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Energy Renovation of the Walloon Residential Building Stock: Determinants and Integrated Approaches

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by

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« A supposer que mon action et ma pensée aient laissé à mes enfants quelques témoignage vivant du désir qui m'habitait, quel parfum respirais-je quand mon existence ne soutiendra plus une œuvre à édifier et pour tout dire un amour à chérir ? »

Ruellan Marc (2001). *La Folie Perdue*

This thesis is dedicated to my father. May it inspire a future to love.

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Thanks to my wife, Elisa Quittelier, whose love accompanies me day after day and, I hope, for many more years to come in our future adventures.

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Summary

Accelerating the energy renovation of existing residential buildings is essential to achieving Europe's long-term climate goals. This renovation is even more important to ensure a certain degree of energy independence for the continent. As a result, several actions have been taken by EU public authorities, but without significantly accelerating the rate of renovation. This doctoral thesis fits into this context. It examines the dynamics of renovation in Wallonia's residential building stock through a multidimensional approach that integrates the technical characteristics of buildings and the socio-economic profiles of occupants to recommend more targeted and effective actions in favor of energy renovation.

Chapter 3.1 characterizes Wallonia's residential housing stock through an analysis of the correlations between the technical attributes of dwellings and the socio-economic data of their occupants. Using comprehensive databases on buildings and inhabitants, statistical analyses identify the main determinants of energy performance and highlight the importance of considering socio-economic categories such as low-income households and property ownership. The study focuses on targeted renovation strategies for specific types of buildings, particularly semi-detached houses, where unfavorable technical and socio-economic factors converge.

Chapter 3.2 builds on these foundations by grouping together archetypal "building-occupant" pairs to shed light on energy renovation strategies. Using ordinal logistic analysis and beta regression followed by clustering using the K-means method, the study identifies representative typologies that reflect the diversity of Wallonia's housing stock. Among the main conclusions are the presence of low-energy-performance houses occupied by low-income households (more than 17% of the housing stock) and, unexpectedly, low-performance houses occupied by high-income households (more than 11%). These typologies provide actionable information for policymakers to implement targeted and scaled interventions and demonstrate the value of integrating heterogeneous datasets.

Chapter 3.3 is based on a review of the literature on InfraRed Thermography (IRT) analyzed considering the general objectives of the thesis. This literature review highlights the advantages and disadvantages of IRT for analyzing the energy performance of buildings, and for quickly and inexpensively estimating the energy losses of a large group of buildings. The study highlights the potential of this technique, not only to improve knowledge of the energy performance of homes, but also to contextualize this performance in relation to the behavior of the occupants.

Chapter 3.4 presents a case study using mixed methods in a historic neighborhood of Liège, combining household surveys, IRT, and participatory focus groups. This chapter examines how the technical conditions of buildings and the socioeconomic characteristics of occupants jointly influence renovation decisions. The results reveal that socio-economic factors, including income, occupancy status, and energy culture, often outweigh technical considerations. Thermography is effective in identifying hidden heat losses and raising occupant awareness, but information alone is not enough; ongoing education and personalized engagement are essential to influence renovation choices. The study also highlights the specific challenges associated with renting and co-ownership, underscoring the importance of policies tailored to the local context.

In general, this thesis provides details on the statistical relationship between technical data on housing and socio-economic data on occupants. Two sets of housing/inhabitant clusters representative of the Walloon region have been constructed. The distribution of these clusters across the Walloon territory also makes it possible to provide recommendations tailored to specific areas. IRT also contributes to improving knowledge of building stock. All this data provides a better understanding of renovation behavior and market inertia. Based on these results, several recommendations can be made to the various levels of government. Overall, this thesis provides a set of recommendations to guide energy renovation policies in Wallonia. By combining statistical modeling and participatory field research, it offers both scientific knowledge and practical recommendations for improving the efficiency, fairness, and context sensitivity of residential energy renovation initiatives. The combined study of the technical characteristics of housing and the socioeconomic levels of residents demonstrates its value, even if a third, more specifically behavioral axis is gradually emerging.

Abbreviations and nomenclature[1]

BFS	Belgian Federal State
CESE	Conseil Economique, Social et Environnemental (Economic, Social, and Environmental Council of the WR)
CO_2	Carbon dioxide
CoDT	Code du Développement Territorial (Territorial Development Code)
CREG	Commission de Régulation de l'Electricité et du Gaz (Electricity and Gas Regulatory Commission)
CWaPE	Commission Wallonne Pour l'Énergie (Walloon Energy Commission)
DER	Deep Energy Renovation
DG TLPE	Direction Général Territoire, Logement, Patrimoine et Environnement (Walloon Administration for Land, Housing, Heritage and the Environment)
EC	European Commission
EED	Energy Efficiency Directive
EN	European Norms
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate
ER	Energy Renovation
ERDF	European Regional Development Fund
ESG	Environmental, Social and Governance
ETS	Emission Trading System
EU	European Union
GCU	Guide Communal d'Urbanisme (Municipal Urban Planning Guide)
GDPR	General Data Protection Regulation
GHG	GreenHouse Gas
GRD	Gestionnaire de Réseaux de Distribution (Distribution Network Manager)
GRU	Guide Régional d'Urbanisme (Regional Urban Planning Guide)
IEA	Internation Energy Agency
ILR	Isometric Log Ratio
IPCC	Intergovernmental Panel on Climate Change
IRT	InfraRed Thermography
IWEPS	Institut Wallon de l'Evaluation, de la Prospective et de la Statistique (Walloon Institute of Evaluation, Foresight and Statistics)
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
MLR	Multiple Linear Regression
nZEB	nearly Zero Energy Building
PACE	Plan Air-Climat-Energie (Air-Climate-Energy Plan)
PCA	Principal Component Analysis
PEB	Performance Energétique des Bâtiments (Walloon EPC)
PFEC	Plan Fédéral Energie et Climat (Federal Energy and Climate Plan)
PNEC	Plan National Energie Climat (National Energy and Climate Plan)
RED	Renewable Energy Directive
SCF	Social Climate Fund
SDC	Stratégie de Développement Communal (Municipal Development Strategy)
SPF	Service Publique Fédéral (Belgian Federal Public Service)
STATBEL	Belgian Statistical Office
SWL	Société Wallonne du Logement (Walloon Housing Society)
SWRLT	Stratégie Wallonne de Rénovation énergétique à Long Terme

[1] Acronyms that have entered everyday language in Belgium (e.g., names of institutions or laws) are retained in French in the text.

	(Walloon Long-Term Energy Renovation Strategy)
UN	United Nations
UNFCC	United Nations Framework Convention on Climate Change
VAT	Value-Added Taxes
VIF	Variance Influence Factor
WCED	World Commission on Environment and Development
WR	Walloon Region

1. Introduction

The introduction summarizes the key insights from the literature that help contextualize the thesis. It covers everything from early discussions on energy conservation to the latest developments in sustainable and sufficient renovation. These elements help establish the general conceptual framework but also identify research gaps that will help define the research questions.

1.1. Context

This recontextualization draws in part on elements set out in three reports and publications:

Ruellan, G. (2016). *La rénovation du bâti résidentiel en Belgique*. ULiège. http://orbi.ulg.ac.be/handle/2268/202946
Ruellan, G. (2016). *Interviews sur la rénovation du stock bâti en Belgique*. ULiège. https://orbi.uliege.be/handle/2268/203194
Ruellan, G., & Attia, S. (2016). Les problématiques de la rénovation du stock bâti dans la ville de demain : Résultats d'une étude initiale en Belgique. *Academic Journal of Civil Engineering*, *34*(1), 348-355. https://doi.org/10.26168/ajce.34.1.43

1.1.1. Climate and energy

In 1972, the Meadows report (Meadows et al., 1972) warned of the physical limits of the planet, which could not sustain indefinite economic growth. Fifteen years later, the Bruntland Report (World Commission on Environment and Development (WCED), 1987) introduced the idea of Sustainable Development as a way of reconciling environmental protection, human needs, and economic development. To summarize the state of scientific knowledge on climate issues, the International Panel on Climate Change (IPCC) was created in 1988 and published its first report in 1990 (IPCC, 1992). Based on this report, the United Nations Framework Convention on Climate Change (UNFCCC) was adopted by most of the world's countries at the Earth Summit in Rio in 1992 (UNFCCC, 1992). Those countries recognize three major principles: (i) the precautionary principle, (ii) the principle of common but differentiated responsibilities, and (iii) the principle of the right to development. These commitments by the signatory states were gradually supplemented, mainly by the Kyoto Protocol (Kyoto Protocol, 1997) and the Paris Agreement (Paris Agreement, 2015). At the same time, companies and financial institutions are encouraged to fully integrate Environmental, Social, and Governance (ESG) criteria with the publication of the report "Who Cares Wins" (UN, The Global Compact, 2004).

Despite this apparent consensus on the need for action, the IPCC's sixth assessment report (IPCC, 2023) highlighted a pressing reality. The Global Carbon Project has been reporting data on CO_2 emissions since 1959 (Friedlingstein et al., 2025). World emissions from fossil fuel combustion and industrial processes continue to rise every year (**Erreur ! Source du renvoi introuvable.**). These emissions accumulate in the atmosphere, among other places, as indicated by the atmospheric CO_2 growth rate estimated directly from atmospheric CO_2 concentration measurements. As a result, the global climate is changing permanently. The goal of limiting the average temperature increase to 1.5°C, set at the Paris COP, now seems outdated. Only a profound transformation of all aspects of our societies could guarantee that we remain below 2°C.

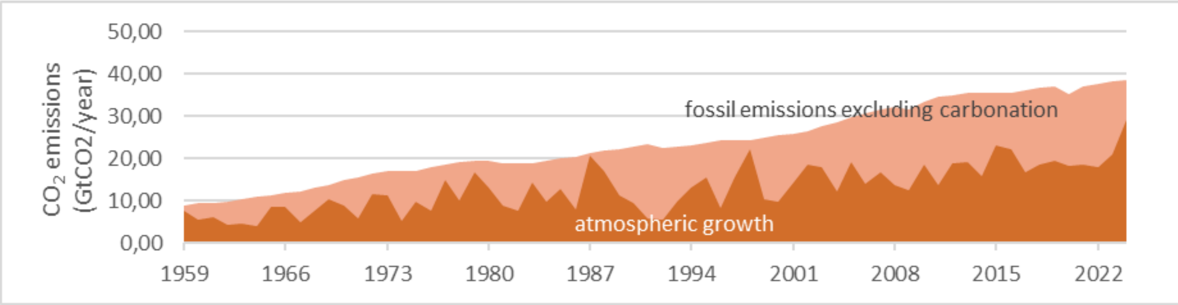

Figure 1-1 Yearly worldwide emissions from fossil fuel combustion and industrial processes (Source: Friedlingstein et al., 2025) and atmospheric CO_2 growth rate (Source: Lan et al., 2025)

Recent events (Figure 1-2) also remind us that energy consumption is not solely an environmental concern. The 1973 oil crisis (Schumacher, 1985), which led to the first energy-saving measures, was already the result of the Yom Kippur War between Egypt and Israel. The second oil shock in the late 1970s was caused by the Iranian revolution and the Iran-Iraq war (Vázquez-Fariñas, 2023). The war in Ukraine and the sanctions against Russia imposed in 2022 reminded European countries of the central importance of energy issues in geopolitical balances (Borowski, 2022). At the time of writing this introduction, the US interventions in Venezuela—the world's largest oil reserve (OPEC, 2025)—and in Iran—world's third largest oil and second largest gas reserve— seems to herald a new era in international relations. Europe, which is heavily dependent on energy imports (De Rosa et al., 2022), finds itself constrained in its diplomatic decisions. Reducing fossil fuel consumption through energy efficiency and the promotion of renewable energies is essential to mitigate geopolitical risk (Carfora et al., 2022; Man et al., 2024; Osička & Černoch, 2022; Proedrou, 2023; Zhang & Usman, 2025).

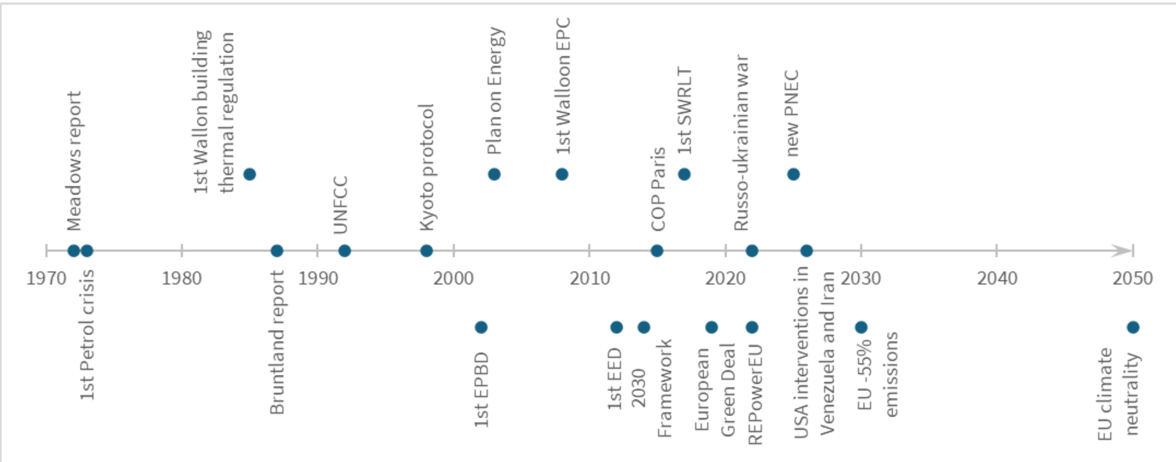

Figure 1-2 Timeline of key events and regulations related to energy and sustainability in buildings, worldwide (center), in the EU (bottom) and in the Walloon Region (top)

To achieve this, even before the ratification of the UNFCCC, the members of the European Union (EU) positioned themselves as pioneers in the field of sustainable development and energy transition. Most recently (Figure 1-2), the European Green Deal (The European Green Deal, 2019) calls for a reduction in emissions from European countries of at least 55% by 2030, and climate neutrality by 2050. This climate neutrality means achieving net zero GHG emissions. These objectives have been transposed into the Climate Law (European Climate Law, 2021). The REPowerEU plan (REPowerEU Plan, 2022) was launched in 2022 to respond to the energy and geopolitical challenges of the war in Ukraine. These various plans are being transposed consecutively at the member state level. Thus, in 2025, the Belgian state and its three regions committed to a new Belgian National Energy and Climate Plan (PNEC) (PNEC (Recast), 2025), which outlines the transition to a sustainable energy system through five dimensions: decarbonization; energy efficiency; security of supply; the internal market; and research, innovation, and competitiveness.

1.1.2. *Issues of housing energy renovation*

Belgium is 88.9% dependent on imports for its energy consumption (IEA, 2024). Looking at Belgium's final energy consumption (Figure 1-3), it is easy to identify the sectors that need to be targeted to reduce energy consumption. As in most countries, three sectors account for most of the energy consumption: industry, transport, and residential. For the residential sector, as well as for the commerce and public services sector, consumption is mainly due to the need to heat buildings.

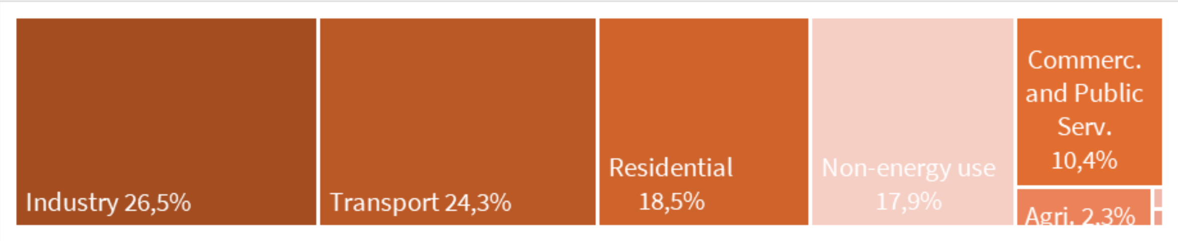

Figure 1-3. Total Final energy consumption by sector in Belgium, 2023 (Source: IEA, 2024)

More specifically, residential energy consumption is broken down as follows (SPF Economie, 2025):

- 70.9% for space heating.
- 14.9% for water heating.
- 11.9% for lighting and electrical appliances.
- 1.9% for cooking.
- 0.2% for cooling.
- 0.3% for other uses.

