonia, and authors' calculations.

3.2. Relations Between Building Types and Occupancy Rate

The results in Section 3.1 indicated that the overall average occupancy rate might not be representative of all types of apartment buildings. Therefore, we used the predefined types of buildings (Table 2) and compared them against the occupation rates.

The results in Table 4 show that in general, the occupation of larger buildings is higher than that of smaller apartment buildings. Very large and large buildings demonstrate the highest occupancy rate of 95–97 percent while the population registry shows 82–82 percent. Medium-sized buildings are less occupied than the larger ones, showing an occupation rate of 93 percent. These types were also built in less significant regional centres and in small towns, resulting in slightly lower occupancy rates compared to larger buildings that are predominantly located in more significant regional centres.

Table 4. Occupation rate varies across different types of multifamily buildings. Data include only buildings that had electricity consumption data available.

Type of Building	Building Size (No of Dwellings)	No. of Buildings	No. of Dwellings in Total	Occupation Rate (Electricity)	Occupation Rate (Registry)	Difference in Percentage Points
Very small	3–4	4879	17,973	76%	66%	10
Small	5–18	10,719	106,349	86%	70%	16
Medium	19–39	2103	58,607	93%	78%	16
Large	40–72	1980	110,353	95%	82%	14
Very Large	73+	1052	111,598	97%	84%	13
	Grand Total	20,733	404,880	86%	71%	14

Source: building registry, Statistic Estonia, and authors' calculations.

Small and very small buildings are generally the most problematic type, constituting the largest proportion of the multifamily building stock. These buildings exhibit low occupancy rates across all the settlement types, with some exceptions found in the growing regional centres, where small multifamily buildings contribute to architecturally valued neighbourhoods characterised by higher occupancy rates.

The average occupation rate of very small buildings is 76 percent, while the occupation registry shows an even lower rate of 66 percent. The type of very small building that has 3–4 dwellings in total is very sensitive to single vacant dwellings. Therefore, the average occupancy rate is also much lower than that of larger buildings.

3.3. Interplay Between Housing Occupation and Major Energy Renovations

The data shows that the occupation rate of renovated buildings is on average 96 percent, which is 10 percent points higher than the overall value. The occupancy rate histogram for renovated buildings in Figure 4 shows that most renovations demonstrate a higher than 90 percent occupancy rate; furthermore, 40 percent of renovated buildings are fully occupied.

The lowest occupancy rate for renovated buildings is 80 percent. The 80 per cent level indicates a specific threshold that limits the renovations in those buildings. In total, there are 5246 multifamily buildings, comprising 36,753 dwellings, that demonstrate occupancy rates below 80 percent.

While some renovated outliers exhibit even lower occupancy rates, these buildings are either partially renovated or the dwellings are owned by the same individual. This calls for a more elaborate analysis for understanding the specific renovation works in low occupancy buildings, and also exploring the ownership structure.

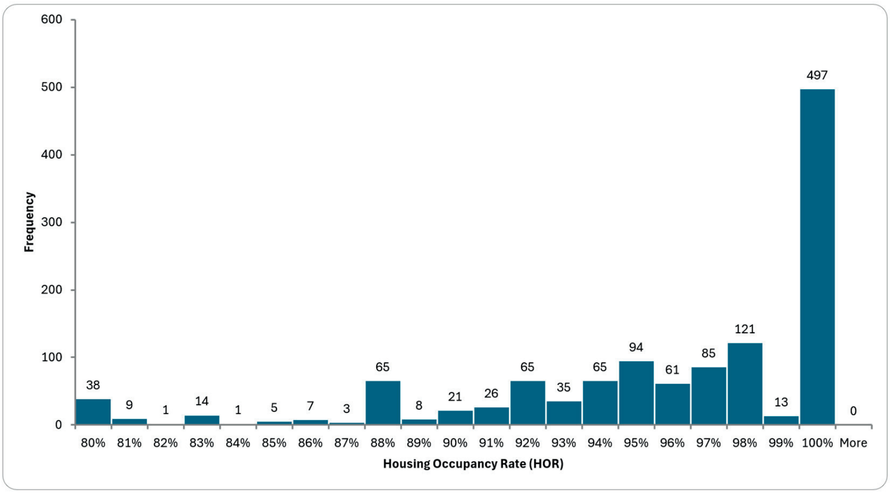


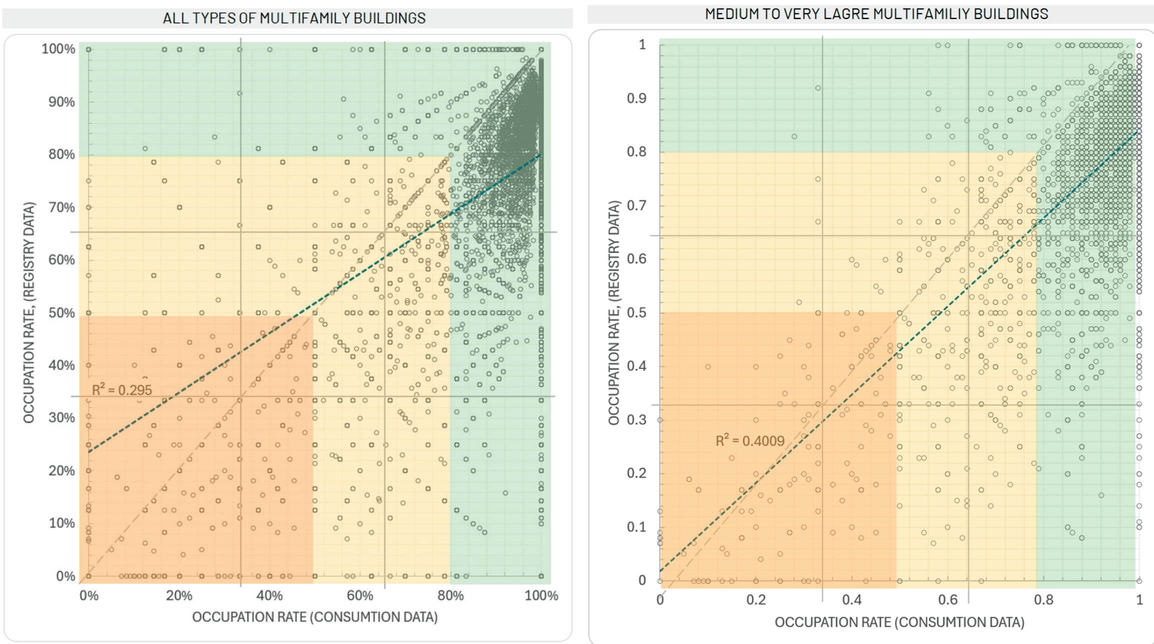
Figure 4. The distribution of occupancy rate of renovated buildings. Source: building registry, Statistic Estonia, and authors' calculations.

3.4. Comparison of Electricity Consumption Data Against Population Registry

Registry-based data systematically underestimates the occupancy rate compared to consumption-based data. For all the buildings in our dataset, the occupancy from the electricity dataset was 86 percent, while registry-based data demonstrated 71 percent. The difference is 14 percentage points.

Dataset differences among the building types are presented in Table 4. Between different building types, we observe that as the building size grows, the difference in occupation rate for the two datasets diminishes. This means that the large average variance in datasets is mostly affected by smaller buildings which demonstrate a high vacancy rate due to the fact that the occupancy rate is more sensitive in smaller buildings, where few vacant dwellings can have a significant impact on the rate. By skipping the data of buildings of very small and small types, the variance explanation rate R^2 increases from 0.295 to 0.4009 as the linear trendline fits significantly better in the scatterplot in Figure 5b compared to Figure 5a. Pearson correlation coefficients between the occupation rate of the electricity and registry datasets are 0.54 for all the building types and 0.63 for medium to very large buildings. Considering the location of the buildings, the two datasets present the same overall trends—as the location of buildings increases from the nearest regional centre, the occupation rate decreases.

While consumption-based data might underestimate the vacancy of dwellings in general, it is quite evident that if there is virtually no electricity consumption for a long period, the dwelling must be empty regardless of what registry data shows. On the other hand, without having daily or weekly data on electricity usage we cannot confirm if the dwelling is occupied full-time. We can conclude that consumption-based data cannot deliver false positives. Therefore, consumption data are superior to registry-based data in terms of identifying long-term vacant dwellings.



(**a**) (**b**)

Figure 5. Scatterplots of occupation rates. Scatterplot (**a**) includes all multifamily building types, and (**b**) shows only medium to very large types. Colours illustrate occupancy rate steps 0–50%, 50–80%, and 80–100%. Source: building registry, Statistic Estonia, authors' calculations.

3.5. Application of Aggregated Electricity Consumption Data

We acknowledge that electricity consumption data for single dwellings might not be readily available in other countries. Therefore, we tested to what extent the aggregated consumption data on a building level can be useful to analyse occupancy rates.

Our results demonstrate that aggregated electricity consumption is not a substitute for detailed data from dwellings. This is because there is a large variation in energy consumption (15–80 kWh/(m^2·a)) in buildings with very high occupancy rates. Therefore, we cannot clearly distinguish underused buildings from occupied ones.

Nevertheless, aggregated data could still provide some insights that can be useful for understanding the dynamics of occupancy. The relationships between occupancy rate and electricity usage are presented in Figure 6, where the orange horizontal line illustrates the average electricity consumption across all the multifamily buildings. The green lines represent the average consumption at each occupancy level, incremented in steps of 10 percentage points. We can observe that for a majority of the high occupancy buildings (HOR > 90%), the total consumption varies between 15 and 40 kWh/(m²·a).

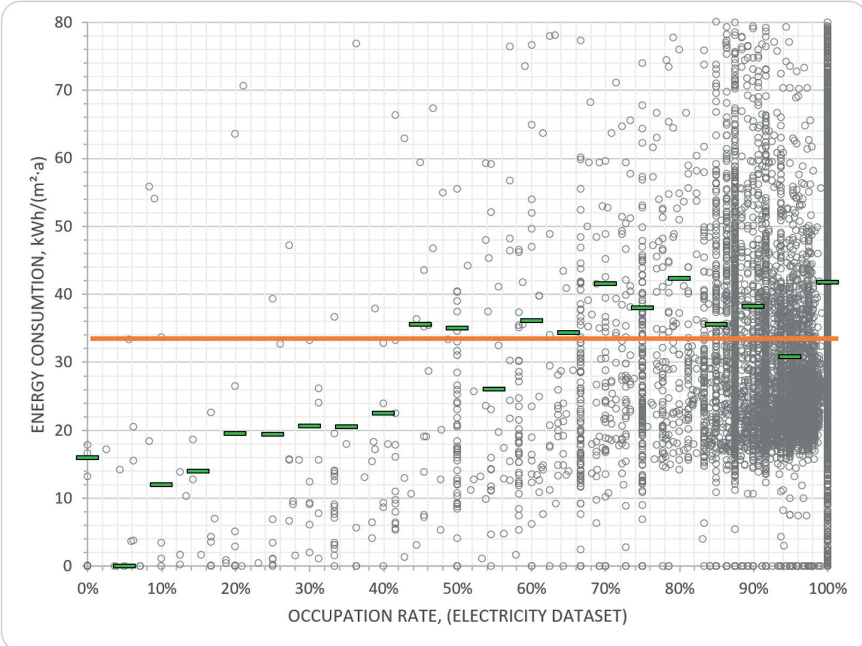


Figure 6. Dependency of electricity consumption on occupation rate. Source: building registry, Statistic Estonia, and authors' calculations.

As the electricity consumption of a building drops below the overall average rate, the occupancy rate also decreases. Therefore, in general, a total consumption below 10–15 kWh/(m²·a) indicates a significantly underused building. However, this level does not show the whole truth when addressing different types of buildings. Using the same building typology presented in the methodology section, we can argue that smaller buildings consume relatively more electricity than larger ones. Therefore, the critical electricity consumption level for low occupancy rate is also different. The risk criteria for the underusage of smaller buildings could be set much higher at 30 kWh/(m²·a).

We recommend other countries to test whether our suggestions are also true in other contexts. This can be carried out using probability sampling. If detailed data on dwelling levels are not available, the total consumption of a building should be used in combination with other metrics that indicate higher vacancies. For example, a low renovation rate, slow real estate market, and low real estate value within a district could refer to shrinkage. Furthermore, as we observed in Section 3.1, the higher distance from a central place is also positively correlated to higher vacancy rates.

4. Discussion and Policy Recommendations

4.1. The Usefulness of Consumption Data for Explaining Residential Vacancy

Consumption-based vacancy analysis is not a novel concept; however, recent advancements in smart metering technology have introduced opportunities for the analysis of large datasets [26,27]. Although some studies have proposed utilising water usage data [16], garbage collection metrics, and other indicators for vacancy analysis, this study focuses exclusively on electricity consumption. This choice is justified by the fact that in

Estonia, every measuring point is monitored by a single central grid operator, ensuring that the data are both comparable and accessible from one entity for all the consumers. In contrast, the water distribution grid, for instance, is fragmented among numerous local service providers, resulting in the absence of a centralised database.

Currently, there are still a few studies that address consumption-based residential vacancy. One noteworthy contribution by Li et al. demonstrates the vacancy trend by utilising consumption data from two different time points [15]. This suggests that there is significant potential for analysing the actual vacancy trends, which our study lacks.

Our general insight is that electricity consumption data are superior to self-reported residency declarations, particularly in distinguishing long-term vacant dwellings. A lack of electricity usage over extended periods serves as a clear indicator of actual vacancy, making it crucial for a critical evaluation of shrinkage. In contrast, residency registration relies on the motivations of residents; in our case, official registry data significantly overestimates vacancy rates in multifamily buildings. It seems that Flas et al. have reached for the opposite result and reported that official statistics in the case of Wallonia underestimate the vacancy rates [14]. This is interesting, but Flas et al. also report that the majority of potential vacancies have been indicated by residency registration which is par with our observations.