Space heating alone therefore accounts for a significant share of Belgium's energy consumption. In addition, the residential sector remains carbon intensive. Data released by the International Energy Agency (IEA) since 1971 shows that Natural gas (43%) and fuel oil (27%) are the two main sources of final energy (Figure 1-4). Although we can welcome the reduction in overall energy consumption due to improved housing efficiency and its gradual decarbonization, there is still a long way to go.

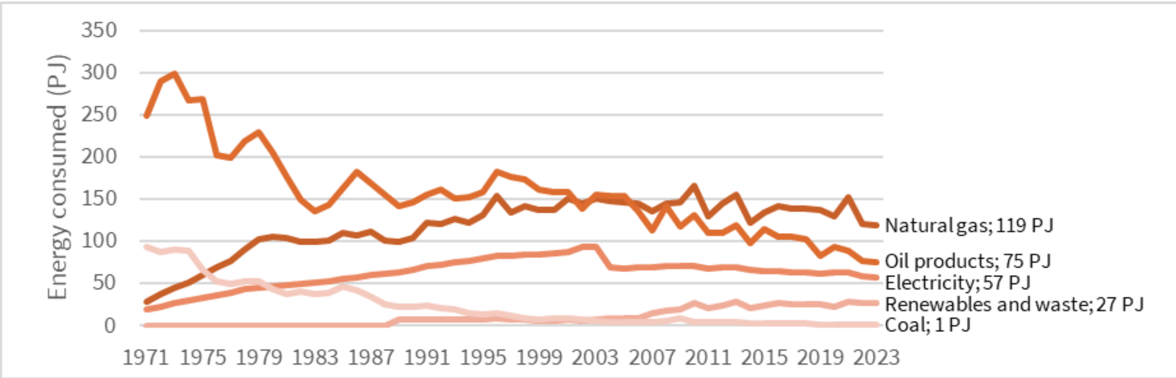

Figure 1-4. Evolution of residential total final consumption in Petajoules by source in Belgium between 1971 and 2023 (Source: IEA, 2024)

It turns out that the residential sector is a considerable source of potential savings. Not only do many techniques exist for achieving low-energy or even positive-energy buildings, but these techniques do not significantly impact usage (Cornet et al., 2013), unlike other sectors that may seem much more complicated to decarbonize without fundamental change. It is estimated that half of Belgium's primary energy saving potential lies in buildings (Verhoeven, 2009).

Kees Duijvestein's team at TU Delft identified three areas to design sustainable buildings in 1979 under the term Trias Energetica. These principles were popularized in 1996 (Lysen, 1996), in order of importance:

1. The priority is to increase the energy efficiency of the building and reduce its energy needs.
2. The second step is to use renewable energy sources where possible and necessary.
3. Finally, for the remaining uses that cannot be decarbonized, their efficiency must be improved.

The technical possibilities for improving the energy efficiency of housing are summarized in Figure 1-5.

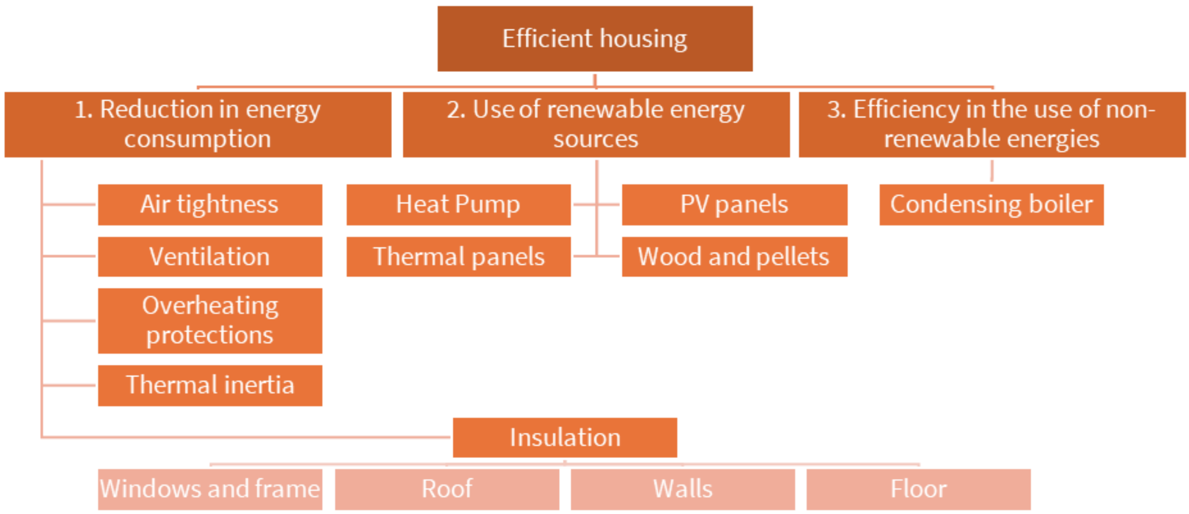

Figure 1-5. Classification of Energy Efficient interventions on buildings

Building energy regulations (Energy Performance of Buildings Directive, 2002; Energy Performance of Buildings Directive (Recast), 2010; Energy Performance of Buildings Directive (Recast), 2018; Energy Performance of Buildings Directive (Recast), 2024) have become increasingly stringent to meet climate targets. These directives have been transposed into local regulations through Energy Performance Certificates (EPCs), such as the Performance Energétique des Bâtiments (PEB) in Belgium, which is also regularly updated (PEB, 2014). New buildings have become low-energy, passive (Dequaire, 2012), nearly Zero Energy Buildings (nZEB) (Szalay & Zöld, 2014). Despite this, Belgium's energy intensity for its residential sector in 2024 remains at 737.79GJ/m², far ahead of its neighbors: Germany (616.92 GJ/m²), France (508.45 GJ/m²), the United Kingdom (478.13 GJ/m²), and the Netherlands (326.12 GJ/m²) (IEA, 2024). This energy intensity, although gradually declining, remains excessive in relation to the targets set. Three reasons are identified in the literature to explain this overconsumption of Belgium's building stock (Mlecnik et al., 2010; Verhoeven, 2009):

- Particularly old buildings. 70.5% of buildings were constructed before 1981 (Statbel, 2025).
- A high proportion of single-family homes. Terraced, semi-detached, and detached houses account for 66% of dwellings and 78% of buildings in Belgium (Statbel, 2025).
- And lower uptake of energy efficiency improvements. 67.5% of Belgian households report living in a building that has not undergone any energy efficiency improvements in the last five years (Statbel, 2025).

Belgium must therefore succeed in implementing a major energy renovation of its housing stock (Hens et al., 2001). Various terms are used in the literature to refer to work carried out on existing buildings: change, adaptation, renovation, restoration, modification, reconstruction, re-commissioning, modernization, adjustment, etc. (Thuvander et al., 2012). In the rest of this text, we will follow Thuvander et al.'s choice to use the term renovation, which “includes middle range to major interventions.” More specifically, we will use the term Energy Renovation (ER) for any renovation work aimed at improving the energy performance of the building, and Deep Energy Renovation (DER) for any combination of at least five interventions (Gepts et al., 2025b).

However, a growing body of scientific research points out that this energy-efficiency-centered approach must necessarily be complemented by a consideration of what constitutes sufficient use (Verbeeck & Bosserez, 2021). Thus, energy efficiency—generally measured in kWh/m² per year—says nothing about actual consumption, which depends largely on floor area. By focusing on energy efficiency, no questions are raised about the suitability of housing for its intended use, and about the adequacy of its floor area relative to the number of occupants. Conversely, it is possible to significantly reduce a household’s energy consumption and carbon footprint by reducing living space to what is necessary (Sula et al., 2025). Furthermore, the very concept of energy efficiency does not question the need for the service or the reality of its use (Verbeeck & Bosserez, 2021). In WR, research from the Slowheat project (Moeseke et al., 2024) illustrates the potential to halve energy consumption by prioritizing the heating of the human body. As Shove points out, the blind pursuit of energy efficiency can become problematic in that it supports energy-intensive lifestyles that are disconnected—or “purified”—from social realities (Shove, 2018). Energy policies as they are currently designed do not promote a radical reduction in our carbon footprint. On the contrary, they can become counterproductive to the point of contributing to increased energy consumption (Adua et al., 2021), in a manner similar to the Jevons paradox (Jevons, 1865), which is widely documented and referred to as the "rebound effect."

Based on these considerations, and drawing inspiration from the principles of the Trias Energetica, Verbeeck and Bosserez propose three new principles (Verbeeck & Bosserez, 2021):

1. Reduce energy consumption to what is necessary, particularly in terms of living space.
2. Use energy dynamically, where it is needed.
3. Promote passive design and practices rather than active systems.

Usage—and therefore the user—must once again take center stage in a discourse that has been dominated for too long by a technocratic approach. And the approach to energy renovation must not be limited to energy efficiency alone.

1.1.3. Sustainable renovation

The benefits of energy renovation policies for housing are not limited to reducing energy consumption (Thuvander et al., 2012). Identifying the various impacts of improving housing energy efficiency reveals its multiple benefits (Figure 1-6) (Campbell et al., 2014; Ferreira & Almeida, 2015; Liao et al., 2023; Sharmina et al., 2009).

Figure 1-6 Multiple Benefits of Energy Efficient Renovation (Source: Campbell et al., 2014)

Energy savings. There is consensus on the energy savings generated by energy-efficient renovations (Ekström et al., 2018; Gendebien et al., 2015; Tuominen et al., 2012). Most research on energy-efficient renovations is based on this objective (Abdul Hamid et al., 2018; Jensen et al., 2018). However, results can vary greatly depending on the technical and behavioral assumptions adopted.

GHG emissions. Reduced consumption directly translates into reduced GHG emissions (Hens et al., 2001; Maia et al., 2023). Replacing the heating system can already reduce CO_2 emissions by 92% (Montero et al., 2022). Depending on the national energy mix, a passive standard DER can lead to a reduction in emissions equivalent to 7 tons of CO_2 (Mlecnik, 2013).

Resources management. The life cycle assessment (LCA) of energy renovation projects highlights a reduction in environmental impact (Verellen & Allacker, 2022) proportional to the energy ambition (Van de moortel et al., 2022). Among other things, increased energy efficiency reduces the extraction of non-renewable energy resources. But energy renovation also requires fewer resources than new construction and reduces waste production (Ferreira & Almeida, 2015; Trachte et al., 2014). It can even be considered that renovation contributes to extending the life of a home and therefore reducing its environmental footprint. Furthermore, promoting energy renovation also reduces urban sprawl (Attia & Mlecnik, 2012; Dubois & Allacker, 2015). However, progress still needs to be made to encourage the implementation of circular practices (Sáez-de-Guinoa et al., 2022).

Local air pollution. Heating methods based on combustion (coal, gas, fuel, wood) can cause significant local air pollution (McDuffie et al., 2021; Stanojević et al., 2024). 72,000 deaths can be attributed annually to the emission of PM2.5 particles from residential heating (Paisi et al., 2024). Energy-efficient renovation and changing heating methods can radically reduce this pollution (Abdul Hamid et al., 2018; Tan et al., 2023). These gains translate into improved health for all residents of the cities concerned (Tan et al., 2023). Wood heating, often touted as a sustainable alternative to fossil fuels, thus has a significant impact on local air quality, which must be taken into account in public policy (Marin et al., 2022).

Health and well-being. Energy renovation directly contributes to improving the comfort, physical health, and mental health of occupants (Deurinck et al., 2012; Dimitroulopoulou et al., 2023; Middlemiss et al., 2023; Mlecnik et al., 2010; Singh et al., 2016; Tan et al., 2023). This improvement indirectly reduces government healthcare spending (Rosenow et al., 2014) and can lead to increased productivity for all activities carried out in the building (Dimitroulopoulou et al., 2023).

Poverty alleviation. Energy renovation reduces the risk of energy poverty (Barrella et al., 2023; Müller et al., 2024; Van de moortel & Allacker, 2023), provided that the needs of occupants are considered (Papantonis et al., 2022) and that they are made aware of the new uses of the building (Middlemiss et al., 2023).

Disposable income. Depending on the technical options, cost-optimum research on Life Cycle Cost (LCC) studies shows that investments can theoretically be recouped over the lifetime of the works (Allacker & De Troyer, 2013; Ferreira et al., 2016; Maia et al., 2023; Verbeeck & Hens, 2005). This profitability would then translate into an increase in disposable income for households (Middlemiss et al., 2023). However, these analyses are based on numerous assumptions that may call into question the profitability of the project (Ekström et al., 2018; Galvin, 2024) and are particularly dependent on the availability and level of subsidies (Laes et al., 2018; Mikulić et al., 2016).

Employment. Energy renovation work can lead to the creation of thousands of jobs that are difficult to relocate, particularly in the construction sector (Mikulić et al., 2016; Mlecnik et al., 2010; Pikas et al., 2015; Rosenow et al., 2014). It is estimated that an investment of €1 million per year contributes to the creation of around 20 direct jobs (Janssen & Staniaszek, 2012; Pikas et al., 2015), not counting indirect and induced jobs. All these jobs also help reduce government spending on unemployment, although these figures should be treated with caution (Rosenow et al., 2014).

Public budget. Public finances benefit directly from an increase in energy renovation through lower energy consumption in the public sector (Fahlstedt et al., 2024), lower emissions trading costs (Mlecnik, 2013), a reduction in energy subsidies (Sgaravatti et al., 2021), and an increase in tax revenues (Mikulić et al., 2016; Pikas et al., 2015; Rosenow et al., 2014; Ruggieri et al., 2023). Energy renovation work can thus lead to a significant increase in GDP (Slabe-Erker et al., 2022).

Energy security. Energy renovation of the building stock helps to limit the country's energy dependence and increase the security of its supply (Gusbin, 2015; Man et al., 2024; Mikulić et al., 2016). This energy security also means that households and public authorities are less exposed to energy price fluctuations (Sgaravatti et al., 2021).

Asset value. While the introduction of mandatory EPCs in 2008 had no impact on housing prices in Flanders, the introduction of the EPC label in 2019 for the most energy-efficient homes did have an effect (Damen & van Kempen, 2025). This trend is likely to increase with the future introduction of performance requirements for purchases. Energy renovation also contributes to the long-term preservation of the technical qualities and value of the building (Ferreira & Almeida, 2015; Mlecnik et al., 2010). Energy renovation also helps to maintain the use value of existing assets (Trachte & Stiernon, 2024).

All these benefits together define the contours of Sustainable Building Renovation (SBR) (Jensen et al., 2018; Thuvander et al., 2012). All these benefits should be observed at a wide range of scales, from the individual to the entire country. This raises the question of whether we should consider and optimize renovation scenarios at scales other than that of the individual building. It is also worthwhile to combine considerations regarding housing energy efficiency with other aspects related to housing location, such as the use of different modes of transportation or the local production of carbon-free energy (Nematchoua et al., 2021). The case of district heating networks is a good example of the need to consider housing energy efficiency and consumption within a broader context (Lidberg et al., 2018). This shift in perspective can lead to solutions that address needs beyond mere energy efficiency, such as roof extensions (Amer & Attia, 2019).

Given this diversity of strengths and solutions, it is impossible to propose a single, one-size-fits-all solution. The policy framework must successfully balance the promotion of more sustainable housing while allowing for the necessary flexibility to avoid becoming locked into suboptimal solutions.