Next, we explain some of the main reasons behind vacancy overestimations in Estonia. Our data on electricity consumption only includes the dwellings that are completely unoccupied. There may be instances where a dwelling is not in use, yet electricity consumption exceeds the vacancy threshold of 100 kWh per year. As we did not have access to electricity consumption data for every dwelling, we were unable to analyse the relationships between registry and electricity usage in detail.

Our electricity consumption data represent a cross-section for one year (2019); therefore, partially occupied dwellings are not classified as empty. However, partially occupied dwellings may be recorded as empty in the registry because residents often do not take the initiative to update their residency status during short periods of absence.

The registry presents a snapshot of a single day at the year's end, implying that a building may have been occupied earlier, with residency potentially cancelled in December. Without access to the most recent residency date for specific dwellings, we cannot assess long-term vacancies using the population registry.

The registry may also overestimate vacancies, as new owners might neglect to report their residency or may have reasons to conceal it. However, electricity consumption serves as a reliable occupancy indicator. Our observations show that recent residential developments in expanding regions are significantly underutilised according to the registry (HOR < 70%), while electricity consumption indicates high occupancy levels (HOR > 96%)

According to Statistics Estonia, the number of rental dwellings has been increasing over the last decade. Compared to the previous census, the share of tenants has nearly doubled and now includes over 175,000 dwellings, which accounts for 10% of all the units in multifamily buildings. It is likely that tenants may not report their residency in rental dwellings due to short rental periods or lack of awareness. Consequently, this may result in such dwellings being recorded as vacant in the statistics.

Additionally, the seasonal use of multiple homes complicates residency reporting and may lead to occupied dwellings being classified as empty. While the Estonian population registry has enabled the reporting of multiple residences, this feature is not widely known or utilised.

4.2. Some Reflections on Residential Vacancy Patterns

We observed that larger apartment buildings exhibited higher occupancy rates compared to smaller ones. This trend can largely be attributed to the fact that larger buildings are predominantly situated in significant central settlements, where the overall occupancy rate tends to be higher. Due to the Soviet planning paradigm, large residential buildings were closely grouped together in estates and constructed in areas where a larger workforce was required. During the 1950s and 1960s, there was also a strong tendency towards urbanisation, resulting in large housing estates being predominantly located in major regional settlements.

We also notice outliers among larger mass-produced buildings from the 1970–1990 era that are losing residents despite a general trend indicating that proximity to central settlements correlates with higher occupancy rates. A significant example is the county of Ida-Virumaa (IVIR), which has experienced rapid emigration in the context of ageing communities and industrial transformations towards a "green economy," resulting in a decreased number of jobs. Despite the deteriorating quality of housing, renovation rates in such regions remain very low, and municipalities are facing serious trends of building abandonment in the near future.

Medium-sized (18–40 dwellings) mass-produced housing was also constructed within the newly established collective farms or in close proximity to other types of industry. A common theme for such collective estates is that these building sites were relatively new additions to the settlement structure. Eventually, the newly established communities of that time lost their purpose during the economic transformation that began in the 1990s. Observations suggest, and our data confirm, that these buildings are becoming increasingly vacant. This is particularly true if the district heating provider has ceased operations. Consequently, this trend has resulted in the retrofitting of local heating systems, which are now also outdated.

We observe that medium-sized buildings maintain relatively high occupancy rates across all settlements. In contrast to smaller, stable, or declining settlements, growing regional centres exhibit higher occupancy rates in medium-sized buildings.

Smaller buildings are generally equally vacant across all settlements. However, some outliers have emerged in recent decades. Economically strong and growing settlements have witnessed a renaissance of neighbourhoods originating from the pre-mass construction era. This phenomenon can be attributed to the rise in local communities that value historic architecture. Consequently, occupancy rates, along with the quality of buildings, are high in certain culturally significant neighbourhoods. In contrast, smaller settlements, which typically possess a notable legacy of smaller wooden apartment buildings, are struggling, resulting in the degradation of these structures.

The sensitivity of small buildings in relation to single vacant dwellings can be directly linked to their renovation capacity. In very small multifamily buildings, the likelihood of undertaking deep energy renovations diminishes significantly when even one dwelling is vacant.

4.3. Lessons for Preparing National Renovation Plans

We observe that renovation grants in Estonia from 2010 to 2023 are correlated with distance zones and, consequently, with occupancy rates. This indicates that as a building's distance from the central area increases, both its value and occupancy tend to decrease. Consequently, the barriers to renovation also increase. This process illustrates how the market ensures the efficiency of investments. Any intervention in such processes must be carefully considered, ensuring that the benefits outweigh the investments that contradict prevailing market trends.

Therefore, we can argue that if the occupancy rate of a building is lower than 80 percent, a major renovation of that building is very unlikely. In Estonia, there are a total of 5246 multifamily buildings, which encompass 36,753 dwellings that can be classified as being in the risk group concerning successful energy renovations. While the risk group constitutes 25 percent of the sample dataset, the majority of these buildings are small, leading to only 9 percent of the dwellings belonging to the risk group. However, when considering the entire building stock, it is likely that the risk group is significantly larger. We currently lack consumption data for 5975 buildings (96,695 dwellings). As the population registry indicates a below-average occupancy rate for these buildings, the risk group may potentially be twice the size.

Renovation subsidies within settlements are typically allocated to buildings with high occupancy rates for two primary reasons. Firstly, banks require a high occupancy rate to mitigate lending risks. Secondly, vacant dwellings signal a low organisational and financial capacity within the apartment association, which impedes its ability to undertake costly investments in deep energy renovations. Therefore, we can conclude that low-occupancy houses have largely remained unrenovated. This is attributable to the limited capacity of the associations, financing barriers, and the complexity of the technical solutions required.

Any long-term renovation strategy must first acknowledge that the market cannot and will not deliver renovations for buildings that are significantly empty. If the preservation of building heritage is a priority within a shrinking settlement, the interventions for the market should be meticulously planned, impactful, and justified.

Medium to very large buildings are typically well occupied and situated in significant locations within the settlement structure. Consequently, deep energy renovations of such buildings are more feasible than those of other types of residential buildings. Additionally, mass-produced buildings are the most scalable for deep renovations [2] and yield the best performance in terms of reducing energy demand and minimising emissions [28].

Medium-sized buildings within artificially created structures, such as collective farms and other types of industry from the Soviet era, have lost their purpose, and the occupancy rate continues to decline. Clearly, there is no need to include such buildings in the renovation plan, and municipalities must prepare for extensive demolitions in the coming decades. We also observe that vacancy rates are high in smaller buildings. This situation renders renovation virtually impossible for the few remaining individuals who are interested in improving their quality of life.

We should point out that as the occupation rates are slowly but surely going to decline, there are some positive aspects for the environment. Achieving carbon neutrality in residential buildings will get easier as more inefficient and old buildings will be out of service in shrinking regions. New housing stock that is very efficient will be built instead of abandoned ones (albite in growing regions), so the transformation to climate-neutral building stock will be achieved eventually. However, some new questions arise. For example, what kind of policy is useful in shrinking regions as they are declining slowly and offer homes for decades? As new housing will be erected in growing regions polarisation of society will be reinforced as the residents of smaller settlements cannot experience the quality of new housing. Major deep energy renovations for residents in underprivileged settlements could be the only possibility to experience quality that is on par with new and modern residential buildings.

4.4. Future Prospects of Residential Vacancy Research

While the cross-sectional study provided valuable insights into vacancy patterns, future research should make an attempt to obtain more detailed data on electricity consumption. Although we possess longitudinal data from the population registry regarding residency, there are significant limitations in the registry datasets that hinder drawing plausible conclusions. However, trends in electricity consumption could provide a better indication of shrinkage trajectories.

In our dataset, we are missing 22 percent of multifamily buildings from the overall stock, as electricity consumption data were not available. It is essential to focus specifically on these missing buildings to ascertain why the consumption data were unavailable and to determine the actual occupancy levels within those structures. We can reasonably infer that the actual occupancy rate must be relatively low among these buildings, as the population registry indicates an average occupancy rate of 60 percent. This figure is the lowest compared to the buildings for which we have consumption data.

Another group that must be addressed within vacancy studies is detached houses. Detailed data on electricity usage would be particularly beneficial for illuminating seasonal patterns and dynamics in detached houses. Summer houses or other seasonal homes may not be suitable targets for large and costly incentives aimed at delivering deep energy renovations, as the emissions reduction effect in such buildings is minimal. Insights into seasonality, particularly how vacancy fluctuates regionally and among settlements, would enable policymakers to better prepare for the significant challenges associated with residential deep energy renovations.

5. Conclusions

The starting point of the study was the lack of insights about residential vacancy in relation to deep energy renovations. Using the electricity consumption data of dwellings, we established the occupancy rates for multifamily buildings.

The overall pattern observed in our analysis indicates a decline in occupancy rates as the distance from the nearest central settlement unit increases. This trend is pivotal in understanding the spatial dynamics of urban sprawl and its implications for housing occupancy. Interestingly, while electricity-based evidence suggests a certain level of occupancy, registry data portrays significantly lower rates. This disparity highlights the need for nuanced interpretations when assessing occupancy patterns solely based on official records.

Our findings reveal a consistent trend: larger buildings tend to exhibit higher occupancy rates compared to smaller apartment complexes. This observation underscores the preference or feasibility of larger accommodations in urban settings, potentially influenced by factors such as amenities, proximity to services, and housing market dynamics.

Conversely, small buildings across various settlements exhibit low occupancy rates, generally irrespective of their location. Exceptions arise in growing regions where older buildings have been rediscovered by younger generations who appreciate their heritage. In contrast, smaller settlements often comprise only single, isolated buildings that undergo extensive renovations, which highlights the overall high vacancy rates.

The dilemma posed by energy policies in reinforcing declining regions versus signalling doom for the current residents is a critical consideration. Our study questions whether energy policies inadvertently hasten urban decline or effectively support sustainable development in these regions. This dilemma warrants further exploration to align policy goals with socio-economic realities and community aspirations.

Our research emphasises the importance of detailed consumption data, such as electricity usage, over self-reported residency declarations, for the accurate assessments of building occupancy. Notably, official registry data tends to overestimate vacancy in multifamily buildings, necessitating caution when interpreting such records for policymaking and urban planning purposes.

The study underscores the challenges and opportunities in using electricity consumption data to analyse building occupancy and vacancy patterns. While the reliance on the 2019 data limits the ability to capture seasonal and long-term trends, the study highlights the value of long-term vacancy as a key indicator for comparative analysis. As energy systems and technologies evolve, the study acknowledges that scenarios like autonomous energy systems and collective energy practices will challenge the conventional methods of vacancy estimation. Although renovation analysis is confined to state-grant-funded projects, it effectively focuses on major deep energy renovations that align with the study's goals.

Future research should prioritise longitudinal studies that capture electricity consumption data over time. Such data are crucial for conducting trend analyses to better understand the evolving dynamics of building occupancy. Longitudinal studies enable researchers to track changes in occupancy patterns, assess the impact of policy interventions, and anticipate future housing needs with greater precision.

In conclusion, our study offers valuable insights into the complex interplay of building characteristics, economic factors, and policy implications on occupancy rates across diverse urban and rural settings. By leveraging multiple data sources, we contribute to the ongoing discourse on sustainable development and housing policy formulation. Continued research in this field is essential to inform evidence-based policies that effectively address housing challenges in both growing and declining regions.

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Article V

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Revisiting spatial distribution of residential energy renovation grants: evaluation of policy change for more equitable use of public funds

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ABSTRACT

We ask whether renovation subsidies are distributed equally among regions and whether such distribution can be considered fair in terms of national regional aspirations. We examine renovation subsidy applications submitted by apartment associations between 2010 and 2024 using three methods. First, we employ quantitative analysis explaining variations in subsidy applications and their relationship to the regional development status. Secondly, we utilise a logistic regression model to identify the thresholds of building characteristics that influence the likelihood of apartment associations obtaining grants. Lastly, we conduct interviews with policymakers, stakeholders, and practitioners to enhance the analysis. The results reveal that subsidies are distributed very unequally across regions, with significant annual variations. While leading regions benefited during the early stages, recent years have shown a shift, with more subsidies being allocated to mediocre regions. Despite outliers, the spatial distribution can be considered fair. The logistic regression analysis indicates that renovation uptake is unlikely for buildings that are underoccupied and either very small or large. Renovation practitioners emphasise that actual renovation uptake is more dependent on intermediaries, whose collective attitudes towards renovations determine a region's success. We suggest that policymakers should focus more on intermediaries who could, in turn, expedite the much-needed renovation activities.

1. Introduction

In March 2024, a consensus on the latest revision of the energy performance building directive (EPBD) was reached (Directive 2024/1275, 2024). The Parliament emphasized the urgent need for EU member states to accelerate the renovation wave (EC COM 662, 2020), as it became apparent that relying solely on market forces would not suffice in achieving the desired outcomes for climate mitigation goals and energy security. Thus, further developing incentive mechanisms is an urgent task for governments and stakeholders.

Deep energy renovation can be expensive investment, therefore, to alleviate market barriers most commonly financial incentives are adopted (Bertoldi et al., 2020). Regarding buildings in different sectors, the incentive approaches are also different. For example, the commercial sector attempts to comply with buildings requirements while considering profitability of a renovations as investment (Kuivjõgi et al., 2021). Buildings managed by public sector can be financed using public resources. The residential sector, however, seems to be most sensitive to expensive investments to renovations as homes are not usually addressed as investment projects and homeowners are not professional clients to procure complex and time-consuming renovations (Balezentis et al., 2024; Lundmark, 2024). Therefore, we focus our discussions on residential sector and address specifically multifamily buildings.