1.1.4. Energy renovation governance

To support this housing (r)evolution, the various levels of government have several instruments at their disposal. Lascoumes and Le Galès identify four types of public policy instruments: (i) legislative and regulatory, (ii) economic and fiscal, (iii) conventional and incentive-based, and (iv) informational (Lascoumes & Le Galès, 2004). To these four types of instruments, we will add a fifth category—strategic and plan—to organize and coordinate them.

United Nations (UN). The United Nations does not have the traditional instruments of public action at its disposal. Nevertheless, the UNFCCC (UNFCCC, 1992) can be considered as the common strategic framework to which all ratifying states subscribe, while the IPCC reports (IPCC, 2023) constitute its scientific basis.

European Union (EU). As already mentioned (Figure 1-2), the European Union has responded to the UNFCCC through several strategies, the most recent of which are the Green Deal (The European Green Deal, 2019) and REPowerEU (REPowerEU Plan, 2022). However, the EU has the tools to implement these strategies. Several regulations govern climate policy (European Climate Law, 2021), energy policy (Energy Efficiency Directive (EED) (Recast), 2023; Renewable Energy Directive (RED III) (Recast), 2023) and building policy (Energy Performance of Buildings Directive (Recast), 2024). Various financial tools are available to support these regulations: carbon taxes (ETS 2, 2023), Social Climate Fund (SCF, 2023), European Regional Development Fund (ERDF, 1999), etc. While conventional and incentive-based involvement remains anecdotal given the way the EU operates, the informational aspect is mainly based on the publication of reports and the creation of ad hoc web pages.

Belgian Federal State (BFS). Belgium has responded to European objectives through its National Energy and Climate Plan (PNEC (Recast), 2025), which itself consists of the BFS's Federal Energy and Climate Plan (PFEC) and the energy and climate plans of the three regions. The BFS has few tools at its disposal to intervene in energy, land use planning, and housing issues, which are largely regionalized. Tax breaks and subsidies have been gradually phased out. Nevertheless, the BFS retains control over Value-Added Tax (VAT), which has been set at 6% since 2016 for renovation work and since 2025 for demolition/reconstruction.

Walloon Region (WR). The Air Climate Energy Plan (PACE 2030, 2023) defines the WR's objectives as part of the PNEC. It has been broken down into various sectoral strategies, including the Long-Term Renovation Strategy (SWRLT) (DG TLPE, 2020). In addition, numerous regulations govern energy and land use planning at this level, such as the Walloon EPC (PEB, 2014) already mentioned, or the Territorial Development Code (CoDT (Recast), 2026), which defines, among other things, rules for establishing Building Permits . The WR also has numerous financial tools at its disposal to tax (property tax, income tax, real estate withholding tax, registration fees, etc.) or, conversely, subsidize (bonuses, tax reductions, zero-interest loans, etc.) its energy and urban planning actions. In addition, most of the European FSC contributes to the Social Climate Plan (PSC) of the various regions to finance the energy transition. From an informational point of view, several guides and websites provide a wealth of information on energy renovation and related subsidies.

Province. The provinces have little power over energy and urban planning issues. The Climate Plan is mainly focused on supporting municipalities.

Intermunicipal. The intermunicipal level corresponds to the union of several cities for the joint management of certain areas of responsibility.

Cities. Cities have crucial urban planning powers for energy renovation policy. They can propose a Sustainable Energy and Climate Action Plan (PAEDC) with the help of the Walloon PolLEC program. Cities also produce a Municipal Urban Planning Guide (GCU) which defines the rules for the development and construction of public and private spaces. Cities have the power to issue building permits. They can coordinate incentive programs (renovation packages, group purchases, DIY buses, etc.). As the institution closest to citizens, it is also the most capable of communicating through guides, websites, and specific service desks.

All these institutions have their own buildings that they must renovate.

A few government and para-governmental agencies are of prime importance regarding energy and building policy. The Commission for the Regulation of Electricity and Gas (CREG) informs and regulates energy markets at the federal level, while the Walloon Energy Commission (CWaPE) transposes and ensures the application of these rules in the WR. The Walloon Center for Sustainable Housing Studies (CEHD) produces several reports on housing quality in the Walloon Region (Anfrie et al., 2021). The Walloon Economic, Social, and Environmental Council (CESE) has an energy advisory unit responsible for issuing opinions on energy policy. Distribution system operators (GRD) manage and bill for the use of energy networks. Energy helpdesks advise individuals and direct them to the appropriate assistance. The Walloon Housing Company (SWL) coordinates the development and management of public housing stock.

Table 1-1 Levels of governance and public policy tools of energy renovation issues

Level	Strategic and planning	Legislative and regulatory	Economic and fiscal	Conventional and incentive-based	Information and communication
1. United Nations	IPCC report UNFCCC				
2. European Union	Green Deal REPowerEU	Climate Law EPBD EED RED III	ETS 2 SCF ERDF		Online
3. Belgium Federal State	PNEC	CREG	VAT PSC	Building ER	
4. Walloon region	PACE SWRLT CESE	PEB CoDT CWaPE	Taxes Subsidies PSC	Building ER SWL POLLEC	Online Guides
5. Province	Plan Climat			Building ER	
6. Inter-municipal			GRD	Management delegation	
7. Cities	PAEDC	GCU Building Permit	Taxes Subsidies	Building ER Renovation train	Online Guides Energy Offices

Many associations and businesses operate around these various levels of public authority. These agencies mainly provide information, sometimes as public service delegations, either to the public or through lobbying institutions.

In Belgium, the regions are at the heart of renovation strategies, as they have both the legislative and economic levers to act on a large scale, while also being responsible for the practical implementation of generic European regulations. Strategic planning follows a Russian doll logic, with each plan integrating and detailing the strategy adopted at the higher level on a regional scale. Conversely, EU financing tools generally support lower levels of government, without directly affecting citizens. These different governance tools are summarized in Table 1-1.

These energy renovation policies are constantly evolving, depending on the international situation and internal trade-offs. There has been an increase in performance ambitions and the integration of new sustainability objectives (C.-H. Baek & Park, 2012). While the EPBD and EPC were mainly focused on new buildings in 2015, the latest versions are more inclusive of renovated buildings. Local policies are also inspired by what works in neighboring countries. The Netherlands has become a benchmark for the industrialization of DER with its EnergieSprong model, which is spreading throughout Europe (Brown et al., 2019; Pellegrino, 2019). The introduction of the SWRLT reflects this shift in priorities and expectations. In 2017, the first SWRLT responded to the EED and aimed to gradually transform all existing buildings into nZEB by 2050. The new 2020 version, developed in response to the latest version of the EPBD, includes a decarbonization target and intermediate milestones in 2030 and 2040. Specific actions are mentioned, as well as strengthened governance and an update on the costs and profitability.

1.1.5. Barriers to energy renovation

Despite all the regulations, building renovation passports (Sesana & Salvalai, 2018), tax incentives (Dubois & Allacker, 2015; Villca-Pozo & Gonzales-Bustos, 2019), rental controls (Bertoldi, Economidou, et al., 2021), communication campaigns, One-Stop-shop (Bertoldi, Boza-Kiss, et al., 2021; Biere-Arenas et al., 2021), and massification strategies (Brown et al., 2019; Pellegrino, 2019) implemented over the past 30 years, the rate of energy renovation is not progressing fast enough in Europe (Filippidou et al., 2017; Wilson et al., 2015). We do not have a reliable indicator for this specific work in Belgium or in WR. The use of building permits is only an imperfect indicator of energy renovation activity, as only 17% of renovation activities require one, and not all renovation activities are energy-related (Gepts et al., 2025a). However, the annual rate for construction and renovation remains stable (Figure 1-7).

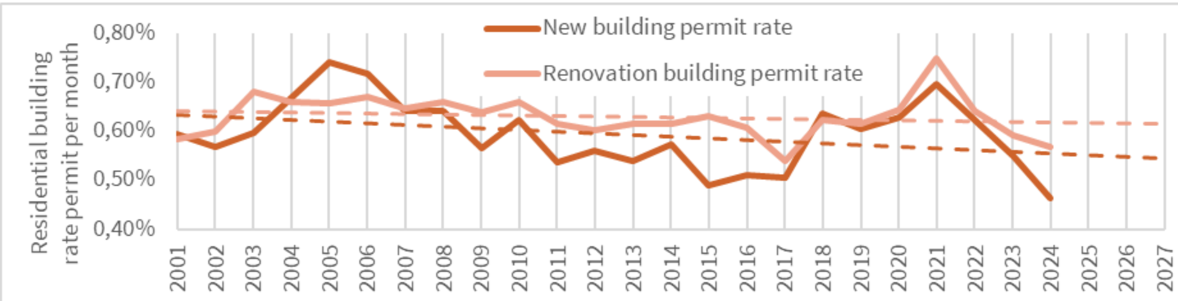

Figure 1-7. Trends in the building permits rate for new construction and renovation compared to the whole stock in Belgium by year (Source: Statbel, 2025)

The European Commission (EC) cites an annual ER rate of around 1% and a DER rate of 0.2% for the EU. According to Verhoeven, the annual energy renovation rate in Belgium is between 0.6% and 1% (Verhoeven, 2009). Gendebien cites an ER rate of 1.5% (Gendebien et al., 2015). Gepts et al. is more optimistic, calculating a DER rate of 4% for Belgian homeowners alone (Gepts et al., 2025b). But even this latest estimate remains below the energy renovation needs estimated at between 3% and 5% in 2010 (Mlecnik et al., 2010). As for the demolition rate, which could help eliminate the least efficient and most unsanitary buildings, it is capped at 0.075% (Verhoeven, 2009).

Yet renovation techniques to achieve low-energy buildings do exist (Attia et al., 2022; Brambilla et al., 2018; CSTC, 2016; Ekström et al., 2018; Mlecnik et al., 2010; Van Craenendonck et al., 2016). Nevertheless, it can be complex to prioritize the multiple solutions available on the market, both for project managers (Abdul Hamid et al., 2018; Jensen et al., 2018; Pannier et al., 2021) and for contractors (Itard et al., 2008; Mlecnik et al., 2010; Tuominen et al., 2012). This can be perceived as a risk for the project owner (Mainali et al., 2021; Wilson et al., 2015). The lack of information available to occupants is a significant obstacle. Owners need credible information on energy efficiency measures (Pannier et al., 2021; Sáez-de-Guinoa et al., 2022; Tuominen et al., 2012; Wilson et al., 2015). However, the diversity of solutions is increasing as new constraints arise. Moving from energy efficiency to decarbonization requires rethinking the way we build, in a more circular way (Mainali et al., 2021). The trade-off between renovation and reconstruction must be made on an almost individual basis (Dubois & Allacker, 2015; Leichter & Piccardo, 2025; Lim, 2025). Buildings of heritage value also require a tailored approach (Trachte & Stiernon, 2024). This diversity of techniques specific to Wallonia's old and heterogeneous buildings makes it more difficult to industrialize ER solutions as advocated by the Energiesprong approach, despite advances in this area (Monfils & Hauglustaine, 2014).

The main barrier to increasing the renovation rate is economic. Energy renovation work is costly, and the return on investment is long and uncertain (Dadzie et al., 2018), which discourages investors (Wilson et al., 2015). Today, the value of a property on the real estate market depends less on its performance than on its location (Mlecnik et al., 2010; Tuominen et al., 2012). In WR, major renovation work can lead to an increase in cadastral income, whereas it would be necessary to favor the most efficient housing (Sáez-de-Guinoa et al., 2022). Energy prices that do not incorporate negative externalities have a negative impact on the profitability of energy efficiency projects (Ruggieri et al., 2023; Tuominen et al., 2012). Conversely, the introduction of a carbon tax that would contribute to increasing these prices increases interest in EE (Laes et al., 2018; Mainali et al., 2021; Szymańska et al., 2022).

Beyond this profitability, a large proportion of homeowners simply cannot afford to invest (Albrecht & Hamels, 2021; Itard et al., 2008; Liao et al., 2023). The introduction of subsidies can therefore unlock these projects and improve their profitability (Laes et al., 2018), provided that DERs are encouraged to reduce the risk of a lock-in to define effect (Dubois & Allacker, 2015) that would block the project in a sub-optimal situation. To avoid this situation, subsidies must be conditional on the preparation of an optimal roadmap through an energy audit or a Building Renovation Passport over several years (Barbosa & Almeida, 2025; Dubois & Allacker, 2015; Maia et al., 2023; Mainali et al., 2021; Sesana & Salvalai, 2018). Subsidies must also limit their uptake by free-riders—households that would have renovated anyway and benefit from a windfall by specifically targeting households that cannot renovate without subsidies (Laes et al., 2018; Rosenow et al., 2014). These households must be specifically identified by public authorities to propose inclusive policies (Papantonis et al., 2022) and combat the non-take-up of existing aid (Middlemiss et al., 2023). A low-interest loan system can complement the range of financial measures (Mainali et al., 2021), if it does not limit the ambition of the projects (Dubois & Allacker, 2015). Thus, the high rate of owner-occupiers and the instability of public aid over time in WR complicates the implementation of an Energiesprong-type model, which is financed by future energy savings, often via energy rents.

When it comes to rentals, the main problem lies in the split incentive between landlords, who pay for the work, and tenants, who benefit from the energy improvements (Ástmarsson et al., 2013; Bird & Hernández, 2012; Dixon et al., 2014; Itard et al., 2008; Melvin, 2018; Meyer & Maréchal, 2016). This holder/leaver dilemma particularly affects households in fuel poverty and ethnic minorities (Papantonis et al., 2022; Van de moortel & Allacker, 2023) and cannot be resolved by a CO_2 tax alone (Müller et al., 2024). A new financial model needs to be put in place to reconcile the interests of tenants and landlords (Papantonis et al., 2022; Van de moortel & Allacker, 2023). The rental market is also highly fragmented. Energiesprong's industrialized approach and economies of scale require large volumes that are difficult to achieve in WR due to the fragmentation of ownership. Only 15% of landlords own more than three rental properties, and only a few rental complexes are managed by professional real estate funds (Mlecnik et al., 2010).

Political barriers are not limited to instability, which undermines investor confidence. Certain regulations directly constrain the technical possibilities for energy renovation, such as urban regulations, property boundary management, heritage protection, etc. A balance still needs to be struck between the perceived complexity of the decision-making and implementation process and the associated uncertainties on the one hand (Ruggieri et al., 2023; Wilson et al., 2015), and the necessary intervention of public authorities to regulate and guide construction practices on the other (Dubois & Allacker, 2015; Liao et al., 2023). This transformation must be accompanied by decompartmentalization and integration of issues. For example, the WR's EPC regulations are primarily designed around individual elements rather than overall performance, and public procurement is still largely based on price, technical specifications, and compartmentalization of lots, which complicates the implementation of an Energiesprong performance guarantee.

Ultimately, the study of barriers to renovation shows us that improving energy performance is rarely the trigger for renovation. People renovate for (i) rational use of living area, (ii) quality improvement, (iii) comfort improvement, (iv) higher quality of life. The integration of energy renovation work is often the result of peer-to-peer communication that has convinced homeowners. This approach of integrating renovation work with maintenance and comfort work tends to increase its profitability (Mlecnik et al., 2010). Thus, several households have the means to carry out energy-efficient renovations but do not do so in the absence of extrinsic motivations (Albrecht & Hamels, 2021). Nevertheless, this attitude is changing, with energy renovation work becoming increasingly well perceived (Wilson et al., 2015), and young households renovating more than older ones (Gepts et al., 2025b).

These motivations have a direct effect on post-renovation energy performance. Indeed, if comfort is the main motivation, then the occupant will take advantage of the renovation to improve their comfort, thus inducing a rebound effect (Berkhout et al., 2000; De Sloover & Albrecht, 2011; Deurinck et al., 2011; Galvin, 2014; Galvin & Sunikka-Blank, 2016; Hens et al., 2010). The rebound effect mentioned earlier refers to an increase in the use of a tool that has been made more efficient: in our case, heating a home more intensely and evenly, while paying less attention to energy consumption. Conversely, occupants of less-efficient homes often adopt energy-saving behaviors to compensate, a phenomenon known as the prebound effect (Galvin & Sunikka-Blank, 2016). This rebound/prebound effect is not so much a sign that energy efficiency, as currently conceived, has failed, but rather an illustration of its shortcomings (Shove, 2018).The EPBD calculation method thus overestimates energy savings by 6% (Deurinck et al., 2012). However, this overestimation is more significant for low-income households, which are most dependent on energy savings (Slabe-Erker et al., 2022). In any case, the actual performance of buildings remains difficult to predict, as it is largely dependent on the behavior of occupants (Liao et al., 2023). This highlights the need to involve them in the decision-making process from the outset to take their needs into account, and to raise their awareness of energy improvements and the use of the new building after the fact (Middlemiss et al., 2023). More specifically, while energy efficiency certification policies are still largely based on static behavior, taking dynamic behavior into account and encouraging it is also a promising approach (Sula et al., 2025).

1.1.6. Energy models of building stock

To estimate the effects of renovation strategies and account for the various barriers that have been identified over the years, numerous energy models of building stock have been developed. These models fall into top-down or bottom-up categories (Swan & Ugursal, 2009). Top-down models aggregate energy consumption data and then allocate it to individual households. They do not take individual usage into account. In contrast, bottom-up models extrapolate energy consumption from a representative sample of housing units, either through statistical analysis of energy bills and surveys (statistical techniques) or by simulating consumption based on the technical characteristics of the building stock (engineering techniques). Among these techniques, bottom-up statistical methods are best suited to account for user behavior and incorporate macroeconomic and socioeconomic effects. Furthermore, these models can adopt a representative approach based on aggregated technical characteristics of buildings, or a typical approach that uses typical buildings from the building stock (Cyx et al., 2011). These models are also characterized by the number of representative typologies they use to capture the complexity of the building stock. Over the past 20 years, numerous models have been developed in Belgium and Wallonia and are presented in the Table 1-2.

However, there are significant discrepancies between the results of these models, which still have considerable room for improvement (Protopapadaki et al., 2014). But above all, they struggle to fully account for the impact of occupant behavior on energy consumption. In fact, research on energy renovation (Abdul Hamid et al., 2018)—tend to focus on technical and economic aspects. While many studies seek to link technical solutions to user needs and behaviors, a more comprehensive integration of these aspects would be desirable to target strategies (Jensen et al., 2018).

Table 1-2 Belgian and Walloon bottom-up built stock models

Study	**Area**	**Dwellings typologies**	**Techniques**	**Approach**
(Hens et al., 2001)	BFS	960	engineering	representative
(Verbeeck & Hens, 2005)	BFS	5	engineering	typical
(Kints & De Herde, 2008)	WR	8	statistical	mixed
(Mlecnik et al., 2010)	BFS	11	statistical	typical
(Allacker et al., 2011)	BFS	16	engineering	representative
(Cyx et al., 2011)	BFS	25	engineering	mixed
(Hauglustaine & Monfils, 2013)	WR	8	statistical	typical
(Mouton et al., 2013)	WR	4	mixed	typical
(Gendebien et al., 2015)	BFS	992	engineering	representative
(Leveau et al., 2018)	WR	42	engineering	mixed
(Nishimwe & Reiter, 2021)	WR	36	statistical	representative
(Coppens et al., 2022)	WR	20	engineering	representative

1.1.7. Energy renovation from the occupant's perspective

This state of the art clearly shows us how central occupants are to the energy renovation process. As initiators, occupancy status (Ástmarsson et al., 2013), income (Meyer et al., 2018), age (Gepts et al., 2025b), life events (BPIE, n.d.), knowledge (C. Baek & Park, 2012), etc. are all determining factors in acting (Ebrahimigharehbaghi et al., 2022). As a user, energy consumption is influenced by six factors (climate, building envelope, technical equipment, maintenance, occupant activities and habits, and indoor space quality), the last three of which depend largely on human choices (Attia, 2020; de Meester et al., 2013; Guerra-Santin et al., 2018; Lindén et al., 2006; Mlecnik et al., 2010).

This issue is all the more important given that the impact of residents' lifestyles is proportionally greater in the most energy-efficient buildings (de Meester et al., 2013).Renovation should be considered a service process rather than a technical process (Thuvander et al., 2012). The integration of social factors makes it possible to both better target energy policies and refine estimates (Amin et al., 2024; Papantonis et al., 2022; Süsser et al., 2022).

The question of energy-efficient renovation considering occupants' priorities ultimately ties into the issue of sufficient energy renovation. Placing occupants at the center of the discussion allows us not only to better understand their capacity to undertake energy-saving measures but also to help them identify their actual needs.

1.1.8. Futures challenges

Given the time horizons envisaged for energy renovation, renovation strategies must be forward-looking to adapt resiliently to both expected and unexpected changes in the context. Older homes often have an average lifespan of more than 100 years (Andersen & Negendahl, 2023). In theory, LCA and LCC often consider a life expectancy of 100 years for the structure, 30 years for the skin, and between 15 and 30 years for services and space (Donatello et al., 2021). Around 90% of existing buildings will still be standing in 2050 (A Renovation Wave for Europe, 2020). Any major energy renovation must therefore be considered as a solution for this timeframe.

In the short term, the establishment of an expanded carbon market (ETS 2, 2023), accompanied by funds specifically dedicated to improving the energy efficiency of the sectors affected by this tax (FSC, PSC), represents both risk and opportunity. As has been pointed out, growing international uncertainty about energy prices and international cooperation also requires reducing energy and material dependence and increasing resilience to shocks. In the longer term, current renovation strategies must already consider the climate in 2050, or even 2100. Thus, while heating needs are expected to decrease by 8 to 13% by 2050, cooling needs could increase by 39% to 65% (Elnagar et al., 2023). Appropriate renovation strategies (Attia et al., 2021) would help mitigate this increase and its impact on comfort and health.

1.2. Problem statement

1.2.1. Knowledge gap

This overview leaves no doubt that the energy issue will be of paramount importance in the coming years for the future of humanity. Across Wallonia, the energy renovation of building stock is one of the main challenges for the coming years. Failure to achieve a significant improvement in the energy performance of housing will not simply mean falling short of the region's, the country’s, and the EU's own targets. It will have major consequences in the short and longer term for the environment, people, and the economy.

Given current trends and without structural changes in the sector, the energy consumption of the building stock will be far from nZEB in 2050. GHG emissions will be much higher than expected, in the context of rapidly deteriorating climate conditions. Energy expenditure will become increasingly dependent on international geopolitics and uncertain hydrocarbon reserves. And the Belgian social and healthcare system will have to bear the costs associated with this deterioration of our environment, assuming it still has the means to do so.

Nevertheless, renovation techniques exist to radically reduce the environmental impact of the building sector. This is a priority for many European governments, which have set out to implement policies promoting energy-efficient renovation. While energy renovation strategies have not yet fully borne fruit, the main problem identified lies in the gap that remains between the development of these strategies and their target audience, the occupants of the building. On the one hand, these strategies have not succeeded in significantly accelerating the transition. But the emphasis placed on energy efficiency obscures a necessary question about what is truly necessary and sufficient. In addition, these strategies, which are geared towards 2050, must already take future needs into account.

Involving occupants in the evaluation of energy policies is a first step toward energy efficiency tools that are more focused on actual needs. To improve the effectiveness of policy actions and take future needs into account, this thesis seeks to propose recommendations for improving the effectiveness of future renovation policies by combining information on the technical characteristics of housing with data on the socio-economic characteristics of residents.

This issue gives rise to a multi-method and multi-scale methodology, which is outlined in Section 2. Research Framework. This commitment to combine quantitative and qualitative data addresses not only accessibility issues but also a growing concern within the scientific community to diversify information sources and tools (Östlund et al., 2011). Changing the scale allows us to highlight additional findings (Srebric et al., 2015). Finally, a long-term research allows us to take a critical look at the results obtained over time (Kuebbing et al., 2018).

1.2.2. Goal

This knowledge gap is completed with a research goal. This underlying goal is to help to increase the rate of deep energy renovation in Belgium, to improve the comfort and well-being of residents, while reducing the environmental impact of the building sector, and contributing to the resilience and energy independence of the Belgian state.

1.2.3. Main research question

To achieve the research goal, the thesis focuses on both the technical characteristics of housing and the socio-economic characteristics of residents to develop an appropriate model of the Walloon housing stock. This coupling of residents and housing should enable (i) a better understanding of renovation dynamics at the regional level and in the various municipalities, and (ii) the subsequent proposal of strategic recommendations for increasing the rate of deep energy renovation. The main research question of this Ph.D. research is formulated as follows:

MRQ. *To what extent can the joint analysis of technical characteristics of dwellings and socio-economic characteristics of residents explain renovation dynamics and support strategies to accelerate deep energy renovation in the Walloon residential building stock?*

1.2.4. Sub-research questions

This main research question can be subdivided into several specific questions, which will be studied in turn. These questions correspond to gaps in the research that have been successively identified and published. Four publications thus constitute the chapters of this thesis, whose research questions can be formulated as follows:

RQ1. *What statistically significant relationships exist between the technical characteristics of dwellings and the socio-economic characteristics of their occupants in the Walloon Region?* **(Chapter 3.1 and 3.4)**
RQ2. *Which representative dwelling–occupant clusters can be identified in the Walloon residential building stock based on integrated technical and socio-economic data?* **(Chapter 3.2 and 3.4)**
RQ3. *What are the patterns of geographical distribution of these characteristics across Wallonia?* **(Chapter 3.1 and 3.2)**
RQ4. *To what extent can façade-based infrared thermography complement statistical datasets to improve the characterization of building performance and energy use at the neighborhood scale?* **(Chapter 3.3 and 3.4)**
RQ5. *How do dwelling–occupant clusters contribute to explaining observed renovation behaviors and renovation inertia?* **(Chapter 3.4)**
RQ6. *What differentiated renovation strategies and policy instruments can be derived from dwelling–occupant cluster analysis to effectively increase deep renovation rates?* **(Chapter 3.1, 3.2 and 3.4)**

1.2.5. Audience

This thesis is primarily intended for policymakers and public administrations involved in energy-efficient renovation. The findings and recommendations presented are intended to inform policy discussions. These insights can help improve the effectiveness of policies aimed at enhancing residential energy efficiency and reducing energy consumption in the residential sector.

At the same time, this thesis also contributes to advancing scientific knowledge in the fields of renovation and energy efficiency. Each chapter provides insights into the composition of Wallonia's building stock, energy efficiency dynamics, and renovation strategies. The development of this knowledge allows for the identification of new research avenues, which are discussed at the end of the manuscript. This scientific contribution also lies in the various methodological tools employed, which can be utilized and further developed. The strengths and weaknesses of the different tools used have been highlighted in each article to enable their judicious and appropriate use in the future. The overall structure of the thesis, which combines quantitative and qualitative approaches, also enriches scientific literature.

Residents of older housing in the Walloon region are also directly affected. They will find little directly actionable information in this manuscript. However, they are the primary target of energy renovation efforts. As noted in the introduction, the current building stock is unable to provide minimum guarantees of comfort and health in a world that must decarbonize. It is therefore crucial to propose solutions to make it more resilient, lest the environmental crisis be compounded by a social crisis.

1.2.6. Scientific contribution

The scientific contributions of the thesis can be summarized as follows:

- This thesis contributes to the development of a new model of Wallonia’s housing stock, based on both technical data on housing and socioeconomic data on residents. The decision to incorporate socioeconomic data addresses the challenges identified in the current state of the art.
- This building stock model was developed by leveraging existing, independent databases that were integrated using a methodology specifically designed for this purpose. Beyond the specific issue of energy-efficient renovation, the ability to analyze increasingly rich and diverse datasets represents a significant challenge in many fields of research.
- To improve the quality of the results obtained, the thesis employs a multi-method, multi-scale approach. Quantitative and qualitative tools are employed, and their results are compared to verifying their validity or identifying any contradictions that inform the discussion. Furthermore, shifting the scale from country-level analysis to local case studies via the regional model also makes it possible to identify both general trends and weak signals.
- This thesis successfully develops a set of recommendations for the energy-efficient renovation of the building stock based on an analysis of the dynamics at play in the WR, considering technical and socioeconomic data.

1.3. Paper based thesis

To address the research questions identified above and to provide the contributions mentioned earlier, this thesis draws on four previously published scientific articles, which form its core.

Chapter 3.1, “*Analysis of the Determining Factors for the Renovation of the Walloon Residential Building Stock*” aims to verify whether it is possible to cross-reference technical and socio-economic data from independent databases. Correlations between these data are established (**RQ1**), and an analysis of the results obtained provides a better understanding of the energy dynamics of the Walloon building stock based on these correlations (**RQ3**). Initial general recommendations can thus be formulated based on this initial statistical analysis (**RQ6**).

Chapter 3.2, “*Clustering of Archetypal Building-Inhabitant Pairs to Improve Energy Efficiency: The Case of the Walloon Region in Belgium*” further develops this new model of the Walloon building stock based on technical and socio-economic data. The algorithms used improve its quality, and the clustering allows us to derive a set of representative typologies (**RQ2**). Principal Component Analysis of the distribution of these clusters across the region and within the various municipalities enables the identification of varied situations based on the urban fabric (**RQ3**). More targeted recommendations can be proposed, focusing not only on the different clusters but also on the different municipalities based on their composition (**RQ6**).

Chapter 3.3, “*Integrating Statistical Data and Thermography Survey for Assessing Energy Renovation Policies: A Review*” discusses the use of a specific technique, IRT, to supplement and validate the results obtained in the two previous chapters. This chapter primarily serves as a transition between Part I: Statistical Analysis, developed in Chapters 3.1 and 3.2, and Part II: Case Study, explored in Chapter 3.4. This article also provides relevant information on the use of IRT to complement other sources of information on the energy dynamics of the Walloon building stock (**RQ4**).

Chapter 3.4, “*Linking Building Conditions and Household Realities for Neighborhood-Scale Residential Energy Renovation*” complements, validates, and critiques the results previously obtained through a mixed-methods analysis of a residential neighborhood in the city of Liège using three qualitative tools whose results are triangulated: the survey, IRT, and the focus group. The results highlight the statistical relationships between technical and socio-economic data in this specific case study (**RQ1**). The study highlights the specific typologies of this neighborhood, which is not representative of the entire building stock (**RQ2**). The results of the IRT highlight the specific advantages and disadvantages of this technique in the context under study (**RQ4**). The responses to the survey and focus group also provide a better understanding of what explains renovation behaviors based on technical and socioeconomic data (**RQ5**). Ultimately, detailed recommendations are proposed to target specific typologies that were not particularly relevant at the regional level and to supplement the previous observations (**RQ6**).

2. Research Framework

2.1. Thesis outline

As previously announced, this doctoral thesis manuscript is divided into two parts that constitute the core of the results, as shown in Figure 2 1. Each part consists of two chapters. Each of these chapters is both independent and correlated with the thesis. Combined, these different studies enable a set of recommendations to be produced, based on quantitative and qualitative data, for all stakeholders in an energy renovation strategy.