While financial instruments are crucial for building renovations, they seldom function alone. Studies show that capacity building for planning and design professionals, effective communication campaigns, and showcasing successful renovations are vital complements to financial incentives (Reindl, 2020). Mismatches in agency and technical capacity among stakeholders can hinder uptake, even with funding. Additionally, tailored communication strategies that leverage social norms or highlight real-world benefits can significantly increase renovation adoption in social housing (Bielig et al., 2024). While our discussion centres on subsidy distribution, integrating these supporting measures clarifies why policy outcomes differ across regions with varying capacities, awareness, and institutional strengths.

Financial incentives for multifamily buildings are varying throughout Europe; still traditional types of support for dwelling owners are tax incentives, loans, and direct subsidies (Economidou et al., 2024). Despite harsh liberal critics (see, for example, Nozick, 1974), subsidies have been identified as predominant instrument in achieving energy performance goals in the building sector by providing vital financial support to facilitate renovations and improvements (Economidou et al.,

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2024). One of the main advantages of subsidies is their ability to reduce the costs of energy performance projects, thereby encouraging greater participation from property owners and managers. Moreover, subsidies can expedite the adoption of innovative technologies like prefabrication (Kuusk et al., 2019) and practices such as district-based renovation (Lihtmaa and Kalamees, 2024) that can contribute to a reduction in energy consumption and greenhouse gas emissions.

However, there are weaknesses associated with subsidies. A critical flaw in the implementation of subsidies is the problem of equitable distribution and efficiency (Hsu et al., 2008). Sovacool and Dworkin (2015) frame energy justice as a comprehensive ethical lens for shaping policy, grounded in principles such as availability, affordability, transparency, and both intra- and intergenerational equity. This perspective shifts energy policy beyond mere technical or economic efficiency, aiming instead to ensure that the benefits and burdens of energy systems are equitably shared. Jenkins et al. (2016) distil this concept into three interconnected dimensions—distributional, recognition, and procedural justice—that together help diagnose and address inequities.

In this context, distributional justice focuses on how energy resources, costs, and risks are allocated across society. In designing subsidies, this means considering not only which households benefit but also which regions, acknowledging that fairness can pertain to both individuals and territories. Regional disparities in energy costs, renewable resource potential, and access to infrastructure may warrant differentiated subsidy levels, with the aim of closing "energy equity gaps" (Cong et al., 2022) between, for example, rural and urban areas. Treating regions as subjects of fairness reframes subsidy distribution as a means of addressing both social and spatial inequalities in the energy transition.

Discrepancies in subsidy distribution frequently arise in the allocation of subsidies, with certain regions or types of buildings receiving more assistance than others, thereby worsening existing disparities. For instance, smaller multifamily buildings or those situated in less economically prosperous areas might not benefit as much from subsidy programs, resulting in uneven progress toward energy performance goals. Such unfair distribution emphasizes the need for a different strategy in allocating subsidies, taking into account various socioeconomic and regional factors.

The objective of energy policy is to ensure that financial support is aligned with broader environmental goals, as set out in the Paris Agreement and national climate action plans. Consequently, subsidies are well addressed to maximise the reduction of carbon footprints (Siddique et al., 2022) but despite of having various positive spillovers, generally not considered as explicit tools for achieving other sectoral goals (Lihtmaa, Hess and Leetmaa, 2018).

In recent years, there has been an increasing focus on the negative spillovers of energy policy, which arise from the ambitious objectives set by the climate agenda. This topic has gained recognition within academic circles. In their recent and extensive review, Garvey et el point out the wider implications of such externalities focusing on decarbonisation transitions and argue that spatially targeted interventions could lead to more just distribution of common resources (Garvey et al., 2022).

In addition to academic works, the last iteration of the EPBD has highlighted the significance of fairness towards climate neutrality transition (Directive 2024/1275, 2024) . This means that subsidies should not only be effective in achieving energy savings, but also fair in their distribution.

Consequently, a significant dilemma in the design and implementation of subsidy programs is whether to prioritize investments based on energy savings potential or to focus on vulnerable social groups and spatial disparities.

Inefficiencies of subsidy programmes often arise from poor targeting (Mikola et al., 2022), whereby funds fail to reach the buildings or areas where they could have the most significant impact. Additionally, the administrative burden and complexity of subsidy programs can discourage potential applicants, resulting in lower participation rates (Ebrahimigharehbaghi et al., 2019).

While an increasing amount of evidence suggests that partially targeted subsidies can result in an uneven allocation of funds (Frantál and Dvořák, 2022), there is still a lack of knowledge regarding the tools and approaches to incorporate the spatial dimension in low-carbon transitions in order to mitigate negative spillovers (Garvey et al., 2022). The ongoing policy process influences the methods of intervention, which in turn affects the outcome of fairness. Consequently, policy impact assessments have the potential to offer valuable insights into the effectiveness and efficiency of intervention practice that specifically aim to address the fairness in subsidy targeting.

We define equality in its simplest distributive sense as the allocation of grants in equal amounts to all regions, irrespective of their differing needs or circumstances (Walker et al., 2016). In contrast, our understanding of fairness aligns with Rawls's notion of "justice as fairness" (Rawls, 1999), which asserts that rules should benefit the least advantaged. When applied to subsidies, this perspective necessitates considering factors such as the development status of each region, the challenges of energy transition, and specific policy objectives. This approach may result in allocations that are unequal in size but yield fairer outcomes. Ideally, equality and fairness would align, but in practice, fairness often necessitates differentiated support to attain substantively equal capabilities across regions (Day et al., 2016).

Taking into account the previous arguments, the aim of this study is to evaluate the extent to which recent changes in Estonian energy policy have resulted in a equal and fair distribution of public resources for extensive energy renovations of multifamily buildings. To achieve this objective, we have formulated three research questions (RQ).

RQ1. To what extent have renovation grants been distributed equally and fairly across regions?

RQ2. What role has renovation application rules played in the grant distribution across regions?

RQ3. To what extent are external renovation barriers capping the renovation uptake?

Our research takes a step further from merely describing the distribution of subsides and how policy has changed. The novelty of the contribution is presenting a method for defining and assessing quantitatively equality and fairness. We elaborate and validate the results by obtaining direct feedback from policy makers and renovation consultants from practice.

Our additional contribution is related to third research question which aims to gain better understanding how the buildings occupancy and buildings' size influences the probability for apartment association to obtain the state subsidy for deep energy renovation. We already have evidence that those variables could be significant thresholds in renovation subsidy uptake (Lihtmaa and Kalamees, 2025). This method can be utilised also in practice for planning subsidy allocations between different spatial units using probability as allocation factor. While we base our study on renovation grant programme developed and implemented in Estonia, the simplicity of developed methods is easily scalable to other countries with similar data available.

2. Housing energy renovation policy evolution in Estonia during 2010–2023

The Estonian housing subsidy programme for improvement of energy performance of apartment buildings was initiated in 2010 and has been ongoing since then. The key aspects of the programme's evolution, with a focus on targeted policy, are outlined in Table 1. The subsidy funds were managed centrally by separate governmental body (originally Fund KredEx and from 2020 b y Estonian Business and Innovation Agency - EIS). This agency also organised all the communication and involvement processes. Support was provided for apartment association during the construction process, effectively reducing upfront costs. To

Table 1
The evolution of deep energy renovation grant programme in Estonia.

Time period	Nr of grants	Budget, million EUR	Description
2010–2014	661	38	Eligible only energy-saving renovations. Grant amount based on the achieved Energy Performance Certificate (EPC) class. No regions, building types or social groups were targeted. All apartment associations had equal opportunities to apply for state support. https://www.riigiteataja.ee/akt/105072023274
2015–2017	401	102	EPI was raised, technical requirements established for building components. Eligible renovation domains were extended. Focus shifted on indoor climate. Regional targeting was introduced: Region of IVIR receives 10 percent points higher support; No low energy ambition renovation for cities of TLL and TRTL;… https://www.riigiteataja.ee/akt/113042017004
2019	47	17	The heat recovery ventilation (HRV) system was mandatory in two major cities. Other regions could forgo HRVs in exchange for a lower grant. Ambitious regional targeting was introduced for grant applications. https://www.riigiteataja.ee/akt/109042019006
2020	72	28	No significant changes in technical requirements. In addition to regional targeting, grant budget has been reallocated to NUTS 3 statistical regions. https://www.riigiteataja.ee/akt/108052020020
2020–2022 COVID	185	60	Support was aimed at helping apartment associations and construction companies during the COVID crisis. As an exception, partial renovations in lagging regions were eligible for support as well. NUTS 3 quotas were dismissed, but regional targeting from 2019 remained. https://www.riigiteataja.ee/akt/105072023314
2021 PREFAB	19	18	Pilot project for promoting prefabricated renovation technology. Targeting of typical mass constructed building regardless of location.
2023–2024	604	372	Regional targeting that was introduced in 2019 was continued. Grant amount was raised for smaller multifamily buildings (less than 18 apartments). Prefabrication grant was introduced. Focus on neighbourhoods and very large buildings. https://www.riigiteataja.ee/akt/111072025002

finance the renovations, apartment association applied for commercially available loans. The final interest rate is combined by EURIBOR and banks risk margin. The loan obligation is legally tied to the apartment but to apartment owners whoa are free to sell or rent their apartment.

In 2010, the Estonian government sold its unused emissions quota, known as Assigned Amount Units (AAU), to the Grand Duchy of Luxembourg as part of the international emissions trading system. The proceeds from this sale were then utilised to finance investments aimed at enhancing the energy performance of multifamily buildings. Subsequently, a new renovation support program was introduced, with a greater emphasis on deep renovation as a means of achieving significant energy savings and emissions reductions in residential properties.

The first period of deep energy renovation programme, which took place between 2010 and 2014, had a budget of 38 million euros. The grant allocation was based on the achieved Energy Performance Certificate (EPC) class and its corresponding energy performance indicator (EPI). Specifically, a 15 % grant was provided for achieving at least 20 % calculated energy savings and EPC E (EPI<250kWh/(m2·a), a 25 % grant for achieving at least 40 % calculated energy savings and EPC D (EPI<200 kWh/(m2·a), and a 35 % grant for achieving at least 50 % calculated energy savings and EPC C (EPI<150kWh/(m2·a). The focus of this period was solely on reducing energy consumption, and all apartment associations were on an equal footing – no specific targeting was used. In total, 661 buildings received support through this program. Average energy savings per apartment building were 43 % and the total annual energy saving was approximately 60GWh (Kuusk and Kalamees, 2016). However, it should be noted that the smallest grant amount of 15 % only facilitated partial renovations. This lower level of ambition was initially introduced to kickstart the program, with plans to increase ambition in subsequent periods.

The support for the second period (2015–2017) was as follows: a 15 % grant was provided for achieving at least 20 % calculated energy savings and EPC E (EPI<220kWh/(m2·a), a 25 % grant for achieving at least 40 % calculated energy savings and EPC D (EPI<180 kWh/(m2·a), and a 35 % grant for achieving at least 50 % calculated energy savings and EPC C (EPI<150kWh/(m2·a). Additional five percentage points was awarded on top of highest grant if heat recovery ventilation was adopted as such systems improves indoor air quality while wasting less energy (Mikola et al., 2022). Furthermore, technical requirements were established for building components. The focus now shifted towards improving the indoor climate. It became mandatory to implement minimum thermal transmittance for external walls, roofs, and windows, as well as minimum ventilation airflow rates. Support was also provided for non-energy-saving renovation works, such as the water and sewer system and electricity.

As technology became more complex, the government began training technical consultants who were qualified to assist apartment associations in their pursuit of deep energy renovations, including the application for grants. Although the term "technical consultants" originates from Estonian renovation practice, they can be better described as general renovation advisers who possess expertise in technical aspects while also understanding the legal and economic implications of deep energy renovations. Their training in management of people and organisations is marginal. However, many of the consultants are also building managers and therefore have extensive experience in dealing with organisations.

The second period marked first attempts in subsidy targeting. For the most lagging region of IVIR subsidy amount was increased by 10 percentage points. The leading regions of TRTL and TLL could not apply for lowest grant rising threshold for energy conservation ambition only in two largest cities.

For the third period of the subsidy programme in 2019 no changes were introduced in technical requirements. However, ambitious regional criteria was proposed based on regional data. Previous research stressed that a disproportionate amount of grants was being obtained by rapidly developing regions with major cities. Consequently, this further exacerbated existing regional disparities (Lihtmaa, Hess and Leetmaa, 2018). It was also revealed that lower real estate values limited the ability to secure adequate renovation loans for carrying out extensive energy renovations in regions that were lagging behind (Lihtmaa, 2018).

The revised grant terms and conditions introduced different grant rates for regions. Two major cities, Tallinn and Tartu, which are also regional centres for two only growing regions and were previously receiving the majority of the grants, are now eligible for a smaller grant of 30 percent. In addition, heat recovery ventilation system was mandatory only in those cities. Other cities, primarily smaller regional centres, with an average real estate value exceeding 500 euros per square meter for a dwelling, were eligible for a grant of 40 percent. Areas with lower real estate values qualify for the highest grant rate of 50 percent. The previous lowest grant rate of 15 percent has been abandoned due to the increasing ambitions of apartment associations and more importantly the measure was deemed mediocre in terms of energy efficiency (Hamburg and Kalamees, 2018).

Buildings of cultural or historical significance were not required to attain an EPC class C (EPI<150kWh/(m2·a). Instead, they were expected to achieve an EPC rating that is one class better than their current rating. This exemption is justified by the fact that these buildings often face restrictions that hinder them from fully carrying out the necessary renovation work, such as limitations on external wall insulation.

To enhance procurement transparency, reduce disputes, and simplify the procurement process for apartment associations, all renovation procurements were conducted through the Public Procurement Register.