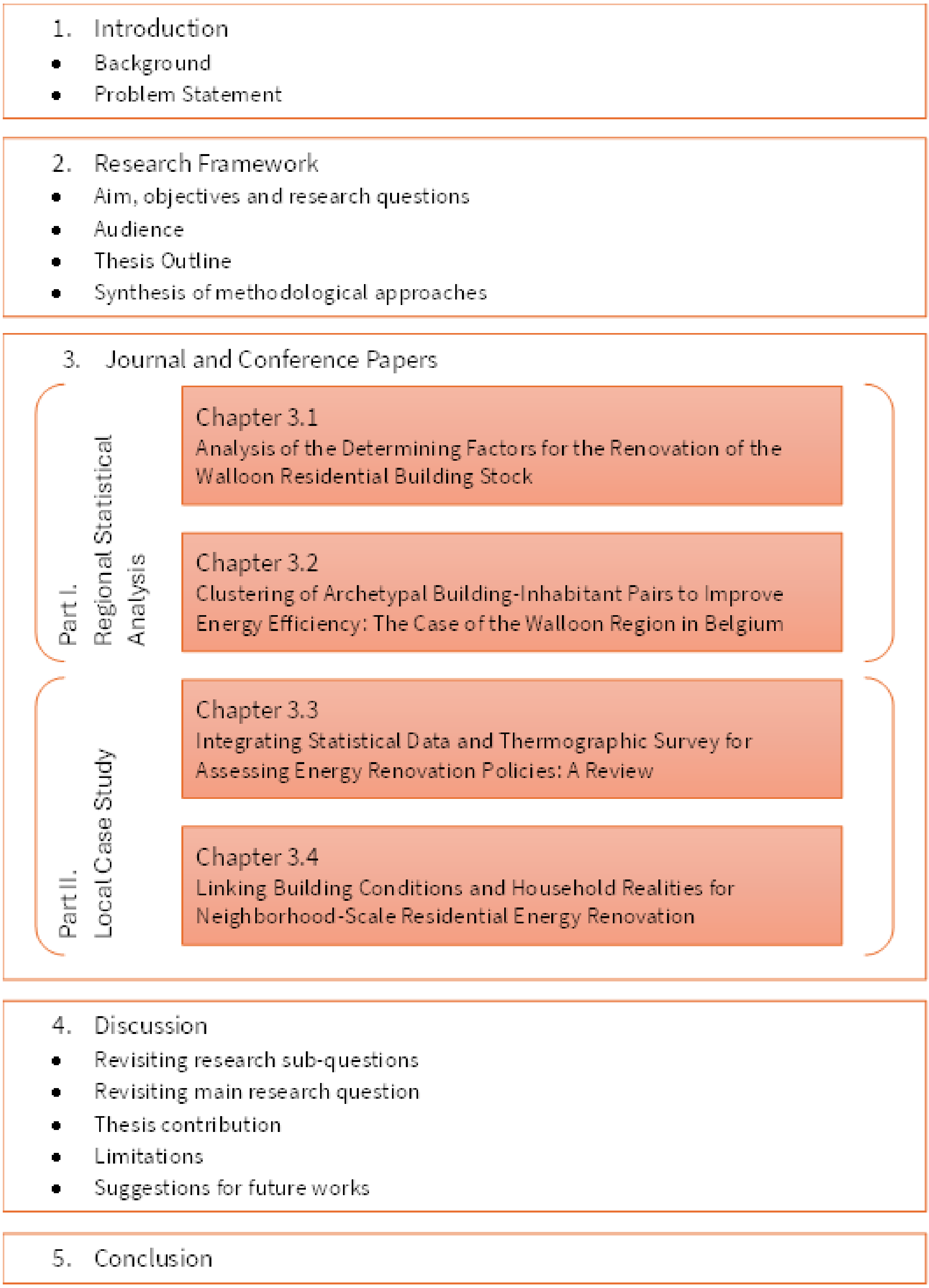

Figure 2-1. Thesis Outline

As a preamble, section 1. Introduction recalls the main contextual elements that constitute the framework within which the thesis is developed. The introduction focuses on the dynamics that influence the energy renovation market in Belgium, through a review of the scientific literature and several interviews with experts in the field. This introduction identifies certain obstacles to increasing the renovation rate. It also highlights the principal areas of research that will be addressed later, and the importance of an approach that combines technical data on buildings with socio-economic data on residents. This step identifies certain research gaps that the thesis attempts to address. The state of the art was gradually supplemented as the thesis developed to respond to new questions.

Section 2. Research Framework presents the general logic that guided the methodological development of the thesis. After specifying the research questions identified in the exploratory introduction, this Research Framework explains the general plan of the thesis and recalls the methodological principles that enabled its completion.

Part I. is a statistical analysis of representative data from the WR. This part allows different existing databases to be cross-referenced to better understand the correlations that exist between the technical characteristics of housing and the socio-economic characteristics of the occupant. This part thus allows a new mixed model of the housing stock to be developed, based on this occupant/housing pairing. Chapter 3.1 draws on existing databases in the WR covering both the technical characteristics of housing and the socio-economic characteristics of residents. This chapter examines the links between these characteristics but also provides an initial overview of their distribution in the WR and their impact on the energy efficiency of the housing stock. Chapter 3.2 is an extension of Chapter 3.1. Using more precise statistical tools, Chapter 3.2 proposes resident/housing clusters that are representative of the WR. These clusters have two roles: on the one hand, to better understand the obstacles and motivations for energy renovation, and on the other hand, to evaluate in more detail the dynamics of energy renovation at the city level.

Part II. is based on a local case study. This case study validates the reasoning developed above and proposes energy renovation actions tailored to the resident/housing clusters. Chapter 3.3 explores the potential of IRT for rapidly collecting mixed data. Based on a review of the literature, this article explores the potential advantages and disadvantages of IRT for mapping clusters more accurately. Chapter 3.4 applies IRT to the facades of houses in an old residential neighborhood, in combination with a survey of occupants and a focus group organized with stakeholders involved in this issue in the city. The results obtained are used to develop and refine the lessons learned in the previous chapters.

Section 4. Discussion aims to provide meaning and coherence to the results obtained in the various articles. Each research question is addressed based on the findings of one or more articles. Furthermore, these results are contextualized considering the literature review conducted in the introductory section. The thesis's specific contributions are highlighted, while also emphasizing the inherent limitations of the approach. Finally, several suggestions for future research directions will conclude the discussion.

Finally, all the results obtained in the distinct parts are summarized in section 5. Conclusion. Based on the main research question of this study, we will demonstrate how this study contributes to an integrated approach to the renovation of the housing stock while paving the way for future issues.

2.2. Variables, dataset and operationalization

2.2.1. Technical and socio-economic variables

The thesis's initial hypothesis is based on a joint analysis of housing-related technical variables and residents' socioeconomic variables to understand the dynamics of energy-efficient renovation in the Walloon Region. Four variables were selected:

Geometry: The layout of a dwelling (apartment, townhouse, semi-detached house, detached house) is a key factor in understanding the dynamics of renovation, as it directly influences both the compactness of the dwelling and the technical challenges (insulation from the inside) and operational challenges (insulation in a co-ownership situation).

Energy efficiency: Since this thesis focuses on the current and future energy efficiency of Wallonia's building stock, we believe it is important to have information on the energy performance of residential buildings. While most models of the building stock rely on typologies representative of different construction eras, we have chosen to directly use the energy labels (from A to G) and energy performance (in kWh/m²·year) derived from the EPC. This data has the advantage of not requiring an additional step to estimate energy performance. However, the EPC also has numerous limitations, which will be discussed later in this paper.

Categories of income : The income category is used to represent a household's financial capacity to undertake energy-efficiency renovations. It should be noted, however, that as income increases, so does the financial capacity to pay for energy. It was initially assumed that this income category might also influence the skill levels required to undertake a renovation project, although this assumption will be called into question during the discussion.

Property title: Ownership status corresponds to the occupant's legal capacity to undertake renovation work. For reasons already mentioned in the introduction, tenants lack the means to undertake major renovations. We therefore wanted to see how this limitation affects the quality of the occupied housing. It should also be noted that this variable partially compensates for the decision to focus on occupants rather than property owners. This choice is based on two reasons: on the one hand, it is much more complicated to find and cross-reference information on homeowners, and on the other hand, residents are both the first to be impacted by energy efficiency and the ones whose behavior can significantly affect energy consumption.

Number of households: This additional variable was included in the very first study to account for the significant differences in the composition of the housing stock between small and large cities in the Walloon Region.

2.2.2. Dataset selection

The choice of variables in this thesis is intrinsically linked to the availability of databases providing information on their distribution across the various Walloon municipalities. Table 2-1 shows the source of the data used and the date they were retrieved. It is important to note that most of these data are publicly available (Statbel, Iweps, Census) and meet the highest quality standards. Only the EPC data is proprietary, mainly due to personal data.

Table 2-1. Summary table of dataset used in chapter 3.1 and 3.2.

Category name	Data name	Source	Data year	
			Ch. 01	**Ch. 02**
Energy	EPC label and consumption	DG TLPE	2018	2020
Geometry	Type of building in housing	STATBEL	2018	
Income	Categories of income	IWEPS	2016	
Ownership	Property title	Census	2011	
Households	Number of households	STATBEL	2018	

The retrieval date does not indicate the age of the entire dataset. For EPC data, the database thus includes certificates dating back to the start of data entry. This inconsistency in the production and retrieval dates of the databases is undoubtedly a limitation that will be discussed further in this paper.

2.2.3. Statistical method

Characterization (Ch. 3.1): Characterization involves analyzing the variability in the distributions of various characteristics studied independently of one another. It provides initial insights into their values and geographic distribution.

Spearman Correlation (Ch. 3.1): Spearman's correlation coefficient is used to explain the linear relationship between two variables, based on their distribution across municipalities. This correlation helps determine whether there is a link between these variables.

Muliple Linear Regression (MLR) (Ch. 3.1): MLR allows us to identify and quantify the relationship between the dependent variable—the one we are trying to understand—and all potential explanatory variables.

Simulation (Ch. 3.1): Based on the results of the MLR, it is possible to simulate new values for the dependent variables based on changes in the independent variables. This simulation allows us to test how this preliminary model responds to different scenarios.

Weighting (Ch. 3.2): To improve the quality of the statistical analysis, the weight of the various certificates is adjusted based on the representation of the certificates for a given building type in the municipality in question, compared to the actual distribution of that building type. This adjustment limits the overrepresentation of newer buildings, particularly apartments.

Isometric Log Ratio Transformation(ILR) (Ch. 3.2): Traditional regression models cannot be applied to variables whose sum equals 1, as is the case with variables expressed as percentages. The ILR transformation allows regression models to be applied to the transformed variables, while retaining the option to reverse this transformation later to recover the original values without any loss of information.

Beta Log regression (Ch. 3.2): Beta regression is a regression model specifically designed for variables whose values must not exceed 1 under any circumstances, as is the case with the variable representing the homeownership rate.

Ordinal logistic regression (Ch. 3.2): Ordinal logistic regression is a regression model specifically designed for variables with an ordered structure, such as different income categories.

K-means clustering (Ch. 3.2): K-means is an unsupervised algorithm for partitioning a set of data points into several distinct clusters whose members share similar characteristics. In this study, this approach enables the identification of clusters of all EPCs based on the technical and socioeconomic characteristics previously assigned to them.

Principal Component Analysis (PCA) (Ch. 3.2): PCA is a dimensionality reduction technique used to reduce the complexity of multidimensional datasets. In our case, the distribution of different clusters across municipalities can be simplified to highlight those municipalities with similar cluster distributions.

2.2.4. Qualitative case study

InfraRed Thermography (Ch. 3.4): IRT involves measuring the infrared emissions from an object. Infrared emissions depend on both the temperature of the object and the emissivity of the material. For most building materials (excluding glass and metals), emissivity is relatively constant, allowing for a comparison of material temperatures. On a building facade, this exterior surface temperature depends mainly on the balance between indoor and outdoor air temperatures and the thermal resistance of the facade, which allows for an initial estimate of the latter.

Door-to-door survey (Ch. 3.4): The door-to-door survey involves distributing a pre-prepared questionnaire to gather information on households' socioeconomic data, technical building data, and their attitudes toward energy and construction issues. Conducting the survey door-to-door allows for a more diverse range of respondents compared to an online survey.

Focus group (Ch. 3.4): A focus group facilitates discussion among a group of people; in our case, stakeholders in energy renovation (scientists, government agencies, and civil society). The participants were divided into three groups and were asked to discuss issues related to energy poverty and potential solutions for two 40-minute sessions. The recorded discussions were then transcribed and summarized.

Triangulation (Ch. 3.4): The triangulation described in Chapter 3.4 involves cross-referencing multiple complementary methods—in our case, IRT, surveys, and focus groups. This triangulation allows us to verify whether the results are consistent and to highlight redundant information or contradictions. Another advantage of triangulation is that it can partially compensate for the inherent limitations of one tool by using another tool that does not share those same limitations.

2.3. Synthesis of methodological approach

The methodology used and the various tools employed are summarized in Figure 2-2. The thesis analyzes renovation dynamics in the WR in terms of the technical characteristics of housing and the socio-economic characteristics of residents. Chapters 3.1 and 3.2 use various statistical tools to study the distribution and correlations between these characteristics at the regional level. Chapters 3.3 and 3.4 use a mixed approach to study a specific case study.

The methodologies used in each chapter are explained below but are discussed in greater detail in the chapter itself. The results of each chapter were used in the following chapters. The questions identified in the introduction led to the choice of characteristics studied in Chapters 3.1 and 3.2. Statistical analyses in Chapter 3.1 were improved, developed, and continued in Chapter 3.2. The model developed in Chapter 3.2 is integrated into the discussion in Chapter 3.3. Chapter 3.3 presents the research questions for Chapter 3.4, which corrects and refines the general conclusions of Chapter 3.2. Each of these chapters provides part of the answer to the main research question. The results and lessons learned from these different chapters are brought together in this thesis to extract the essence.

2.3.1. Introduction

The core of the thesis, summarized in the four chapters below, was preceded since 2015 by extensive research aimed at identifying the key issues affecting the energy renovation sector in Belgium. Two main approaches were employed to inform and develop this state-of-the-art analysis. First, a literature review on energy renovation issues was conducted, with particular attention given to research focusing, in order of priority, on the WR, Belgium, and Western Europe. This literature review led to the drafting of an initial report (Ruellan, 2016b) and a conference paper (Ruellan & Attia, 2016) on the state of renovation in Belgium. In parallel, several contacts were established with Belgian experts in the energy renovation sector from the scientific, political, and business communities to conduct semi-structured interviews on the challenges of energy renovation in Belgium. These interviews were also published (Ruellan, 2016a). The introduction written in this manuscript draws in part on this exploratory work, which was enriched and revised as this thesis progressed over the course of a decade.

The analysis conducted at the time helped identify the initial research questions for Part I of this thesis, which will lead to the development of a mixed-methods model of the building stock that integrates technical and socioeconomic data.