In 2020, the grant budget was allocated to European statistical regions (NUTS level 3). The aim of this change was to allow apartment associations with fewer resources more time to prepare their applications. NUTS 3 regions were chosen because the total budget of 28 million euros was insufficient to allocate at the county level. The budget was divided among five NUTS regions based on the total number of dwellings in multifamily buildings within respective region. In other words the funds were allocated proportional to housing stock, however occupancy was not considered. Based on research studies, the average real estate value was taken into account to reflect the region's economic capability as a whole. The average real estate value of apartments was based on statistics from the Estonian Land Board (national government agency), which keeps records of real estate transactions. However, the regional differentiation of grant amount remained the same.

The support provided in the fourth period in 2020 aimed to assist apartment associations and construction companies during the COVID-19 crisis. In order to distribute funds quickly, regional allocations were not implemented. The grant program followed the same principles as introduced in 2019, with one additional exception. There was an option to carry out partial renovations in areas with low real estate values (below 200 euros per square metre) without having to meet energy-saving requirements. The purpose of partial renovations was to enhance living conditions in regions where deep energy renovations are unlikely to happen.

In 2021, a dedicated grant scheme was introduced to promote the use of prefabricated renovation technology that had been pioneered in 2018 (Pihelo et al., 2017; Pihelo et al., 2020) and 2020 (Nigumann et al., 2024). The early adopters of 19 typical mass-constructed multifamily buildings were awarded a grant rate of 50 percent, regardless of their location.

The fifth period of the grant programme in 2023 largely followed the same principles as in 2019, including the same regional differentiation terms and conditions. However, no regional allocation of funds was employed. The main changes included a 10 percent increase in support for smaller apartment buildings (less than 18 apartments) because of higher unit costs in renovating smaller buildings. There was also a greater emphasis on improving the accessibility of existing apartment buildings. For instance, energy renovations can now include the addition of an elevator to a building that previously did not have one.

3. Methodology

3.1. Analysis framework

To address the research questions, we employ mixed research methods. Initially, we use quantitative methods to analyse renovation patterns, specifically focusing on the spatial distribution of renovation grants. We calculate the Proportionality Index (PRI) of subsidy distribution and compare this metric across different regions to evaluate the equality of subsidy distribution. Next, we attempt to assess whether the distribution is fairly allocated between regions. For this purpose, we specify the Regional Development Index (RDI) and compare it against the PRI. Our assessment of fairness is grounded in the Estonian national interest, which defines balanced regional development as a significant national goal Estonian national strategy Estonia 2035; Estonia 2035, 2021); thus, regional policy must support the lagging regions. Therefore, if regions with a low RDI obtain more subsidies, the allocation can be considered unequal yet fair.

Additionally, we investigate the dynamics of subsidy distribution across regions to evaluate how the evolution of subsidy application waves has influenced regional distribution. We utilise annual subsidy data from 2010 to 2024 and define three distinct waves that illustrate significant milestones in changes to subsidy allocation criteria. Our main assumption is that the introduction of criteria to differentiate renovation grants based on regions will lead to a fairer distribution of common resources.

In developing the PRI, we observed that there seem to be thresholds that cap the renovation decisions, which in turn influence subsidy distribution. We noted that buildings with low occupancy are often not renovated. While this may not be the case throughout Europe, in countries with a high owner-occupancy rate, where buildings are managed collectively by apartment associations, under-occupied buildings face significant challenges in undertaking deep energy renovations. Moreover, this issue is exacerbated in shrinking regions. Our second observation is that both small and large buildings have rarely received grants. Consequently, we provide additional logistic regression analysis to evaluate the extent to which occupancy and building type determine the likelihood of receiving a renovation subsidy.

In addition, we use qualitative analysis to provide explanations of the observed distribution patterns. To achieve this, we conduct expert interviews with policymakers and practitioners.

3.2. Data collection and analysis

3.2.1. Quantitative analysis

For quantitative analysis we use several datasets. The detailed information about data sources and availability is presented in Appendix Table A1.

3.2.1.1. Evaluating equality of subsidy distribution. To evaluate equality of grants distribution, we calculating the Proportionality Index (PRI) for regions using annual subsidy distribution data from 2010 to 2024. We follow the original methodology by Lihtmaa et al. (2018). The PRI is a simple ratio of the grant share divided by the share of buildings in the respective region (equation 1).

$$PRI = \frac{Share\ of\ subsides\ in\ Region}{Share\ of\ building\ stock\ in\ Region} \quad (1)$$

The building stock includes only apartment buildings which are in need of renovations. We exclude buildings that were erected after year 2000. To better account for unused building we only include buildings that are demonstrate occupation rate greater than 50 percent according to population registry. This is based on recent study on residential vacancies in Estonia (Lihtmaa and Kalamees, 2025). The share of housing stock and subsidy share are calculated in dwelling units to mitigate the influence of building size which are not distributed equally among regions.

A PRI value of one indicates perfect equilibrium between grants and building stock. Values above one indicates that a region has received more grants than the building stock would suggest. PRI values below one suggests that a region is underperforming in acquiring grants. PRI thresholds are presented in Table 2. For evaluation of the equality across

Table 2
PRI score threshold classification.

	PRI deviation	PRI lower bounds	PRI upper bounds
Slight	10 %	0.90	1.10
Moderate	25 %	0.75	1.25
Strong	50 %	0.50	1.50

regions we use average PRI between 2010 and 2024 and employ variation analysis.

3.2.1.2. Evaluating fairness of subsidy distribution. To assess the fairness of subsidy distribution in relation to regional development goals, we propose a Regional Development Index (RDI), a composite index represented by a single value. The RDI was necessary to create, as Estonia does not publish an official RDI but instead relies on various single-component indicators, such as GDP per capita. EU-level composite indices are unsuitable for regional analysis, as the smallest regional unit, NUTS3 (EU Nomenclature of territorial units for statistics), is too large when compared to Estonian administrative division.

The RDI is based on two pillars of economic and social indicators covering the period from 2010 to 2023 (Table 3). All values are initially normalised using the min-max method. The indicators are then organised into pillars and ultimately combined into a single composite value using equal weights based on the mean average. The composite index is calculated for each year and averaged to produce a single index value for every region (refer to Appendix B2. for details). This approach yields the most representative index values over the specified timespan, making it suitable for comparison with the PRI. For PRI and RDI relationships we use correlation analysis (Pearson and Spearman) and linear regression (equation 2).

$$y_i = \beta_1 x_{i1} + \beta_2 x_{i2} + \cdots + \beta_p x_{ip} + \varepsilon_i, \quad (2)$$

where.

y_i: Response (dependent) variable for observation i.
x_{ij}: j-th predictor for observation i (j = 1, …,p).
β_j: Coefficient for predictor j.
ε_i: Random error term for observation i.
p: Number of predictors.

3.2.1.3. Classifying regions using RDI. We use standard-deviation classes, which highlights outliers. The RDI mean (0.403) and SD (0.207), results is four bands: Very high ≥0.403 + 0.207 = 0.610 (HAR, TRT); High 0.403–0.610 (RAP, PAR, SAA); Low 0.196–0.403 (LVIR, VIL, HII, JAR, LAA, VOR, VAL, POL, JOG.); Very low <0.196 (IVIR).

3.2.1.4. External renovation barriers. We specify a logistic regression model (equation 3) to evaluate how the probability of grant acquisition is influenced by the two variables (1) housing occupancy rate (HOR) and (2) the type of the buildings (). The logistic regression equation is as follows:

$$logit(p) = ln(p / (1 - p)) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n \quad (3)$$

where logit(p): Log-odds of the probability p, β_0: Intercept (bias term), $\beta_1, \beta_2, \ldots, \beta_n$: Coefficients (weights) for each feature, $x_1, x_2, \ldots, x_n$: Input features (independent variables), e: Euler's number (≈2.718).

The buildings' size typology (Table 4) is not official but is often used

Table 3
Indicators in Regional Development index (RDI).

Pillar	Source in Statistic Estonia	Indicator	Unit
Economic	RV06U	DEMOGRAPHIC LABOUR PRESSURE INDEX	index
Economic	RV088	POPULATION PROJECTION 2020–2080	percentage
Economic	SK15	SHARE OF PENSIONERS IN TOTAL POPULATION	percentage
Social	TT442	UNEMPLOYMENT RATE	percentage
Social	RAA0050	GROSS DOMESTIC PRODUCT	EUR/per capita
Social	ST14	MEAN EQUIVALISED ANNUAL DISPOSABLE INCOME	EUR/per capita

Table 4
Multifamily building types.

Designation	Size type	No of dwellings in type	Main construction type	Main Time period	Share of buildings, %
XS	Very small	3 to 4	Wooden	1924–1970	26
S	Small	5 to 17	Wooden and brick	1900–1995	47
M	Medium	18 to 39	Prefab and brick	1960–1990	14
L	Large	40 to 71	Prefab	1960–1980	9
XL	Very large	72 and more	Prefab	1970–1995	5

in practice as it presents simple yet robust method to break down different types of apartment buildings. Both variables (HOR and type) are used as categorical in analysis for easier interpretation of the result. In addition, raw data already indicates specific thresholds in for both variables justifying the use of categories instead of continuous data.

We have chosen these independent variables for three specific reasons. First, both variables represent renovation barriers that apartment associations have no control over. For instance, building type are difficult to change due to economic, legal, planning reasons. While some structural configuration changes have been implemented in practice, mass-adoption is unfeasible. At same time, renovation barriers like poor leadership can be relatively easily mitigated (see Fig. 1 for reference). Therefore, barriers that are external to apartment associations should be addressed much more comprehensively at the governmental level in order to achieve climate goals. This principle is analogous to works of Ronald Dworkin who by addressing responsibility in justice distinguishes between brute luck and option luck (Dworkin, 1977). As the former "luck" type is not controlled by the individual, it can thereof be addressed as external barriers to renovations.

Second, occupancy rate and building type are available for the entire building stock, reducing data collection costs for future iterations if these variables prove promising. Furthermore, the method is scalable for other countries that also implement this exercise, as such data is more likely to be available as well.

Third, based on experience and a published study (Lihtmaa and Kalamees, 2025), we assume that the occupancy rate and building type could be used as thresholds in calculating a more elaborate PRI and planning for regional grant budget allocations.

Quantitative data was analysed with MS Excel, IBM SPSS v26 and QGIS v3.28 software.

3.2.2. Qualitative analysis

Qualitative data is gathered through expert interviews with: (1) policymakers and stakeholders who directly influence energy policy; and (2) technical consultants who advise apartment associations on their grant applications. As technical consultants collaborate with all market participants involved in renovations, they also represent the collective views of these participants.

3.2.2.1. Respondents: policy makers and stakeholders. There are several governmental parties that shape residential energy subsidy interventions. The official leader of policy design is the Ministry of Climate (KLIM), which is responsible for housing and energy policy. KLIM works closely with the Estonian Business and Innovation Agency (EIS, formerly known as Fund KredEx), which acts as the subsidy application unit for the government. Subsidy planning is supervised by the Ministry of Finances, and spatial advice is provided by the Ministry of Regional Affairs and Agriculture (AGRI) at the time of the interviews. Governmental institutions have since the been restructured.

The renovation wave for multifamily buildings is supported by several stakeholders, the most notable of which, in the context of our

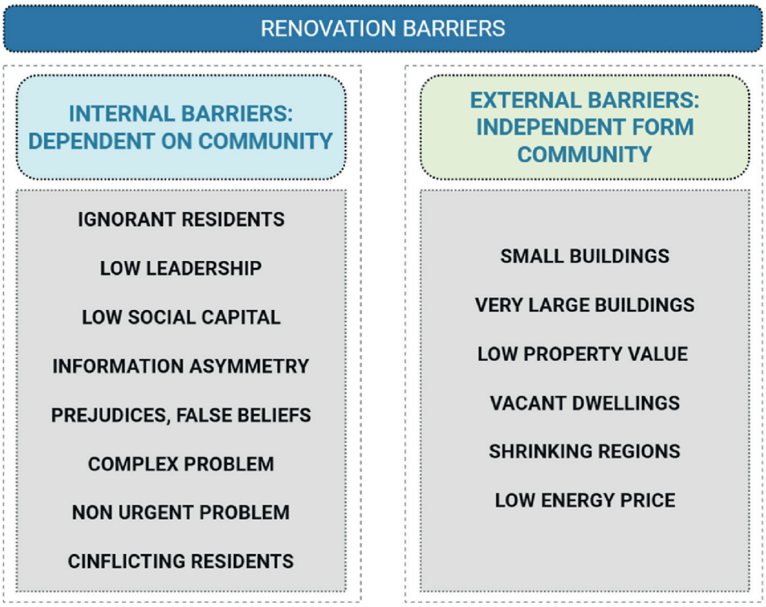

Fig. 1. Typology of deep energy renovation barriers in owner occupied multifamily buildings that are managed collectively by the residents that from apartment associations. Figure adapted from (Lihtmaa, 2018).

research, are The Association of Estonian Cities and Municipalities (ELVL), The Estonian Union of Co-operative Housing Associations (EKYL), and the Estonian Central Association of Owners (EOKL). The respondents are shortly described in Table 5.

The interview plan is detailed in Appendix Table C1.

3.2.2.2. Respondents: technical consultants. As most technical consultants operate across various regions, we began by recruiting respondents from the capital region. Using a snowball sampling method, we successfully conducted in-depth interviews with five consultants who have been actively working with apartment associations since at least 2012. Consequently, these consultants possess experience relevant to all phases of the subsidy application process. We ground the interview sample size in saturation criteria that refers to the stage at which no new themes, codes, or insights arise from additional interviews (Saunders et al., 2018). Achieving this threshold signifies that the collected data adequately reflects the diversity and depth of the phenomenon being studied, suggesting that further data collection is unlikely to provide any meaningful information. In our case, saturation was achieved after only three interviews, as the information provided by new respondents closely mirrored that of previous participants. The low number is plausible, considering we had consultants with extensive and active experience. The interview plan can be found in Appendix Table C2.

3.2.2.3. Data analysis of the interviews. The semi-structured interviews were conducted in Estonian language using online video conferencing tools within May 2024 to August 2025. Each session lasted about 1 h. Some interviews were group interviews if several respondents were present from the same institution. The discussions were recorded with the consent from the respondents. The data was then transcribed and analysed using QDA Miner Lite.

The data were analysed using thematic analysis following the six-phase approach outlined by Braun and Clarke (2006). This method was selected for its flexibility in identifying, analysing, and reporting patterns within qualitative data while allowing both inductive and deductive coding. First, all data were transcribed and repeatedly read to ensure familiarisation. Second, initial codes were generated systematically across the dataset, capturing features of interest relevant to the research questions. Third, these codes were collated into potential themes, gathering all relevant data under each theme. Fourth, the themes were reviewed and refined, ensuring they accurately reflected the coded extracts and the dataset as a whole. Fifth, themes were defined and named to capture their essence and scope. Finally, the main finding were presented across themes.

Table 5
Respondents who shape the energy policy.

Acronym	Institution type	No of respondents	Position
KLIM	Ministry	2	Adviser, project manager
AGRI	Ministry	2	Head of department, adviser
EIS	Foundation	1	Project manager
EKYL	Union	2	Board members
ELVL	Union	1	Adviser
EOKL	Union	1	Board member

3.3. Research limits

We only observe renovations that have applied for a state renovation grant. We acknowledge that there are renovations implemented without grants, which may be relevant for pattern analysis. Unfortunately, the Building Registry has very limited documentation on renovations that have been carried out without grants. Therefore, it is necessary to conduct a separate study in order to create a comprehensive database of renovations without grants. However, the primary focus of this study explicitly addresses how state aid is allocated among beneficiaries.

Although renovation decisions are influenced by various factors, we solely examine how occupancy and building properties impact the likelihood of a successful subsidy application. We exclude other variables for several reasons: (1) they are not available for the entire population, (2) occupancy rates and building types can be obtained for the entire building stock, and (3) we intend to utilise occupancy and building type as thresholds for evaluating renovation probabilities.

While the result is limited by the variables used in model, we justify the method as occupancy and building size could be addressed as thresholds.

4. Results

4.1. Equality and fairness of renovation subsidy distribution

4.1.1. Evaluating subsidy distribution equality

To measure the distribution of subsidies, proportionality index (PRI) is used. PRI value of one can be considered as perfect equal distribution of subsidies. The distance from PRI value of one in percentage points illustrates large differences and can be observed in Table 6. The best performer (LVIR) is +155 % away from equality, while worst performer (IVIR) deviates −88.5 % below equality. The Coefficient of Variation (0.556) shows high relative variation and PRI values differ strongly between regions. The mean (1.285) is notably higher than the median (1.06), meaning the distribution is right-skewed, driven by a few high-performing regions (LVIR, POL, RAP). The bottom region (IVIR at 0.11) is far below the mean, indicating large regional disparities in renovation uptake proportionality. Such a variation can be considered unequal.

4.1.2. Evaluating subsidy distribution fairness

We hypothesise that if a lagging region receives progressively more support than growing regions, the distribution of renovation subsidies is fair. In terms PRI we expect lagging regions to have PRI values over proportional value of one and for the leading regions PRI value should be under one. To measure regions' development status, we specify Regional Development Index (RDI, see methodology section for reference).

The average RDI values are used in analysis and are presented in Table 6 and annual RDI values in Appendix Table B2. The average RDI values range from 0.049 to 0.884, giving a total spread of 0.835 points. The mean RDI is 0.403, with a median of 0.373, indicating a slightly right-skewed distribution (more regions below the mean than above). The standard deviation is 0.214, producing a coefficient of variation of 0.53, which signals substantial relative dispersion—regional development levels vary by more than half of the mean value.

RDI variation in Estonia is pronounced, with a clear divide between the two largest urban regions (HAR and TRT) and the rest of the country which aligned with earlier reports (Raagmaa, 2023; OECD, 2025). While most regions fall within a relatively narrow middle band, the presence of these high-performing outliers significantly inflates the national average. The lower tail shows no formal statistical outliers, but the extreme underdevelopment of IVIR relative to the mean has major policy relevance and should therefore account for interpreting the fairness evaluation. The relationship between PRI and RDI is shown in scatterplot Fig. 2 (a).

Across all 15 regions, the correlation between RDI and PRI is weak (Pearson r = 0.094; Spearman ρ = 0.207). Linear regression slope is 0.317 with $R^2 \sim 0.009$, and the robust slope is 0.363—both tiny and non-significant. Consequently, we observe no linear relationships.

Sensitivity checks are revealing. TRT and IVIR are two major outliers considering fairness of subsidy distribution. These regions demonstrate a strong positive correlation between RDI and PRI – TRT performs well in both areas, while IVIR lags behind in both. This means that subsidies are increasing exiting regional disparities which is against regional goals. Excluding TRT and IVIR, the parity-slope turns negative (regression slope −1.16; robust −0.91), Spearman rank association becomes slightly negative (ρ ∼ −0.03), and the share above parity is very similar in bottom vs top halves (≈86 % vs 83 %). In other words, once IVIR and TRT are removed, the pattern moves toward a mild catch-up orientation—lower-RDI regions are not disadvantaged and the fitted relation tilts in their favour, though effects are still modest.

In conclusion, removing those two high-influence cases yields a pattern that is consistent with Estonia's even-development objective: the slope of deviations becomes negative and the probability of being above parity is favours the less developed half. Thus, the aggregate system looks largely fair once the outliers are handled, but fairness is not uniform – IVIR appears chronically underserved and requires targeted capacity-building or earmarked calls, while TRT's recurrent over-representation warrants monitoring to avoid excessive concentration of subsidies.

4.2. Dynamics of subsidy distribution across regions

4.2.1. Annual analysis

For the dynamic analysis of subsidy distribution, we separate two largest cities Tallinn (TLL) and Tartu linn (TRTL) from the regional dataset, because subsidy distribution rules in 2019 explicitly address those cities as separate regions. TLL is the capital city and belongs to the region of HAR and Tartu linn (TRTL) belongs to the region of TRT.

The annual dynamics of subsidy distribution across regions (presented in PRI values) is shown in Appendix B1. The PRI percentage distance from perfect proportionality (PRI = 1) is shown in heatmap (Fig. 3). The regions in heatmap are ranked in the descending order of average PRI value in region. To interpret the results, we use PRI score classification (Table 2).

Analysis of the annual PRI deviations across regions reveals pronounced temporal and spatial disparities in the proportionality of renovation grant allocation. Early years (2010–2012) show relatively moderate absolute deviations, with mean values ranging from −31.5 to −14.0 percentage points, suggesting a closer—though still uneven—alignment between grants and building stock distribution. A marked shift occurs from 2013 onwards, when both positive and negative extremes intensify, culminating in exceptionally high overrepresentation in certain regions, such as TRT in 2014 (+485.2 p.p.) and 2019 (+597.4 p.p.), alongside persistent severe underrepresentation in others, most notably IVIR, which repeatedly records the lowest values (down to −96.3 p.p. in 2017). The absence of data for 2018 reflects the depletion of grant funds, but the volatility before and after this gap indicates that allocation patterns were not structurally corrected over time. The distribution thus appears increasingly polarized, with a small set of regions disproportionately benefiting from grants while others remain chronically disadvantaged. This persistence of extreme deviations suggests that systemic factors—rather than random fluctuation—drive the inequity in grant distribution, potentially linked to administrative priorities, political influence, or differential application capacity across regions.

4.2.2. Three renovation waves

PRI values during three distinct renovation waves are presented in Fig. 4 where the red line illustrates perfect proportionality (equality, equilibrium, parity) as PRI value is equal to one, and the green box represents the equality zone (PRI deviation distance of 10 % in linear scale; PRI values 0.90–1.10). PRI values are listed in descending order

Table 6
Average RDI and PRI. PRI deviation from perfect equality (PRI = 1) in percentage points across regions.

Region	LVIR	POL	RAP	TRT	VIL	SAA	JOG	PAR	JAR	HAR	VOR	VAL	LAA	HII	IVIR
RDI, avg	0.23	0.39	0.51	0.37	0.82	0.38	0.36	0.45	0.34	0.33	0.22	0.47	0.25	0.88	0.05
PRI, avg	3.00	2.75	2.15	1.87	1.86	1.85	1.61	1.49	1.30	1.30	1.26	1.14	0.92	0.86	0.18
PRI Deviation, %	200.4	174.9	115.0	87.5	86.2	84.6	60.6	48.8	29.6	29.6	26.3	13.8	−7.6	−14.3	−82.1

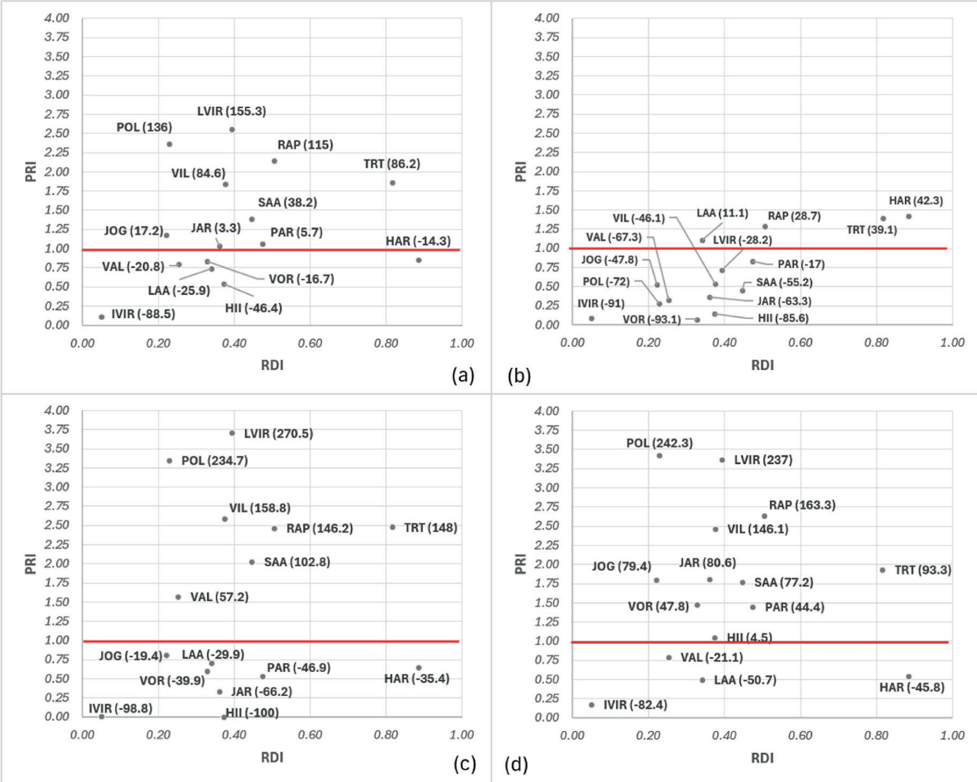

Fig. 2. Relationship between subsidy distribution proportionality (PRI) and regional development index (RDI) across regions. The PRI value distance from perfect equality (PRI = 1, red line) is shown in percentage points in brackets beside every region. (a) PRI average between years 2010–2024; (b) PRI First wave 2010–2014; (c) PRI in second wave 2015-1027; (d) PRI in third wave 2019–2024. Data source: Statistics Estonia & EIS, authors' calculations. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

	phase one					pahase two			phase three					
	2010	2011	2012	2013	2014	2015	2016	2017	2019	2020	2021	2022	2023	2024
TRT	-51	-1	46	262	485	221	291	30	597	187	80	137	342	78
LVIR		-73	-38	130	-77	211	201	344	371	184	192	340	163	149
POL			-31	-37		406	88	154	237	266	160	546	234	-4
RAP	59	24	2	83	-51	181	120	109	-19	180	379	70	209	146
VIL	-42	-76	-46	-59	-27	119	60	241	97	52	16	270	304	89
TRTL	-59	31	48	131	-93	141	124	152	24	157	106	53	-18	29
HAR	35	33	30	81	44	64	13	38	2	47	182	-11	6	16
SAA	-43	-48	-62	-85	-45	281	-26	33		255	14	139	133	24
JOG	-76	-60	-18	-3		46	-29	-92	-27	-8	87	228	17	163
PAR	-30	-54	-4	18	-30	-84	18	-80	230	54		11	36	42
JAR		-35		11			-44	-59		-59	117	-73	242	389
VOR		-92	-75			-72	10	-66		-37	45		315	186
TLL	85	61	42	-14	58	-59	-41	-43	-63	-58	-82	-69	-73	-56
VAL		-25	-32	-91		16	159	-39	-69	-85	-31	27	-3	-1
LAA		-67	19		294	12	-65	-41					-6	72
HII		-35										184	106	22
IVIR	-78	-86	-91					-96	-91	-92	-41	-79		-84

Fig. 3. Heatmap showing PRI deviation from PRI = 1 in percentage points. Data source: EIS, authors' calculations.