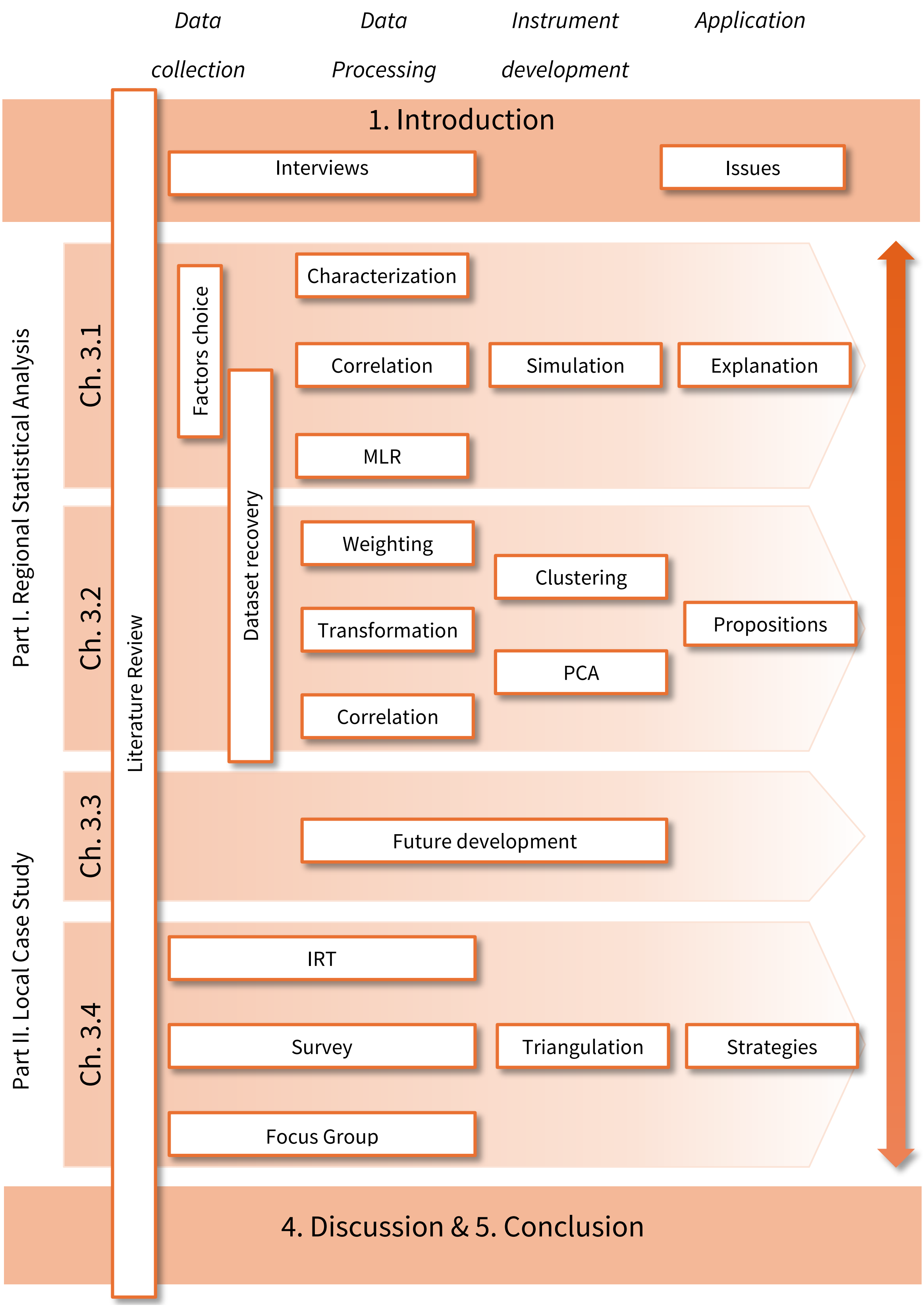

Figure 2-2. General Study Conceptual Framework

2.3.2. *Part I - Chapter 3.1*

The methodology used in Chapter 3.1 is based on statistical analysis of existing databases (Table 2 1). The first step in this chapter was to define the databases that are used, based on their relevance to energy efficiency and energy renovation issues on the one hand, and their availability at the same geographical scales on the other. Two data sets represent the technical data for housing: the PEB label–representing the energy efficiency of the building envelope–and the geometry– supplementing information on the compactness of the urban fabric. Two data sets represent the socio-economic data for occupants: income–reflecting the household's financial capacity to invest directly in energy-efficiency renovations–and title deed–affecting the occupant's legal ability to make major changes to the building envelope. To comply with the General Data Protection Regulation (GDPR), energy performance certificates are anonymized (no names or exact locations).The various data sets are studied at the level of Walloon municipalities, with each of the 262 municipalities representing statistical individuals. Using existing databases helps speed up the time-consuming data collection phase, while ensuring data quality by leveraging known datasets whose limitations and weaknesses are well understood.

The first phase of the analysis involves cleaning the collected data to ensure it aligns with the research objectives. Using R software, these different databases are characterized separately to better understand their distribution in the region. This distribution is compared with state-of-the-art results to ensure consistency and identify initial differences. Spearman's correlation coefficient (Xiao et al., 2016) is calculated to study the joint evolution of these distinctive characteristics, two by two. Finally, MLR (Uyanık & Güler, 2013) is performed to estimate a dependent variable (average energy consumption) using various explanatory variables carefully selected according to the Variance Inflation Factor (VIF) (Akinwande et al., 2015). This selection allows us to retain only the variables that are truly relevant, while eliminating those that have the least impact. Calculating the Mahalanobis distance (Ghorbani, 2019) during MLR allows us to check for and analyze the presence of outliers. The Breusch-Pagan test (Astivia & Zumbo, 2019), the VIF, and the Shapiro-Wilk test (González-Estrada et al., 2022) were used to test the validity of the hypotheses. The methodology developed has the advantage of being simple, robust, and easily adaptable to other datasets.

The results obtained provide a better understanding of the correlations between technical and socio-economic data. The study also makes use of the theoretical model obtained via MLR to carry out several simulation experiments on raw renovation scenarios to demonstrate their impact on the energy consumption of housing in the WR. This initial study demonstrates that it is possible to leverage databases from a variety of sources to better understand the energy dynamics of the housing stock in the WR. It also confirms the value of combining technical and socioeconomic data and offers several recommendations for renovation policies and future research. The objective of Chapter 3.2 is to strengthen and develop the model whose foundations have been laid.

2.3.3. *Part I - Chapter 3.2*

The methodology used in Chapter 3.2 continues to develop a model of housing stock based on cross-referencing technical data on housing with socio-economic data on residents, refining them during the process. Datasets used are the same as those in Chapter 3.1, except for an update to the EPC dataset (Table 2 1). All statistical analysis is performed using R software. The core of statistical work consists of identifying and characterizing statistical units. These statistical units represent the distribution of the characteristics under study across an entire municipality—“individual-cities”—or across a single dwelling—“individual-certificate”—depending on the stage in question.

The first step in data processing is the collection and cleaning of datasets. To comply with the GDPR, energy performance certificates are anonymized (no names or exact locations).. The weighting step for “individual cities” allows us to verify and correct the number of energy performance certificates in each city by comparing the proportion of different types of housing in the EPC database with that in the “Type of building” database. This step already provides a better understanding of the actual energy performance of the Walloon housing stock. The data obtained in this way can be cross-referenced in a second step, using specific algorithms that are better suited to their mathematical characteristics. Applying an Isometric Log Ratio (ILR) (Egozcue et al., 2003) transformation allows a regression model to be applied to categories whose sum is equal to 1. like all the categories that express representation as percentages. The ILR transformation also has the advantage of being reversible, which ultimately allows us to recover results expressed as percentages. Ordinal logistic regression (Scott et al., 1997) allows model 1: explanatory variables to be sought for the hierarchical distribution of the Income category. This hierarchical distribution of income categories, ranging from the lowest to the highest, must be reflected in the results of our regression to ensure its quality. Furthermore, the ownership rate must necessarily remain between 0 and 100%. The use of a beta regression algorithm (Cribari-Neto & Zeileis, 2010) allows model 2: explanatory variables to be sought for the distribution of the ownership rate. A probability of income and ownership categories could then be deduced from the two regression models created, based on the geometry of the dwelling, the energy label, the province, and the size of the city. All this information is then available for all “individual-certificates”.

To convert the probabilities of income and property into membership in a specific category, we conduct several random drawings weighted by these probabilities. These draws allow us to verify that they do not affect the overall distribution of the different categories and that they are consistent with their actual distribution. Resident/dwelling clusters representative of the Walloon housing stock can be calculated using an K-means clustering algorithm (Ikotun et al., 2023) of all “individual-certificates”. Among the various tests conducted, and in line with current best practices, the results are presented for both a six-cluster and a ten-cluster clustering. Increasing the number of clustering iterations up to 200 and varying the number of initial clusters from four to ten allows us to assess the quality of the clustering. The cluster results can then be adjusted by de-standardizing (ILR) the variables and re-weighing each certificate. The distribution trends of these different clusters in Walloon cities are then evaluated using PCA (Jolliffe & Cadima, 2016).

The results demonstrate the potential for identifying a set of clusters that are representative of Wallonia’s housing stock and its residents. Among the clusters, it is possible to identify a few priority pairs in terms of renovation who require different strategic approaches. The PCA highlights municipalities with particularly specific distributions. The discussion highlights the insights this model provides into the energy dynamics of the building stock, while also emphasizing the need to compare these results with field data. This comparison is the focus of Part II of the thesis (Chapters 3.3 and 3.4).

2.3.4. Part II – Chapter 3.3

The methodology in Chapter 3.3 is based on the cross-analysis of the results from Chapters 3.1 and 3.2, on the one hand, and on the state of the art in the use of IRT to measure the thermal characteristics of buildings on the other hand.

This state of the art focuses particularly on reviews of previously published literature. The following keywords are used: "building infrared thermography review." Articles that focus solely on defect detection, envelope degradation, structural analysis, and historical heritage are excluded. The ten articles selected are analyzed separately, then cross-referenced to identify recurring themes. This methodology provides an initial overview of the current state of the art regarding the use of IRT in energy audits. Given sufficient time, it would have been valuable to conduct a more quantitative assessment of the literature review to complement the qualitative analysis.

The results obtained are then discussed in relation to the general objectives of the thesis and the results previously obtained in the statistical analysis in Chapters 3.1 and 3.2. This discussion results in a preliminary draft methodology for using IRT in a case study focusing on the joint study of the technical characteristics of housing and the socio-economic characteristics of the inhabitants. Chapter 03 thus sets the stage for the case study presented in Chapter 3.4.

2.3.5. Part II - Chapter 3.4

The methodology used in Chapter 3.4 is based on the triangulation of three complementary empirical tools: a non-representative survey of residents, IRT of building facades, and a focus group of local stakeholders. The approach is exploratory rather than predictive. The survey and thermography are conducted on the same case study—an old suburb of the city of Liège—while the stakeholders invited to the focus group all work in or near the city of Liège. The case study was chosen specifically for the assumed homogeneity of the technical characteristics of its building stock, as opposed to the assumed heterogeneity of its socio-economic characteristics. This aspect allows for a more detailed analysis of the impact of varying socio-economic characteristics on ER dynamics. The department of the City of Liège responsible for the SCEPA program was also consulted to determine whether they had any preferences or suggestions regarding the choice of case study. The purpose of this collaboration was to make the results more directly usable by the relevant authorities.

Thermography is conducted systematically on all street-facing facades within the perimeter defined for the case study. This IRT is conducted during periods that are cold enough to highlight heat loss from the dwellings. To compensate for the thermal camera's short focal length, the images obtained are combined to produce a complete thermal footprint of 522 facades. These images are then analyzed to detect redundant thermal signals. Due to the low definition of camera, the image analysis is qualitative and focuses on the relative temperature contrasts between surfaces rather than on absolute temperatures. The door-to-door survey collected a wealth of information about the residents in the area: the socio-economic characteristics of the household, the technical characteristics of the dwelling, energy consumption and comfort levels, the respondent's knowledge and behavior, any renovation work that has been carried out, and the occupants' motivations for renovating or not renovating. The decision to conduct a door-to-door survey is driven by the desire to reach a broader and more diverse audience, as well as by the opportunity to assist respondents with more technical questions. A pilot survey conducted with 11 respondents helped refine the wording of the questions and the length of the questionnaire. The main survey collected responses from 67 respondents. Two of them responded twice, allowing the questionnaire to be validated through test-retest analysis. The focus group was organized as part of the UNIC CityLabs initiative to promote collaboration among public authorities, university researchers, and civil society actors. The focus group challenged scientists, elected officials, administrative staff, members of associations and businesses, and other housing experts on the issue of energy poverty and the policies to be adopted in response. The 25 participants are divided into three mixed-ability groups to encourage balanced interactions during two consecutive sessions. All sessions were recorded, transcribed verbatim, and analyzed jointly to produce an anonymized summary.

The use of triangulation (Donkoh & Mensah, 2023) made it possible to cross-reference the results of each tool and strengthen the robustness of the analysis. Conversely, the weaknesses inherent in each tool were mitigated. Equal weight is assigned to the analysis of each set of results, in accordance with the principles of triangulation. The decision to prioritize qualitative data rather than seeking to obtain enough responses to allow for quantitative analysis stems from the fact that this chapter serves as a complement to the previous analyses, which focused precisely on that quantitative aspect. Nevertheless, the low response rate to the survey and the poor quality of the thermal camera used remain issues that could benefit from further study. Furthermore, the choice of case study resulted in a wide range of socioeconomic profiles among residents, at the expense of diversity in building types. While the findings of the study are largely applicable to other contexts, they should be supplemented by additional studies of other sites with different characteristics.

Special attention is paid to compliance with GDPR regulations during the collection and processing of personal data. All information that could identify survey respondents, facades, and focus group participants has been anonymized. In addition, survey participants received comprehensive information about the study’s objectives, the nature of the data collected, privacy protection measures, and their rights as participants before signing a consent form. The full survey dataset is available in the associated Harvard Dataverse dataset (Ruellan & Attia, 2025).

The results obtained are analyzed in the discussion section of the article to understand the specific characteristics of the case study. More specifically, the IRT results are compared with the findings in Section 3.3 to highlight the strengths and limitations specific to this technique. Finally, these results are also analyzed considering the findings from Part I to draw broader conclusions regarding the challenges of ER in WR and the strategies needed to accelerate its implementation.

2.3.6. Table Mapping

Figure 2.3 below synthetizes how the thesis manuscript relates the methodological tools developed earlier to the various research questions outlined in the introduction.

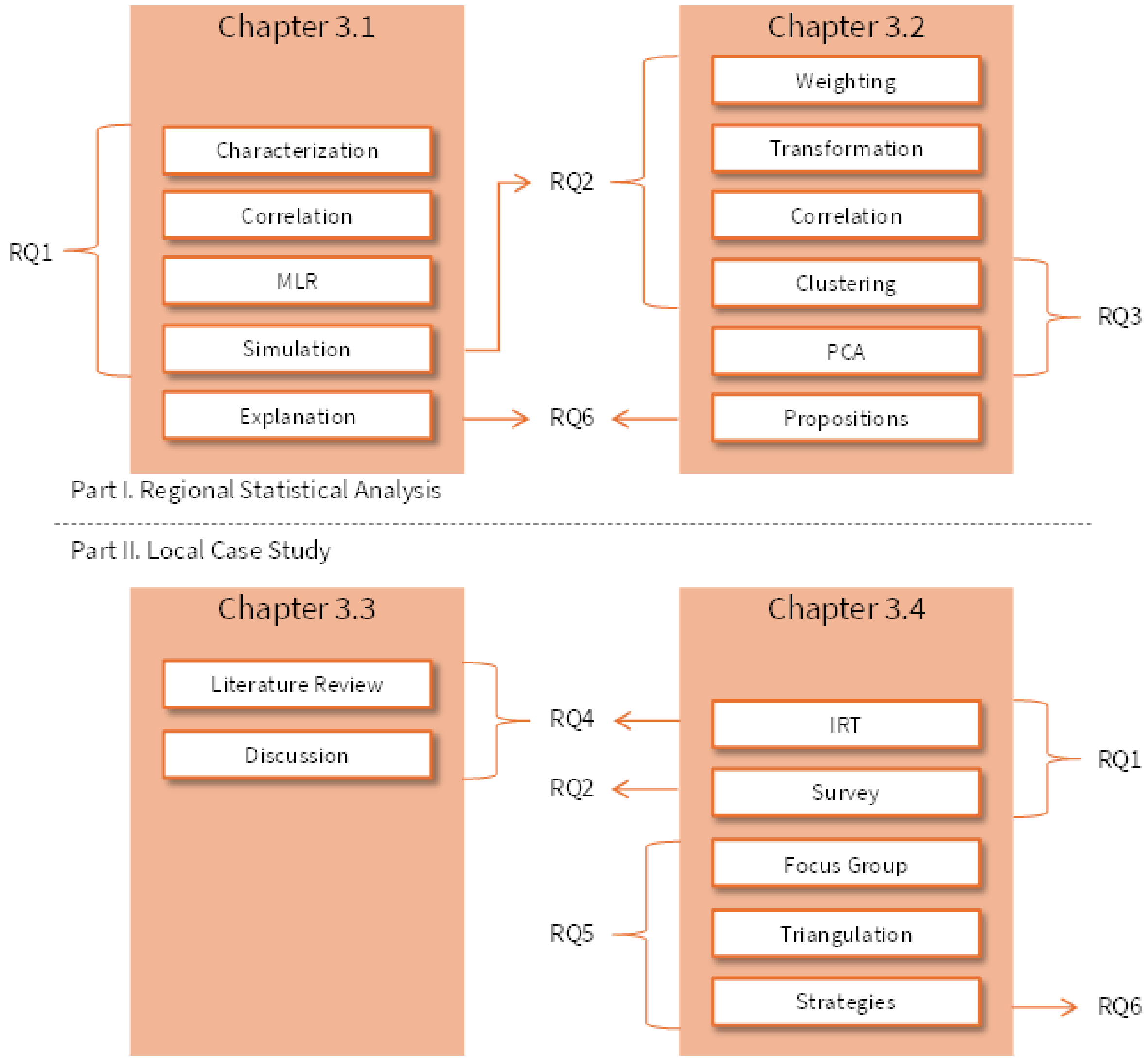

Figure 2-3. Thesis table mapping

2.4. Critical reflection

The first step in developing the methodology described above involved the decision to design a model of building stock that integrates socioeconomic data on residents alongside technical housing data. It was clear that socioeconomic data were central to understanding the dynamics of renovation across the Walloon building stock. However, there was a lack of joint analysis of these variables, which are often treated independently. Once the decision was made to analyze technical and socioeconomic data together, efficiency considerations led to the use of existing databases. Within the scope of this thesis, it seemed too time-consuming to conduct a survey with enough respondents to obtain a database representative of the distribution of socioeconomic and technical data. Once this initial decision was made, the various steps followed from an ongoing dialogue with statistical experts to propose iterative improvements to the statistical algorithms.