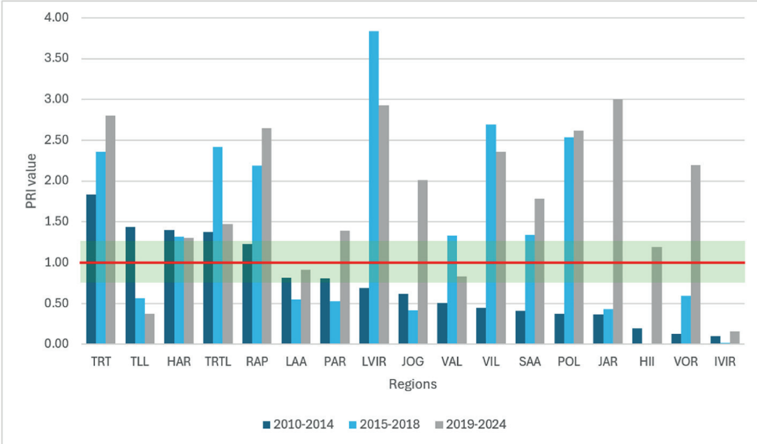

Fig. 4. The regional distribution of subsidies across the regions within three application waves. Data source: EIS, authors' calculations.

based on the first wave (2010–2014).

The first wave reveals that the growing regions (HAR including TLL and TRT including TRTL) that have the highest level in regional development status (RDI>0.80) are among the top performers in grant accumulation. Majority of other regions with low development status (RDI >0.51) are well below the equality line. This means that well developed regions were better prepared to take advantage from the first comprehensive subsidy programme which had moderate efficiency targets and no regional differentiation established. This wave demonstrates unfair subsidy distribution as leading regions acquire most of the subsidies and policy makers were therefore recommended to address regional aspects in deep energy renovation policy in Estonia (Lihtmaa, Hess and Leetmaa, 2018). The relationships between PRI (without TLL and TRL) and RDI for first wave is shown in Fig. 2 (b).

The second wave of grant distribution began in 2015 with the introduction of additional energy performance criteria (see Table 1 for reference). The most notable change compared to the first wave is the significant decline in the PRI value of TLL ($PRI_{F2} = 0.52$, dev = −47.6 %). This is particularly surprising, considering TLL's large housing stock and the performance in the first wave. Results indicate that Tallinn, the capital city, has lost its momentum and acquired fewer grants than the building stock would otherwise suggest. In contrast, TRTL, the second-largest city in Estonia and similarly a growing region with relatively large housing stock, managed to increase its grant acquisition compared to the first wave ($PRI_{F2} = 2.39$, dev = +139.1 %). Second wave also marks shift in the performance of lagging regions which now got unproportionally many subsidies (LVIR, VIL, POL). This is notable trend as renovation subsides had equal support share across regions. IVIR, however still lags behind and showing even worse performance compared to first wave and therefore hinting for serious structural renovation uptake barrier. The relationships between PRI (without TLL and TRL) and RDI for second wave is shown in Fig. 2 (c).

The next major change in the grant criteria regarding regional differentiation was introduced in 2019 and has been maintained since then. This change marked the beginning of the third wave of grant distribution, with the primary aim of achieving a more even distribution of grants while considering the national interest in balanced regional development. This wave several lagging regions (JOG, JAR, VOR, HII) were able to increase gran acquisition significant and therefore influencing the yearly averages that were basis for the fairness evaluation. Well performing regions from previous wave like RAP LVIR VIL POL were able keep their performance in third wave as well. Regional criteria did not however affect significantly IVIR, we can only observe slight increase of PRI over average of previous waves (PRI 0.09 to 0.22). Therefore, structural barriers still prevail in IVIR. The relationships between PRI (without TLL and TRL) and RDI for third wave is shown in Fig. 2 (d).

Consequently, the data indicates that comprehensive deep energy renovation subsidy programme started in 2010 very unfairly with leading regions benefitting most. During the evolvement of subsidy programme grant distribution has been changing much fairer where regions needing the support benefitting the most. There are two outliers TRT and IVIR which demonstrate unfair subsidy allocation and should therefore be addressed in policy design.

4.3. Renovation uptake and external renovation barriers

We specify a logistic regression model grounded on annual data to evaluate the impact of the independent variables, such as occupancy rate and building type, on the probability of grant application success (a binary dependent variable). The model's pseudo R^2 (Nagelkerke) results in a value of 0.207, which is relatively low and indicates limited explanatory power. Additionally, the model failed to predict any grant applicants correctly. This was to be expected as the independent variables do not encompass a sufficient range of factors that could influence the renovation decision. For instance, important variables such as leadership, trust (Ojamäe and Paadam, 2015), social capital (Cirman et al., 2013), and even ethnicity (Hess et al., 2022), which have been shown to be associated with collective decision-making among residents, are missing from our model.

However, we can still observe the significance of occupancy rate and building type in determining the success of grant applications, while also acknowledging that there are other variables that can have a greater impact on the probability of application approval. The findings from the logistic regression analysis are shown in Table 7.

Since we used categorical variables, the odds ratio (OR), which is represented as the exponential beta coefficient [exp(B)], is of interest to us. The odds ratio indicates the influence on the probability against the reference variable within the same category group. Therefore, as the occupancy rate increases, the probability of renovation also increases. Compared to a moderate occupancy rate of 80 percent, the probability of a successful grant application is 3.7 times greater when the building is close to full occupancy. A grant application is unlikely if the occupancy rate drops below 77 %, resulting in an odds ratio of 0.133.

The second independent variable, building type, reveals that medium-sized buildings (type: M) are the most likely to receive grants

Table 7
Results from logistic regression for dependent variable of grant application success. Data source: EIS & Buildings Registry, authors' calculations.

Variable	Frequency	B	Sig.	Exp (B)
Occupancy rate: 95–100 %	9848	1.322	0.000	3.752
Occupancy rate: 89–94 %	1717	1.298	0.000	3.662
Occupancy rate: 83–88 %	1540	1.006	0.000	2.736
Occupancy rate: 77–82 %	1415	reference		
Occupancy rate: 71–76 %	538	−2.014	0.006	0.133
Occupancy rate: 65–70 %	523	−1.282	0.015	0.278
Occupancy rate: 59–64 %	140	−17.588	0.996[a]	0.000
Occupancy rate: 53–58 %	1468	−0.255	0.569[a]	0.775
Occupancy rate: 47–52 %	967	−1.323	0.070[a]	0.266
Occupancy rate: 0–47 %	1074	−2.925	0.004	0.054
Building type: XS (3-4DW; wooden)	4439	−3.115	0.000	0.044
Building type: S (5-17DW; wooden&brick)	9931	reference		
Building type: M (18-39DW; brick&prefab)	1898	1.114	0.000	3.046
Building type: L (40-71DW; prefab)	1926	0.933	0.000	2.543
Building type: XL (72+DW; prefab)	1036	0.459	0.000	1.583

[a] Statistically insignificant.

for renovations compared to our reference category of small buildings (type: S) (OR = 3.046). Larger buildings (type: L) are less probable that medium sized, but still more likely than small buildings (OR = 2.543). The largest buildings (type: XL) are less likely to renovate compared to type L, but more likely than the reference type (OR = 1.583). The smallest category of multifamily buildings is very unlikely to succeed in a grant application (OR = 0.044).

4.4. Reflections from regulators and market participants on renovation policy

4.4.1. Policymakers and stakeholders

The main statements provided by the respondents for our inquiry regarding key themes are presented in Appendix C3.

The distribution of subsidies among regions was a subject that all respondents were able to relate to based on their experiences. In general, there was agreement that state assistance should be distributed in a fair and rational manner.

However, the first challenge arose when the concepts of equality and fairness were not perceived in the same way, leading to many questions during the interviews. The overarching insight is that respondents possessed a significantly greater understanding of equality than of fairness, as they identified more objective methods for measuring equality.

It was interesting to observe that in its simplest forms, equality may not be the desired outcome for policy makers. For instance, some respondents questioned whether the regional proportionality for renovations is a reasonable indicator to strive for. AGRI pointed out that if regional development is so unbalanced, with 60 percent of GDP originating from the capital region, then perhaps state aid for renovations must counterbalance the effect, and unequal distribution of grants (against the growing regions) should serve a specific purpose in such action. This idea strongly resonates with fairness articulated by (Rawls, 1999)

There was common agreement that while achieving a perfect proportional balance of subsidies is debatable, the PRI could be still a valuable indicator for monitoring subsidy distribution, particularly when aiming to quantify policy changes.

The unequal distribution of grants, particularly in the capital region of Harjumaa, was surprising to stakeholders. For instance, ELVL admitted that they had not previously witnessed this aspect of the impact, and they are now interested in other metrics that indicate the progress of state aid, especially how subsidies influence municipalities and regional development. As ELVL represents municipalities, they showed interest in the PRI between and within municipalities.

Respondents admitted that their institution is not monitoring the equality of grant distribution in a specific manner, such as tracking the PRI. EIS and KLIM stress the time constraints involved in designing the subsequent period of the grant programme that often hinders the use of more sophisticated approaches. Instead leading working groups evaluate the outcomes of previous periods on an ongoing basis and make policy decisions intuitively as they process data and opinions.

The speed required in policy development often results in a more superficial engagement of the parties and stakeholders. AGRI expresses dissatisfaction with the underutilisation of their expertise in the spatial domain. Involvement typically takes place through the coordination of the formal policy decree. AGRI, on the other hand, expects a greater level of debate and discussion regarding the regional aspects of the grant design. Conversely, KLIM acknowledges these limitations but defends the formal approach based on time constraints and the multitude of responsibilities faced by KLIM officials.

While addressing the disparities between short- and long-term priorities in energy policy design, policymakers acknowledged the potential for developing a comprehensive regional strategy through enhanced cooperation. Although the time constraint may not be immediately evident, other pressing tasks could impede the realisation of these aspirations.

Most stakeholders reported perceiving the involvement less critically and affirmed that their feedback on policy design is anticipated and well-received. ELVL indicated that the current practice of involvement is satisfactory, and they do not possess the capacity to engage more extensively in policy design. If municipalities are entrusted with more responsibilities in the context of the renovation wave, it is reasonable to expect a more inclusive approach. This, in turn, necessitates the union to enhance its capacity to contribute. EOKL, on the other hand, adopted a more critical stance, asserting that their perspectives are not well-received.

4.4.2. Technical consultants

The extended result of the interview analysis is presented in Appendix C4. Here we present concise overview of most relevant topics emerged.

Renovation momentum has been driven more by property managers, consultants, and municipal programmes than by households themselves. Demonstration projects often triggered strong positive spillover effects, with neighbouring apartment associations following suit. Periods of low interest rates, accessible grants, and expanded eligibility created surges in applications. Simple payback narratives and favourable conditions helped associations act quickly when funding windows opened. A shift to first-come-first-served electronic subsidy application systems generated perceptions of procedural unfairness and even legal disputes.

Local contexts shaped renovation subsidy uptake. In Ida-Virumaa, distrust and low heating costs dampened interest, while in Tartu, municipal support and poorer-quality stock encouraged renovation. In Tallinn, better-financed associations often bypassed subsidies to avoid bureaucracy.

Very small buildings faced prohibitively high costs, while very large ones struggled with inflated contractor fees and complex governance. Mid-sized buildings were the most likely to succeed. Even well-prepared projects sometimes failed due to opposition within associations.

Organised resistance could halt projects despite strong financial conditions. Autonomy, trust in known contractors, and control over scope often outweighed financial incentives. Concerns about loans, maintenance, and uncertain energy savings were common. Residents responded more to promises of comfort, health, and stable bills than to climate targets. When subsidies were seen as politically motivated, resistance grew. Framing subsidy programmes as neutral home improvements made them more acceptable.

The interview respondents address deep energy renovations as a triangle: (1) mobilisation problem influenced by instruments, (2) intermediaries, and (3) local context. The instruments are significant — ventilation regulations, project caps, and the mechanics of openings not only change how buildings are renovated but also whether grants are utilised at all. Intermediaries play a critical role—when building managers and consultants actively engage, and when cities support them, there is a noticeable spike in uptake (cases in TRTL and LVIR). Context also matters—factors such as the availability of cheap legacy heat, language and trust issues, and previous maintenance practices help explain why identical national rules lead to different regional outcomes.

5. Discussion and policy recommendations

5.1. Learning from successes and failures of energy policy evolution

The initial study regarding the distribution of grants for residential renovations drew attention to notable regional discrepancies (Lihtmaa, 2018; Lihtmaa, Hess and Leetmaa, 2018). In the absence of targeted intervention, subsidies tended to concentrate in already prosperous regions, reinforcing existing disparities. This pattern illustrates how economically advanced regions are better positioned to capitalize on policy instruments, perpetuating cumulative advantages. While the idea of equal opportunities advocated by many distinguished thinkers (Friedman, 1962; Nozick, 1974; Dworkin, 1977; Hayek, 2011) seems rational, the outcomes of such polices, as we can see, might turn out unfair.

The government's recognition of these disparities was pivotal in shaping Estonia's renovation policy in 2019. Unlike other contexts where the gap between research and practice remains wide (e.g Cairney, 2015; Wellstead et al., 2018)), Estonia's small scale and open "policy window" (Kingdon, 1995) facilitated rapid adjustment. Revised grant allocation rules aimed to reduce concentration in Tallinn and Tartu and support lagging regions. This objective appears to be well-founded, given that regions experiencing growth are more likely to have affluent communities that would reap the benefits of such grants. Research indicates that the occurrence of grant freeriding may be as high as 72 % (Risch, 2020).

The data shows that the average distribution of grants between 2010 and 2024 across regions is very unequal, as the deviation from the equilibrium distribution ranges between −88 and +150 percent. One of the national aims of Estonia is to achieve even regional development, which means that the lagging regions should receive proportionately more subsidies than the leading ones. This aim inherently excludes the idea of equal distribution of subsidies as fair. This notion strongly resonates with principle of difference by Rawls (1999), which legitimizes inequalities if they benefit disadvantaged groups or in our case – lagging regions.