The decision to rely on separate databases linked by regression algorithms logically results in a significant simplification of our housing stock model. The connections between technical and socioeconomic data are established solely through geographic proximity, rather than being derived directly from the same questionnaire.

With more time, it would have been possible to conduct a survey of a sufficiently large sample to directly build a mixed-methods model of the housing stock without going through the correlation and regression stages. However, this approach allowed us to subsequently use a questionnaire to ask specific questions about knowledge and motivations, in addition to the data needed to build the model.

At the conclusion of Part I, it was clear that the model of Wallonia's built stock needed to be validated by comparing it with on-the-ground realities. Among the various options available, the approach of triangulating the survey, the IRT, and the focus group meets several requirements. It is important to note that this triangulation also aligns with scheduling constraints unrelated to the thesis. On the one hand, the laboratory had planned to acquire a professional thermal camera, which would have been of great assistance in conducting the IRT. Furthermore, the focus group was organized as part of a CityLab UNIC initiative. The survey itself had been under consideration for several years as a method for validating statistical data and analyzing individual renovation dynamics.

The decision to use a triangulation of qualitative tools for the case study analysis has limitations regarding the representativeness of the data obtained (survey) or their quality (IRT) due to an inadequate thermal camera. Although triangulation ensures a certain level of quality and reproducibility, each tool independently has significant intrinsic limitations.

The scope of the case study was a topic of discussion: how many buildings should we limit ourselves to obtain the maximum amount of information without unduly prolonging the IRT processing time? Taking this reasoning to the extreme, it would have been possible to study only a few buildings typical of the previously identified clusters, delving much deeper into their characteristics through advanced modeling. However, it seemed to us that this risked extrapolating results that were too dependent on a specific situation on a large scale.

2.5. Research ethics

Personal data, as defined by the GDPR, is any data relating to an identifiable individual, whether directly or indirectly. The GDPR regulates the collection, use, storage and transfer of personal data within and outside the EU, as well as the information given to data subjects. The FAIR (findable, accessible, interoperable and reusable) principles mean that data must be as open as possible. However, personal data must be as close as necessary. Rather than stop collecting personal data, it is generally better to anonymize the data that will be published. If the person concerned by the data is no longer identifiable, it is no longer personal data.

This thesis involves IR photographs. These are personal data insofar as the published images make it possible to identify an address, and therefore a person. This is why it was important to pay particular attention to data management and protection in this study. To limit these risks, all visible building numbers, street names and car plates were blurred. The priority in terms of data protection is not to disseminate any personal information either directly or indirectly. Our study aims to cross-reference socio-economic data with technical data. It should be noted that socio-economic data is particularly sensitive and cannot under any circumstances be disseminated without being anonymized. Disseminating a photograph of the facade may enable a location to be identified. No link is communicated between images of facades and the socio-economic data of residents.

Informed consent is the very first step in any survey. The respondents were informed about the use of the data collected. Under no circumstances must this data be used for anything other than its stated purpose. In our case, respondents were informed that their answers were used to gain a better understanding of energy consumption and renovation. The respondents were informed of all the measures taken to limit the risk of personal data leaks. They were informed of the personal data that will be used. They were informed of how this information will be processed and how any risk of identification of the questionnaire will be avoided. The respondents were informed of the data management policy and the possibility of contacting the study manager if they wish to consult their data, find out how it is used or request that it be deleted. Finally, respondents were informed of the possibility of contacting the University of Liège Ethics Committee if they wish to make a complaint. Following this communication, the respondents dated and signed a form containing all the above information. This form was attached to and kept with the questionnaire. Any questionnaire not accompanied by a signed consent form was destroyed immediately to prevent any leakage of personal data.

Survey data is collected on paper forms filled in by the scientists in charge of the study. These paper forms will be digitized directly for the purposes of processing the study. The paper forms will be kept at the university, in the SBD Lab, in a dedicated box kept in a secure room and will be destroyed 5 years after the completion of Mr Guirec Ruellan's thesis. All the digitized data will be stored in a digital file on the university's own servers, managed by the Dox system. This data will also be deleted 5 years after the completion of Mr Guirec Ruellan's thesis.

3. Journal and conference publications

As outlined in Section 2. Methodology, this Section 3 consists of four chapters, each of which is a journal article or conference paper written during this thesis. Each chapter can therefore be read independently of the other three, but together they form a coherent body of work that progressively develops a reflection on the dynamics of energy renovation in WR, on the links between the technical characteristics of the building and the socioeconomic characteristics of the residents, and on how these characteristics can enrich a discussion of strategies for increasing the rate of energy renovation.

Part I - Chapter 3.1

Journal Paper: Analysis of the Determining Factors for the Renovation of the Walloon Residential Building Stock

RQ1. *What statistically significant relationships exist between the technical characteristics of dwellings and the socio-economic characteristics of their occupants in the Walloon Region?*
RQ3. *What are the patterns of geographical distribution of these characteristics across Wallonia?*
RQ6. *What differentiated renovation strategies and policy instruments can be derived from dwelling–occupant cluster analysis to effectively increase deep renovation rates?*

As a primary step in this research, this first journal paper serves to validate the thesis's initial working hypotheses regarding the methodological feasibility and scientific value of linking technical building data with socio-economic inhabitant data. Following an initial review of the literature and several interviews with industry experts, the plan is to study the effectiveness of energy renovation strategies based on the technical characteristics of housing units and the socioeconomic characteristics of residents. After compiling various existing databases selected for their relevance to the research questions, these were carefully prepared and cleaned. The distribution of the observed data is examined individually. Correlations between the different variables are calculated. Finally, a theoretical model of the energy efficiency of Walloon housing is proposed based on an MLR.

The results obtained confirm the possibility of cross-referencing existing databases covering different statistical populations to propose a theoretical model. The results also provide a better understanding of the energy dynamics of the Walloon building stock.

The article's discussion encourages further development of this Regional Statistical Analysis to enhance the accuracy and potential of the mixed theoretical model thus constructed. It appears necessary to develop renovation strategies that focus on both housing conditions and the socioeconomic characteristics of residents.

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Analysis of the Determining Factors for the Renovation of the Walloon Residential Building Stock

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Abstract: The issue of energy retrofitting of existing building stock occupies an increasingly prominent place in energy transition strategies in Europe. Adopting models representing the building stock and accounting for occupancy influence on final housing energy use must be developed to advise new policies. In this respect, this study aims to characterize the Walloon residential building stock and to analyze the existing correlations between the stock's technical data and its occupants' socioeconomic data. This study uses existing databases on buildings and inhabitants in Wallonia. Several statistical analyses make it possible to highlight the preponderant criteria and existing correlations between these different criteria. This study affirms the importance of accounting for certain socioeconomic categories, such as low-income groups, in a global strategic reflection on energy renovation. Multiple linear regression shows us that each percent increase in the category of households that declare between 10,000–20.000 EUR of income per year corresponds to an increase of 7.22 kWh/m^2·y in the average energy efficiency of the built stock. The results highlight the importance of focusing on renovation strategies for particular types of buildings, such as semi-detached houses, which combine unfavorable technical and socioeconomic factors. Thus, the results confirm the interest of a mixed model approach to adapt to effective renovation policy strategies.

Keywords: sustainable renovation; energy policies; statistical analysis; Walloon region; bottom-up model

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1. Introduction

Recent developments in European directives addressing energy issues in buildings (Energy Performance of Buildings Directive (EPBD) 2010/31/EU [1], Energy Efficiency Directive 2012/27/EU [2], and the Directive amending the Energy Performance of Buildings Directive 2018/844 [3]) reflect the importance given in the sector to meeting the objectives of reducing energy consumption and greenhouse gas emissions. Belgium is characterized by an ancient building stock (32% of the housing stock was built before 1945 against 23% for the European average), high proportion of single-family houses (76% in Belgium against 53% for the European average), and low renovation rates that lag behind that of neighboring countries (e.g., 58% of Belgian homes have roof insulation compared to 73% in the UK) [4]. In 2017, the residential sector's direct energy consumption represented 20% of Belgian energy consumption [5].

For a long time, national regulations focused on new construction to the detriment of renovation [6]. Thanks to the energy renovation campaigns [7], renovation is slowly entering the political field [8,9]. Home energy retrofitting is crucial as it reduces energy consumption [10] and integrates multiple sustainable development aspects [11]. A European research project from the Eracobuild program thus lists five categories of drivers: (1) durability/building physics, (2) economy, (3) environment, (4) comfort, and (5) others [12].

Despite this clear awareness, all indicators showed little change in the energy renovation rate over the last decade [13], and it is far from the estimated target of approximately 5% [4]. Much research and development on energy retrofitting has focused on the evaluation of technical solutions [14]. In Europe, this has resulted in policies focused on technical aspects [15], and few studies address the development of strategies that encourage retrofitting and improve process productivity [12]. The role of housing energy renovation policies is changing [9], no longer focused exclusively on reducing energy consumption. They now focus more on meeting the needs of the population [16]. Energy renovation policies appear as real social policies [17].

The principal barrier, at all levels, is financial aspects [14]. Consequently, subsidies, incentives, or new business models must be created that highlight the project's environmental factors. Because of the lock-in effects of unambitious policies, improvements to buildings' energy efficiency can be stranded below the best standards [14]. Nielsen et al. [18] voiced the need for more research to better target existing buildings and to prioritize actions following the built stock's characteristics. Walter and Sohn [19] suggested that the most cost-effective renovations should be identified and that an estimated confidence in expected savings should be provided. Calculating the anticipated savings implies the capacity to estimate uncertainties related to climate, behavior, specific building characteristics, and the interactions between these effects. In their literature review, Kavgic et al. [20] considered that the synergies between different policies in favor of energy efficiency, health, and comfort could be improved using adapted models of the built stock.

Two distinct approaches are used to model energy consumption in the residential sector. Top-down models analyze macroeconomic variables to distribute the different uses. Bottom-up models generalize users' final consumption to extrapolate the total energy consumption on a larger scale [21]. We distinguish between statistical and physical (or engineering) models among the bottom-up models [20]. Top-down models rely on past projections to forecast future trends. They lack detail at the technological level and are not very effective for evaluating technology-centered policies. Bottom-up statistical models require large samples, are inflexible, have difficulty predicting the impact of consumption reduction measures, and are subject to multi-collinearity. Finally, physical bottom-up models require excessive amounts of technical data, do not consider macroeconomic effects, and do not directly assess the impact of human behavior. A few hybrid models were developed to combine physical and statistical models [20].

Cyx et al. [22] distinguished approaches based on the selection of representative and typical buildings. The first case allows for a better approach to the average characteristics of the stock. Still, the second allows for better study of technical solutions adapted to the specificities of each building typology.

We note that the different models developed often have difficulty accounting for energy demand's sociotechnical factors: how people consume energy in their homes and how they invest in energy savings [20]. There are significant differences in consumption between two dwellings with the same performance, depending on the inhabitants' behavior [15,23]. Numerous studies have shown how socioeconomic conditions affect energy performance and investments in the field [24]. This is the case for income [25], education [26], or age [27]. The prebound [28] and rebound [29] effects directly translate the impact of behavior on energy efficiency.

By definition, sustainable renovation must include a social component [11]. The risk is that high-performance renovation is reserved for the wealthiest [30] and owners [31–33]. Energy and housing policies must be designed to encourage sustainable renovation projects and to limit rent increases [30]. Energy renovation, which has traditionally focused on the efficiency of heating and lighting systems, tends to evolve towards a more global approach that integrates social benefits [12].

In Belgium, several studies were carried out to model different energy aspects of the built stock. Verbeeck and Hens [34] studied the financial viability of different types of energy works on a countrywide scale. In 2008, Kints [35] proposed a typological classification of dwellings in the Walloon region (southern part of Belgium). The Low Energy Housing Retrofit research project [4] analyzed the characteristics of Belgian built stock to define target groups for energy renovation. The SuFiQuaD study [36] proposed a multifactorial evaluation of different types of buildings. The TABULA project [22] defined building types related to the Belgian housing stock, to which different renovation scenarios were applied. In 2015, Gendebien et al. [37] proposed a bottom-up model, mixing hybrid and representative approaches, to analyze the built stock's energy consumption. The last two jointly analyzed models [38] highlight the importance of reliable and complete data when modeling the built stock to limit significant variations between models. A recent study estimated the heat consumption and heat demand of more than 1,700,000 buildings in the Walloon region using a geographic information system (GIS) [39]. However, all these studies focus on the physical aspects of the built stock. They do not consider the social factors essential to achieving a large-scale energy transition in Belgium [40].

The above review underlines the lack of a model based on the Walloon built stock to guide the elaboration of policies in favor of energy renovation that accounts for a household's socioeconomic aspects. To make such a model, it is first necessary to select and characterize the appropriate indicators, indicators for which databases are accessible and between which correlations exist to build this model. Therefore, this study aims to analyze different building stock characteristics and to correlate them to their occupants' socioeconomic conditions. The study aims to allow researcher and policymakers to create long-term renovation strategies informed by these study outcomes. The following questions are answered in this research:

- How to cross analyze building databases that do not represent the same statistical individuals?
- What types of correlations are there between the technical housing characteristics and the socioeconomic characteristics of the occupants? What is the value of these correlations?
- Which trend does the combination of technical and socioeconomic characteristics make the deduction of the built stock's performance and the identification of representative typologies possible?
- What is the potential impact of these correlations on a building policy in favor of energy renovation?

Finally, this study highlights the essential links between the least affluent households and the least efficient buildings and finds that increased homeownership is accompanied by decreased energy efficiency. Developing energy renovation policies targeted more towards certain groups identified through this analysis could be useful.

2. Methodology

In this section, we present the research methodology, including the study concept. Our research methodology combines a literature review with three main statistical analysis methods. We developed a study conceptual framework that summarizes and visualizes our research methodology, as shown in Figure 1.