The fairness analysis, based on averages throughout all renovation periods, does not really show that subsidies are being distributed fairly, neither is unfairness observed. The annual analysis, however, based on three subsidy application waves, shows that fairness of subsidy distribution has significantly improved over time. Back in 2010, leading regions were benefiting most from the grants. Now, over ten years later, more grants are received by regions that demonstrate mediocre development status. Despite still observing unfairness within some outliers, the current renovation policy is at least on the right track and helps to mitigate strong regional disparities.

At the same time, our study underscores that local contexts critically shape outcomes. For example, Tallinn (TLL) and Tartu (TRT) — both leading regions — experienced diverging patterns despite identical rules. In Tallinn, fragmented building management and skepticism toward comprehensive renovations, especially around mechanical ventilation (Mikola et al., 2022), hindered uptake. In contrast, Tartu's proactive city government and initiatives like the SmartenCity project (Ahas et al., 2019) pushed forward ambitious renovations, even aiming at EPC class A standards, delivering much needed messages about improving quality of life (Ebrahimigharehbaghi et al., 2022). These differences highlight how local governance, technical perceptions, and intermediary actors influence grant uptake as much as formal policy design.

The case of Võrumaa (VOR) further illustrates the power of intermediaries pointed out in earlier studies (Owen and Mitchell, 2015; Kivimaa and Martiskainen, 2018). Initially reluctant, the dominant management company in VOR discouraged deep renovations, resulting in low uptake. This not surprising, as the information asymmetry regarding to energy efficiency might also affect a management company internally (Palm and Reindl, 2018). However, when some associations switched to a more supportive management company, the original company started to shift its attitudes. In turn applications surged, and VOR became one of the top-performing regions. This shift suggests that trust in local managers often outweighs national-level campaigns.

By contrast, region of Ida-Viru (IVIR) remains the starkest outlier. Despite higher subsidy rates, renovation uptake is extremely low, reflecting a combination of structural and social barriers. Very large, under-occupied apartment buildings, historically low district heating prices, weak administrative capacity, and reliance on the declining oil shale industry (Hermwille et al., 2023; Cantoni and Claire Brisbois, 2024) all undermine renovation incentives. Added to this are issues of trust and identity, as a predominantly Russian-speaking population remains influenced by narratives sceptical of state-led modernization. The outlook for IVIR seems depressing, as one respondent vividly expressed: "the children go to better places and they are not coming back … for the elderly, the living conditions are sufficient … they do not need fancy renovations … ". These interlocking barriers demonstrate the limits of financial incentives alone in driving renovation.

The renovation proportionality indicator is influenced by the number of buildings requiring renovation. Since underused buildings could deflate PRI values, it is essential to consider underoccupied buildings. Renovation consultants emphasise that low occupancy rates present a significant barrier to renovation, as banks view underoccupied buildings as a risk. Systematically low occupancy often signifies deeper structural issues with spatial implications (Van et al., 2022). Consequently, decisions regarding renovations and applications for subsidies are unlikely to arise from buildings with low vacancy rates (Lihtmaa and Kalamees, 2025). Our analysis provide additional evidence using logistic regression and showing that if the occupancy rate drops below 77 %, renovations are improbable.

Logistic regression analysis also indicated that the construction type of buildings serves as a threshold for subsidy applications. This implies that renovation subsidies are primarily allocated to medium and large-sized buildings, while very small and very large buildings tend to be excluded from receiving these subsidies. Consultants explained that smaller buildings typically incur higher renovation costs, rendering subsidy requirements incompatible with residents' financial capabilities. In contrast, large apartment buildings are more cost-effective to renovate; however, the extensive communities often struggle to achieve consensus on renovation decisions.

While the revised subsidy scheme has improved regional fairness, two major challenges persist. First, energy performance: in cities where grant rates were reduced, many apartment associations opted for lower-budget, unsubsidized renovations, resulting in poorer technical outcomes and diminished climate benefits. Second, justice for vulnerable groups: despite better regional balance, socio-economically disadvantaged households in Tallinn and Tartu remain excluded, as citywide grant reductions do not account for within-city inequalities. From a Rawlsian perspective, this outcome contradicts the principle that inequalities are justified only if they benefit the least advantaged.

Thus, Estonia's renovation policy demonstrates both achievement and limitation. Redistribution at the regional level has reduced disparities, yet finer-grained targeting — attentive to household vulnerability and local socio-technical dynamics — is essential for ensuring both fairness and effectiveness. Future research should explore not only subsidy distribution but also the quality of outcomes, decision-making processes, and the role of intermediaries. Addressing these issues is key to designing renovation policies that are not only regionally balanced but also socially just and environmentally robust.

5.2. Policy recommendations

eFirstly, we recommend that central government and all stakeholders monitor the distribution of renovation subsidies across different regions. It is advisable to employ more sophisticated indicators than simple average subsidy rates, as these do not account for variations in building stock. Monitoring should be aligned with performance indicators; otherwise, progress may seem arbitrary. To facilitate this, the subsidy proportionality index and the regional development index can be utilised. Policymakers need only to reach a consensus on the desired outcomes in terms of quantitative indicators.

Secondly, outliers must be addressed in renovation policy. IVIR deserves special attention as this region performs worst in RDI and PRI. As the special incentives have not yielded any significant changes, structural barriers dominate in IVIR, which cannot be mitigated using traditional methods like simply increasing the subsidy size. Considering RDI, and especially the population projection, PRI could be calculated based on the dwelling abandonment forecasts. This could change the PRI and present more realistic expectations of renovation potential. While manipulating numbers does not affect the fact that IVIR`s performance on RDI is the worst, an enhanced PRI could indicate a better reality.

Thirdly, we recommend that governments shift their focus more towards local intermediaries (especially in lagging regions) who are largely responsible for investment decisions related to property management in apartment buildings. The study indicates that the willingness of apartment associations to undertake renovations can be greatly influenced by the attitudes of technical consultants and building managers when advising their clients. If these professionals maintain a positive attitude towards renovations, it is likely that apartment associations will follow their advice, as suggested by the data from this research.

Fourth, renovation policy should be shifted towards the very large and very small apartment buildings, as those are virtually missing in subsidy applications. The large buildings need better communication strategies and an upgrade of practical meeting methods, as the communities are very large. Collective action in large communities is challenging, as interview respondents point out in this research. The communities in small buildings can easily communicate; however, the renovation costs are significantly higher for deep energy renovations compared to large prefabricated apartment buildings.

Finally, regarding the concerns of the Estonian policy makers and stakeholders we propose that equality and fairness in the distribution of subsidies require improved communication between policy makers, stakeholders, and public as well. Addressing and specifying the concepts of fairness and equality enables more sophisticated debates over the terms and conditions that determine the distribution of the public resources for private use.

6. Conclusions

Our study demonstrates that renovation subsidies distribute very unequally across regions. While in the early years of subsidy programme back in 2010 only leading regions benefitted from subsidies, recent data indicates that mediocre regions have been applying for proportionally more grants than their housing stock would assume. At the same time subsidy acquisition has partially decreased among leading regions. Consequently, we argue that renovation subsides are distributing among regions rather fairly considering regional development goals that aims for even regional development between regions.

The spatial distribution of renovation subsidies has shifted in response to the changing renovation policy. The variation in grant sizes and technical requirements across regions has allowed apartment associations in underperforming areas to undertake more ambitious projects, as the high costs associated with deep energy renovations have become more manageable. However, the rate of renovation uptake is significantly influenced by local intermediaries who collaborate with apartment associations. Consequently, we see a greater number of subsidy applications in regions where the attitudes of building managers, consultants, and local authorities are supportive of energy renovations.

While renovation uptake has increased there are still structural barriers which single apartment association are unable to mitigate. We observe that application for renovations subsidy is unlikely if buildings occupancy rate is under 77 %. Similarly, the data indicates for declining probabilities for buildings which size lower than 18 and higher than 40 dwellings.

Differentiating between types of multifamily buildings is key to understanding which communities are receiving grants. This distinction should be incorporated into the calculation of proportionality between regions. The latest long-term renovation strategy in Estonia addresses multifamily buildings but fails to differentiate between their types. This oversight treats the entire multifamily building stock as a homogeneous pool of energy performance potential, hindering the targeting of incentives. Building type is a critical factor in determining the likelihood of renovations, and failing to account for this variation can impede effective policy implementation.

Our analyse demonstrates that although the renovation grant distribution policy has improved in terms of fairness, there remains insufficient collaboration between different ministry departments in policy design. Responsibilities for energy performance, housing policy, and regional development are fragmented across various departments and ministries. The most significant gap exists between policymakers responsible for regional development and housing, as they operate within different ministries.

Finally, the methodology for monitoring grant distribution lacks rigor, and the methods employed in policy design are neither published nor publicly communicated. Policymakers from various departments are often unaware of these methods, which hinders their ability to contribute to new policy designs. Therefore, to enhance communication and track progress towards regional goals, we recommend implementing a more sophisticated indicator system for monitoring subsidy distributions.

CRediT authorship contribution statement

Lauri Lihtmaa: Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Kalle Kuusk:** Writing – review & editing, Writing – original draft, Resources. **Targo Kalamees:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Large Language Model of ChatGPT version 5 in order to improve the clarity and spelling. While using this tool, the authors carefully reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Estonian housing stock

Table A1
Data sources

Data	Description	Provider	Availability
Renovation subsidy data	Subsidy application date on the building level.	Estonian Business and Innovation Agency (EIS)	not publicly available
Indicators for regional development index	Codes for indicators: RV06U RV088 SK15 TT442 RAA0050 ST14	Statistics Estonia	Opendata: www.stat.ee/en
Occupancy rate of apartment building	Dwelling based data aggregated to building level. Occupancy is determined by electricity usage.	Statistics Estonia	confidential
Building features	Building age, number of dwellings	Building Registry	Opendata: www.ehr.ee

Appendix B. Statistical indexes

Table B1
Subsidy distribution Proportionality Index (PRI) across regions including two major cities

	2010	2011	2012	2013	2014	2015	2016	2017	2019	2020	2021	2022	2023	2024	AVG	RANK
HAR	1.35	1.33	1.30	1.81	1.44	1.64	1.13	1.38	1.02	1.47	2.82	0.89	1.06	1.16	1.41	7
HII	0.00	0.65	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.84	2.06	1.22	0.48	16
IVIR	0.22	0.14	0.09	0.00	0.00	0.00	0.00	0.04	0.09	0.08	0.59	0.21	0.00	0.16	0.12	17
JAR	0.00	0.65	0.00	1.11	0.00	0.00	0.56	0.41	0.00	0.41	2.17	0.27	3.42	4.89	0.99	11
JOG	0.24	0.40	0.82	0.97	0.00	1.46	0.71	0.08	0.73	0.92	1.87	3.28	1.17	2.63	1.09	9
LAA	0.00	0.33	1.19	0.00	3.94	1.12	0.35	0.59	0.00	0.00	0.00	0.00	0.94	1.72	0.73	15
LVIR	0.00	0.27	0.62	2.30	0.23	3.11	3.01	4.44	4.71	2.84	2.92	4.40	2.63	2.49	2.43	2
PAR	0.70	0.46	0.96	1.18	0.70	0.16	1.18	0.20	3.30	1.54	0.00	1.11	1.36	1.42	1.02	10
POL	0.00	0.00	0.69	0.63	0.00	5.06	1.88	2.54	3.37	3.66	2.60	6.46	3.34	0.96	2.23	3
RAP	1.59	1.24	1.02	1.83	0.49	2.81	2.20	2.09	0.81	2.80	4.79	1.70	3.09	2.46	2.07	4
SAA	0.57	0.52	0.38	0.15	0.55	3.81	0.74	1.33	0.00	3.55	1.14	2.39	2.33	1.24	1.33	8
TLL	1.85	1.61	1.42	0.86	1.58	0.41	0.59	0.57	0.37	0.42	0.18	0.31	0.27	0.44	0.78	13
TRT	0.49	0.99	1.46	3.62	5.85	3.21	3.91	1.30	6.97	2.87	1.80	2.37	4.42	1.78	2.93	1
TRTL	0.41	1.31	1.48	2.31	0.07	2.41	2.24	2.52	1.24	2.57	2.06	1.53	0.82	1.29	1.59	6
VAL	0.00	0.75	0.68	0.09	0.00	1.16	2.59	0.61	0.31	0.15	0.69	1.27	0.97	0.99	0.73	14
VIL	0.58	0.24	0.54	0.41	0.73	2.19	1.60	3.41	1.97	1.52	1.16	3.70	4.04	1.89	1.71	5
VOR	0.00	0.08	0.25	0.00	0.00	0.28	1.10	0.34	0.00	0.63	1.45	0.00	4.15	2.86	0.80	12

Table B2
Regional Development Index (RDI) across regions

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	AVG	RANK
HAR	0.78	0.79	0.86	0.85	0.87	0.89	0.89	0.92	0.94	0.91	0.93	0.92	0.91	0.92	0.88	1
HII	0.46	0.43	0.41	0.43	0.38	0.37	0.41	0.33	0.3	0.36	0.38	0.39	0.27	0.32	0.37	8
IVIR	0.08	0.06	0.06	0.05	0.05	0.03	0.04	0.03	0.06	0.03	0.02	0.05	0.07	0.06	0.05	15
JAR	0.34	0.31	0.4	0.36	0.36	0.29	0.35	0.35	0.4	0.35	0.37	0.38	0.38	0.41	0.36	9
JOG	0.21	0.23	0.22	0.27	0.23	0.21	0.27	0.17	0.16	0.22	0.27	0.23	0.19	0.2	0.22	14
LAA	0.35	0.36	0.36	0.37	0.39	0.23	0.38	0.28	0.32	0.35	0.37	0.37	0.32	0.33	0.34	10
LVIR	0.47	0.41	0.43	0.39	0.4	0.4	0.33	0.42	0.41	0.39	0.4	0.39	0.33	0.35	0.39	6
PAR	0.54	0.49	0.47	0.47	0.46	0.4	0.52	0.5	0.48	0.42	0.46	0.47	0.46	0.5	0.47	4
POL	0.23	0.21	0.23	0.2	0.13	0.1	0.16	0.26	0.24	0.23	0.29	0.31	0.29	0.3	0.23	13
RAP	0.47	0.47	0.52	0.5	0.48	0.48	0.48	0.53	0.52	0.54	0.57	0.52	0.47	0.51	0.51	3

(*continued on next page*)

Table B2 (*continued*)

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	AVG	RANK
SAA	0.56	0.45	0.44	0.42	0.37	0.45	0.48	0.45	0.39	0.48	0.47	0.45	0.41	0.42	0.45	5
TRT	0.76	0.75	0.8	0.8	0.81	0.8	0.8	0.81	0.83	0.8	0.84	0.87	0.86	0.88	0.82	2
VAL	0.31	0.25	0.21	0.3	0.27	0.29	0.28	0.26	0.19	0.23	0.27	0.25	0.21	0.22	0.25	12
VIL	0.39	0.36	0.37	0.37	0.35	0.31	0.34	0.37	0.41	0.37	0.41	0.41	0.38	0.42	0.38	7
VOR	0.34	0.33	0.37	0.24	0.35	0.24	0.38	0.22	0.24	0.37	0.38	0.37	0.39	0.39	0.33	11

Appendix C. Interviews

C1. Interview plan with stakeholders who shape energy policy

The primary objective of this study was to gather feedback on the quantitative analysis of subsidy distribution. Specifically, we aimed to explore how equity in subsidy distribution is addressed and monitored within policy design practices. Furthermore, we sought to explore policymakers' perceptions of collaboration to inform the creation of a more inclusive and equitable energy policy.

The key questions posed to respondents were as follows.

- Why is the equitable distribution of common resources significant, and what measures should be implemented to achieve it?
- How is the equality of subsidy distribution measured and monitored in policy design?
- Who is responsible for developing incentive programmes for residential renovations, and what role do stakeholders play in the policy design process?
- What hinders current policy design, and how could the policy design process be improved?

During the interviews, we presented only the results related to the distribution of subsidies across regions, without discussing assessments of fairness.

C2. Interview plan with technical consultants who advise apartment associations

The aim of the interviews with technical consultants was to explore how different waves of the subsidy application process have impacted regional subsidy distribution.

Leading questions in interview plan according to predefined topics:

Regional distribution of subsidies.

1. How to explain the annual dynamics in subsidy distributions?
2. Why is the demand for support so low in IDAVIR throughout the entire support period?
3. Why TRT and TRTL could maintain is strong subsidy uptake consistently for majority of application periods?

Changes in renovation policy.

1. Why did TLL dropped quickly in 2015? Why hasn't it recovered and why TRTL succeeded at same time?
2. How did the 2019 regional criteria affect the renovation market?

Renovation Barriers.

1. Why do apartment associations choose to renovate without financial support?
2. Why large and small buildings do not apply for renovation subsidies?

During the interviews, we presented only the results related to the distribution of subsidies across regions, without discussing assessments of fairness.

Table C1
Main themes emerging from interviews with stakeholders who shape policy

	THEME 1: equality and fairness	THEME 2: Policy leading and involvement	THEME 3: Measuring policy outcome	THEME 4: Policy design improvement
KLIM	Distribution on common resources is very important. Different social groups mut be treated fairly. Regional disparities are rather large in Estonia; therefore, it is reasonable to differentiate grants for regions and communities.	Ministry leads but EIS contribution is significant. Taltech is very close and valuable partner in policy design.	Our input about the distributions of the grants comes from the close cooperation between EIS and Taltech. It would be useful understand how PRI indicates for policy change.	Long-term strategic decisions should be better planned and more inclusively developed.
AGRI	Renovation subsidies must consider regional aims, otherwise the policy increases current uneven regional development. The lagging regions must	KLIM leads formally but it seems that Taltech and EIS are contributing more substantially. Involvement is weak	We are not monitoring for such developments on our own. During the formal consultation we receive reports	Better data-based methodology for considering regions and social groups in subsidy planning is needed. More substantive workshops between policy

(*continued on next page*)

Table C1 (*continued*)

	THEME 1: equality and fairness	THEME 2: Policy leading and involvement	THEME 3: Measuring policy outcome	THEME 4: Policy design improvement
	be supported more, however, districts that are shrinking should not be targeted.	and mostly based on the coordination of the regulation decree.	about the progress on subsidy applications.	designers from different departments is needed.
EIS	More equal distribution is needed to balance even development, however, absolute equality between regions might not be desirable.	KLIM leads and involvement is exhaustive. There are weekly meetings with KLIM to develop support measures further.	We are looking which regions obtain grants as the subsidy programme develops. We are not using proportionality as a indicator of grant distribution. Application of complex methods might not be rational in policy development practice.	Simple indicators are needed that are not overly analytically intensive and do not rely on excessive data collection. Policy makers should have the flexibility to modify the terms and conditions of ongoing programmes if certain rules are not functioning effectively in practice.
ELVL	This is very important as the capacity of municipalities differ a lot. Subsidies must not be used in districts that are shrinking.	Involvement is sufficient and increase would be harder to manage. Proposals are well received.	We are not monitoring the distribution of grants. The PRI seems interesting and useful tool that present new evidence that we have not been aware of. RPI should be shown among municipalities as well.	Considering the preview of PRI, more such analysis should be presented to stakeholders while expecting their effort for engagement.
EKYL	The topic on general is important. The concepts of equality and fairness in the context of renovation subsidy distribution are somewhat confusing. Equal distribution might not be fair.	Involvement is sufficient. Proposals are well received.	We are not monitoring the distribution of grants on our own. We follow only KLIM and EIS reports and minutes. PRI present surprising results for us. Still, stronger regions must be supported continually.	Process seems rather well established and significant changes are not necessary.
EOKL	Grants should only be used to mitigate the risk for of vulnerable social groups. Well off apartment owners should not benefit from grants. Capable communities should be enforced by government to renovate their property.	KLIM supposed to lead, but practise shows that EIS is more in charge. Involvement is mostly formal as the proposals are not well received.	Not aware of such tools or methods	Different views by stakeholders should be more explicitly considered by the government.

C4. Extended results of the interviews with technical consultants

Market Catalysts: Managers and Consultants as Key Players

A consistent finding is that renovation momentum is driven more by proactive intermediaries—such as property managers, consultants, and city-backed programmes—than by "average households." The consultant describes the surge during 2015–2018 as "100 % reliant on lobbying and outreach by housing managers and technical consultants to undertake whole-building reconstruction." They connected the increased uptake to targeted campaigning: "It genuinely worked that way—purely through outreach to apartment buildings by property managers and consultants." Municipal initiatives enhanced this impact (e.g., SmartenCity pilots in Tartu city (TRTL) and renovation initiatives of Rakvere city government which belong to region of LVIR), creating demonstration effects: "One or two buildings are completed; then neighbours want the same—and the leap in demand is significant.“.

Economics and Timing: When Finance, Scope, and Knowledge Align

The consultant recounts a significant shift in 2017 when funding was exhausted within a week, credit was affordable, and associations had gained insights into expectations: "At one point in 2017—bang—tens of millions were allocated in a week … Euribor was very low … knowledge had increased; people thought, why wait?" Previously, the grant narrative communicated a straightforward payback rationale: "Implement the core systems with 35 % support, take out a loan, and the savings on heating costs would cover the debt service—that's what appealed to associations." The expansion of eligible works (e.g., apartment windows) further enhanced the attractiveness of comprehensive projects.

Procedural Design and Perceived Fairness

The transition to a "first-come-first-served" approach—administered through an overstretched electronic system—has led to significant perceptions of procedural unfairness. The consultant references a court case following a crash of the e-system: "They went to court … yesterday's ruling states that EIS is required to provide support because equal treatment was not guaranteed." He is unequivocal in his assessment of queue-based openings: "Stop the damned 'fastest-fingers' rounds."

Geography, culture, and trust

Regional differences reflect more than just issues of access to information. In Ida-Virumaa (IVIR), the consultant identifies three key barriers: historically low prices for district heating, language and information gaps, and pervasive distrust: "In Ida-Virumaa, renovations have not been carried out … the cost of district heating was negligible … people did not trust it at all—'Who provides this support for free? Why take out a loan?'" In contrast, Tartu's (TRTL) recent renovation growth can be linked to smaller, poorer-quality properties that could thrive with proactive support from the municipality and intermediaries. Meanwhile, parts of Tallinn exhibit a different dynamic: well-maintained properties, greater ability to self-finance, and less appetite—or patience—for grant-related bureaucracy: "We've already done enough piece by piece … why seek support and do more?"

Effects of building typology and occupancy

Both very small and very large buildings rarely apply for grants, albeit for different reasons. For small associations, even higher support rates do not alleviate the high costs per square metre and stricter bank requirements: "For very small buildings, the support rate up to 40 % still renders reconstruction prohibitively expensive," with small houses facing a loan burden that is "two to two-and-a-half times" higher than that of typical mid-sized blocks. In the case of large over 5 buildings, per-unit costs rise due to safety and accessibility regulations (e.g., lifts, fire safety), procurement limits, and complex decision-making processes: "From the sixth floor up, contractors increase costs by 1.5 or 1.7; the requirements differ, which drives up the price … and with 144 apartments, coordinating meetings is much more difficult than with a 40-apartment building." The outcome is a rational as big multifamily buildings tend not apply for renovation subsidies.

Consultants argue that occupancy directly influences renovations. In shrinking areas low occupancy indicates for future abandonments as the demand is missing. "It all depends on the location … in periphery empty buildings mean that soon local authority must plan for demolitions". In such settings the renovations decisions cannot be made, as the apartment association does not function properly. Underoccupied buildings cannot get renovation financing as banks risk assessment factors in the vacancy rate. In Estonia where rental market is marginal, high vacancy usually indicates for serious socioeconomic problems within larger area. Consultants point to VAL and IVIR regions where underoccupied buildings emerge even in urban centres.

Internal social dynamics: opposition can derail well-prepared projects

Beyond economics and regulations, projects often fail due to social factors. The consultants recall two cases in Valga (VAL) where organised internal opposition derailed advanced projects, despite having low per-square-metre loans and contractors ready: "We even had half million in support … the builder was ready … the loan burden was 1.05 euro per square metre … but opposition arose and killed it; we had to return the support." In a second instance, a building faced a coordinated blockade: "They simply didn't want to listen … and that was the end of it."

Behavioural responses: bypassing grants to get the job done

The queue-based, stop-start nature of subsidy application openings has led capable associations to renovate without grants, often foregoing heat recovery ventilation and concentrating on the building envelope and systems. "Many homeowners grew tired of waiting and decided to take matters into their own hands—removing heat recovery ventilation, renovating façades, roofs, and heating systems … the key priority was to get the building fixed." According to the one consultant, the ability to self-finance, sidestep procurement challenges, and select contractors directly makes this approach appealing in stronger markets like Tallinn.

Decisions to forgo renovation subsidies reflect more than narrow cost–benefit math. From the consultants' vantage point—sitting between policy, engineering, and volunteer boards—the calculus is anchored in trust, autonomy, perceived risk, and administrative capacity. As one consultant put it, "Most boards aren't anti-renovation; they're anti-uncertainty."

Durability and maintenance anxieties are equally prominent. Boards fear being locked into fragile systems and thin local service markets. "Buying a unit is an event; maintaining it is a relationship," observed one consultant. A colleague echoed: "In smaller towns the nearest technician is a long drive away—clients ask who will come at −15 °C when the alarm starts blinking."

A strong preference for control over scope and partners is a next recurrent theme. Procurement rules and lowest-price obligations are seen as undermining quality assurance and accumulated trust with known contractors. "Lowest price has taught boards to distrust winning bids," said one consultant. "When clients self-finance, they feel free to hire the engineer who already knows their building."

Credit aversion surfaces as both psychological and distributional risk. Long-tenor loans alienate older residents and lower-income households, making consensus fragile. "The phrase '20-year loan' can end a meeting," reported a consultant. "Phasing—façade now, systems later—often keeps people on board because monthly fees stay readable."

Consultants also highlight value misalignment with climate-policy framing. Comfort, health, and bill stability resonate; abstract carbon targets do not. "Comfort sells; carbon doesn't," summarized a consultant. "When I reframe from 'kilowatt-hours saved' to 'no drafts in the kid's room,' heads start nodding."

Bureaucratic burden remains a structural deterrent despite support schemes. Volunteer boards face complex applications, procurements, audits, and reporting that outstrip their capacity. "For a small association, the paperwork is a second job," said one consultant. Another added, "Even with me guiding, timelines slip; by approval day, the quotes have expired."

Skepticism about promised energy savings stems from opaque modelling and scarce, comparable ex-post data. "Models are convincing; meters are decisive," remarked a consultant. "Boards ask me for a building like theirs, two winters post-retrofit, with bills to match—too often I can't show it."

Finally, several consultants noted perceptions of politicization around subsidies. Programs can be read as instruments of the green transition rather than neutral home-improvement support. "When a subsidy logo reads like a party logo, doors close," observed a consultant. "De-politize the message and talk about warmer, quieter homes—resistance drops."

Across these accounts, consultants converge on pragmatic remedies: independent, building-specific advisory; transparent, metered performance datasets; procurement flexibility beyond price; credible maintenance pathways; streamlined compliance; and communication anchored in tangible household benefits. As one consultant concluded, "If I can walk a board through a nearby twin block with two winters of verified savings and a maintenance contract in place, the vote usually flips."

Data availability

The authors do not have permission to share data.

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