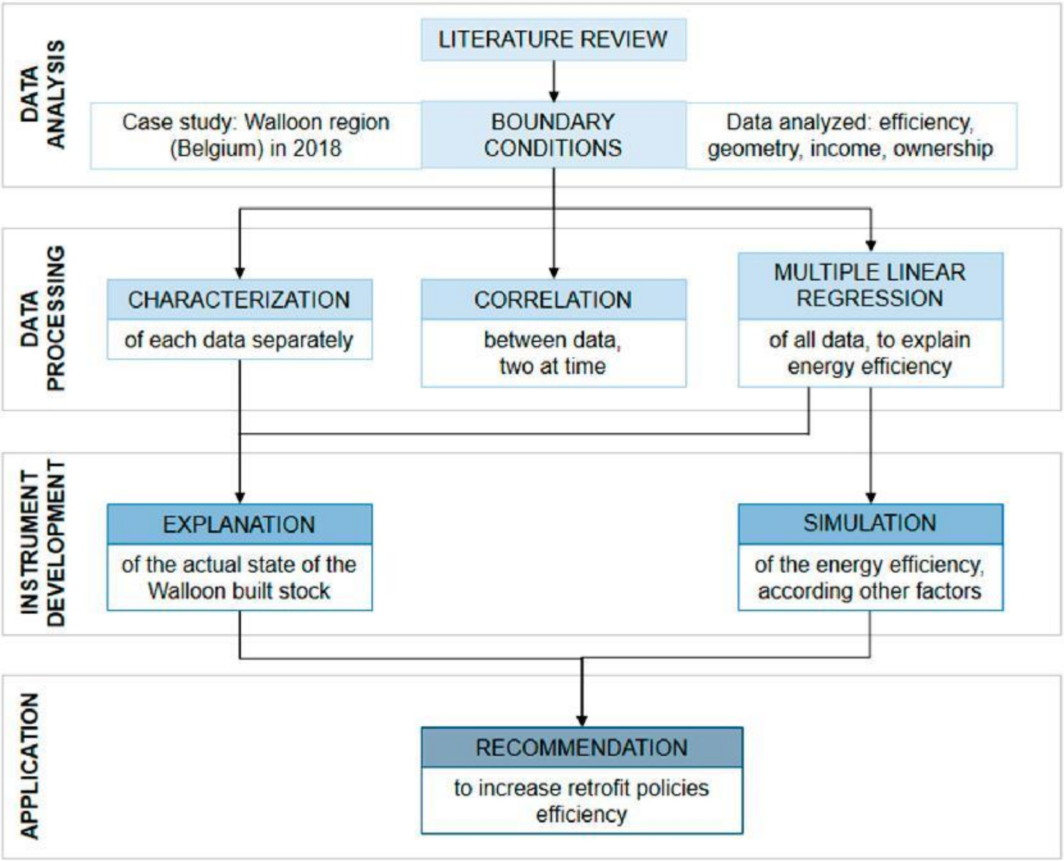

Figure 1. Study conceptual framework.

2.1. Boundary Conditions and Data Collection

2.1.1. Boundary Conditions

The boundary conditions are defined in the literature review analysis. As the study's objective is to analyze the links between technical and socioeconomic characteristics, choosing relevant variables and avoiding excessive variables is essential to simplify the results and to facilitate straightforward interpretation [41].

Two technical characteristics were studied. Our study relies on the data collected within the Energy Performance Certificate (EPC) because the energy efficiency of a dwelling partly conditions its consumption. In this study, we make the same choice as other similar studies in the USA [19], Switzerland [42], Sweden [24], or the Netherlands [15].

The geometry of the dwelling ((1) an apartment, (2) a house with 4 facades, (3) a semi-detached house, or (4) an attached house) is the second characteristic studied to improve EPC quality [24,43,44]; it directly impacts the energy needed to heat the dwelling and indirectly impacts the urban fabric and, therefore, the energy required for household activities [45].

Two socioeconomic characteristics were also studied. Household income not only has a significant impact on the quality and size of housing but also influences energy behavior [27] and investing in energy efficiency [24,25]. The last characteristic studied was ownership. Depending on its status, the occupant does not have the same motivations and possibilities to renovate his dwelling [32,40,46]. The Walloon Region was chosen as a case study because energy regulations vary slightly between Belgium's three regions (Brussels, Flanders, and Wallonia). Each entity is autonomous to set its own measures (for example, the expected insulation levels for each wall) within the framework of the EPBD [44].

The different datasets were studied on the Walloon municipalities' scale, with each municipality constituting a statistical individual. This analysis scale makes it possible to reduce the size of the databases compared to a by-building analysis. Databases are easier to access by the city when they are not the only ones. However, the scale should remain small enough to detect variations between individuals. Finally, the municipal scale avoids any confidentiality issues.

The study at the city scale adds the number of households in each city, allowing for identifying possible statistical differences between small villages and large cities.

2.1.2. Data Collection

The chosen study characteristics lead to a search for existing databases that meet the criteria above.

The use of existing databases (Table 1) speeds up the study to test the methodology with data already validated elsewhere and to obtain databases representing the entire studied population.

Table 1. Summary table of data.

Category Name	Data Name	Source	Data Year
Energy	EPC label and consumption	DG TLPE	2018
Geometry	Type of building in housing	STATBEL	2018
Income	Categories of income	IWEPS	2016
Ownership	Property title	Census	2011
Households	Number of households	STATBEL	2018

The EPC data is the EPBD application for the Walloon region and comes from the DG TLPE (Direction Général Territoire, Logement, Patrimoine et Environnement), part of the Walloon government. For each EPC certificate, we obtained the city, destination (single-family house or apartment), specific energy (kWh/m^2·y), and label (from A++ to G). The database contains information on 495,470 dwellings, which represents almost one third of the Walloon building stock. Since 2010, only buildings that need to be sold had to have an EPC. The other two-thirds of the building stock did not have an EPC label A. A previous study by CEHD [47] conducted in 2017 proved the representativeness of the half million EPCs. Despite the statistical overrepresentation of apartments and underrepresentation of single-family houses, the database represents the seven EPC categories—A to G—in a balanced way. Therefore, the current EPC database provides a useful snapshot on the building stock characteristics and measures the energy efficiency tendencies. The database obtained is sampled to obtain the percentages of the different labels and the average consumption of certificates in each municipality. The sum of these percentages equals 100% and represents the entire housing stock.

The type of housing building is public data published yearly by STATBEL, the Belgian Statistical Office. We have the percentage of terraced houses, semi-detached houses, detached houses, and apartments for each municipality. These percentages equals 100% and represent the entire stock of 1,615,774 dwellings listed by STATBEL.

Income level is a public classification of annually reported income into 6 categories by the IWEPS (Institut Wallon de l'Evaluation, de la Prospective et de la Statistique), the Walloon statistical office. For each municipality, we have the percentage of each category. The sum of these percentages equals 100% and represents all households.

The property title represents the proportion of owners and tenants in each municipality. The public data come from the Census, the population census database conducted by the Belgian government.

The households of the cities represent the sum of income declared by each municipality (statistical individuals). These are public data published annually by STATBEL.

As we can see, the data were not studied at the scale of the building but the municipality scale. This data compression allows for the aggregation of independent databases. Each municipality represented one of the 262 statistical individuals, which is the sample size.

These data were collected by government agencies and met the highest quality standards.

2.2. Data Processing

All the statistical tests were performed and programmed on the R software.

2.2.1. Characterization

Characterization, the first step (Figure 1) of data processing, provides knowledge of the studied statistical variables of the Walloon built stock and details the variability of their distribution.

The collected data were aggregated in a single table to simplify statistical processing. This also allowed for the detection of possible errors, such as changes in the individuals' names concerned. Because the Walloon region is bilingual (French-German), municipalities may have several names.

This sampling makes it possible to analyze the geographical distribution of each variable independently of the others. Comparing the obtained data with state-of-the-art results and comparisons of the results between different cities, provinces, and neighboring regions and countries is an interesting exercise.

This first part of the analysis was done by combining municipalities across the province to simplify exploiting the results in the first instance. It makes it possible to validate the study's hypothesis, which is based on a sufficiently large variability of the criteria studied between different geographical entities.

The first results were expounded upon in search of correlations.

2.2.2. Correlation

Studying the correlations between the different characteristics is the second stage of data processing. This step consists of determining the directing coefficient of a simple linear regression between two characteristics to analyze the relationships between characteristics.

To simplify the research of correlations, labels A, A+, and A++ were merged into a single category A. The mean energy consumption estimated by the EPC (epcMean) was calculated for each municipality.

The Spearman correlation coefficient could be calculated to explain the linear correlation between the different statistical variables.

A linear regression could further be performed after obtaining the correlation results.

2.2.3. Multiple Linear Regression

An MLR (multiple linear regression) objective was conducted to obtain a model of the relationship between a dependent variable and several explanatory variables, allowing for identification of each explanatory variable's impact on the dependent variable. The dependent variable is the average energy efficiency (epcMean) of the certified buildings in each city and better represents the entire housing stock than the proportion of EPC A or G. Thus, we can estimate that the model's unit is the $kWh/m^2{\cdot}y$.

The independent variables are the different housing types, income categories, ownership rate, and relative number of households in the city. For each category where the sum of the variables is the same for all individuals (e.g., equal to 100%), there was one redundant variable. To avoid redundancy, one variable was eliminated. The choice was made by simulating various combinations of explanatory variables and by keeping the combination where the variance influence factor (VIF), i.e., the collinearity, of the different explanatory variables was the lowest. The proportions of detached houses, income category 6, and renters were redundant information and were not considered explanatory variables.

The first three explanatory variables were the proportion of apartments, semi-detached houses, and attached houses for geometry. The following explanatory variables were the proportions of income categories 1–5 for income. The ownership rate in each city was another explanatory variable. The final explanatory variable was the relative number of households in the city. It was obtained by dividing the total number of households in the city by the number of households in the region's largest city (Liège households = 114,115 households). This modification gives a variable of the same size as the other explanatory variables (≤ 1). We obtained a total of ten explanatory variables.

A calculation of the Mahalanobis distance was performed ahead of the MLR to detect and analyze outliers with an excessive influence on the dataset to assure the analysis's robustness.

The results were also tested for hypothesis validity. The Breusch–Pagan test verified the homoscedasticity of the errors. The variance influence factor (VIF) allowed for the estimation of multicollinearity. The normal distribution of the residues was verified using the Shapiro–Wilk test.

2.3. Instrument Development

2.3.1. Cross Analysis

The results obtained during the various stages of this methodology provide a better understanding of the composition of the built stock, confirm or correct the results previously found in other studies, and better understand the correlation between different factors that have not yet been compared.

2.3.2. Simulation

The theoretical model obtained by MLR allows us to express an estimate of the value of the dependent variable (the energy efficiency of the built stock) as a function of the value of the different explanatory variables (of this built stock). The exploitation of the results allows the simulation of one or several renovation scenarios to demonstrate their impact on the Walloon Region. This is a theoretical estimate to be taken with the usual precautions.

2.4. Recommendation

A more open recommendation stage will attempt to use the results obtained and the analysis that will have been made to promote several recommendations to better target the buildings to be renovated, the populations to be assisted, and the type of assistance to be provided.

3. Results

This study's focus is the Walloon Region in Belgium and includes five provinces: Hainaut, Liège, Luxembourg, Namur, and Walloon Brabant (see Figure 2). The Walloon Region has its energy performance regulations for building and calculation methodologies (EPC) in line with the European EPBD.

The study parameters chosen to characterize the building stock are based on three primary criteria:

- The estimated impact of the parameters on energy use
- The estimated impact of the parameters on the choice of energy-efficient renovation
- The availability of representative data on the study parameters at the Walloon municipality level

The collected data are grouped in a database listing each parameter's rate in the different Walloon municipalities to provide a view by province and for the whole region. Table 2 describes the variables used afterwards, synthesizing their minimum, mean, and maximum values.

Figure 2. Walloon region map with provincial boundary (d-maps, 2020).

Table 2. Synthesis table of the separate results for each part.

	Min	Mean	Max
epcA	0%	0.88%	6.29%
epcB	1.4%	8.04%	26%
epcC	4.88%	12.78%	23.81%
epcD	7.74%	15.09%	23.83%
epcE	10.84%	15.93%	23.68%
epcF	8.83%	14.81%	20.22%
epcG	10.77%	32.48%	57.74%
epcMean	297.5	443.5	607.6
apartments	0.36%	9.56%	61.45%
attached	1.14%	18.68%	56.93%
semidetached	9.27%	25.59%	40.70%
detached	3.4%	46.17%	80.81%
income1	10.32%	13.70%	20.51%
income2	14.89%	27.44%	41.17%
income3	16.42%	21.25%	25.96%
income4	10.27%	12.84%	15.95%
income5	4.96%	7.97%	11.11%
income6	5.6%	16.8%	34.91%
owner	48.06%	72.15%	88.22%
households	766	7743	114,115
relativehouseholds	0.67%	6.78%	100%

3.1. Characterization of the Walloon Built Stock

For this first part, the statistical individuals are grouped by province to facilitate the results' graphical analysis. Figure 3 shows that Walloon Brabant has a particularly efficient housing stock, with a high number of EPC A, B, and C (37.52%). The provinces of Liège (45.89%) and Hainaut (49.93%) visibly suffer from an overrepresentation of EPC F and G certificates.

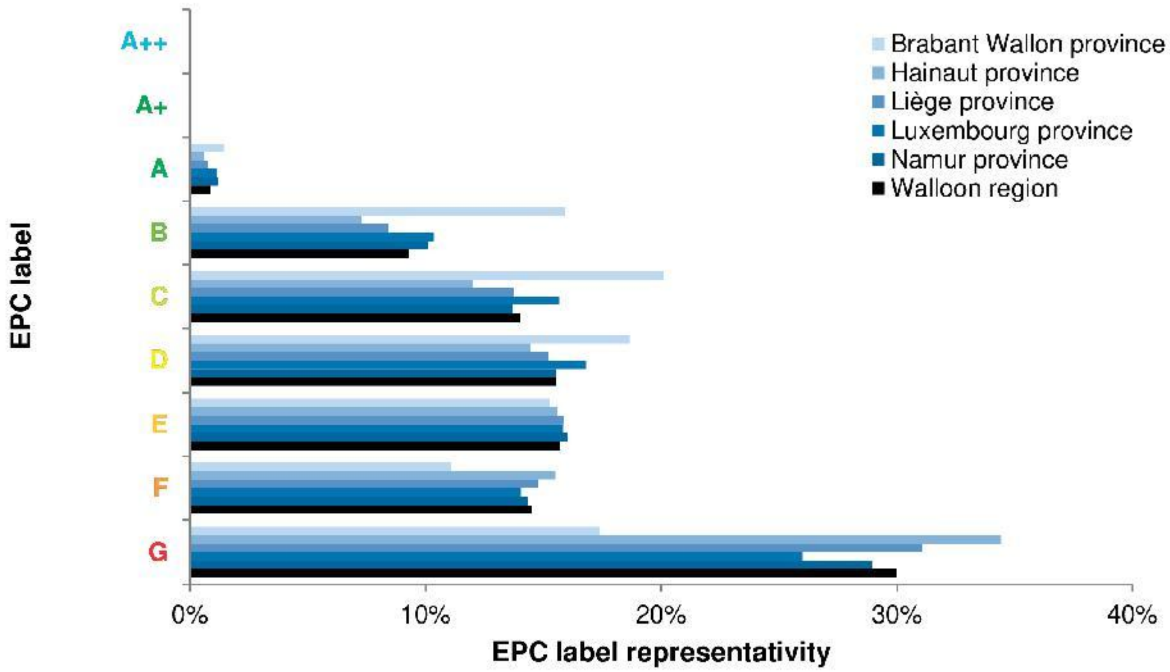

Figure 3. Distribution of energy performance certificates by province in the Walloon region.

The distribution of building types can be categorized into two groups (Figure 4). The provinces of Liège (30.09%) and Hainaut (36.90%) are primarily comprised of attached houses. The provinces of Luxembourg (50.65%), Namur (43.29%), and Walloon Brabant (40.97%) have more detached dwellings. A higher proportion of apartments characterizes the provinces of Liège (19.29%) and Walloon Brabant (23.23%).

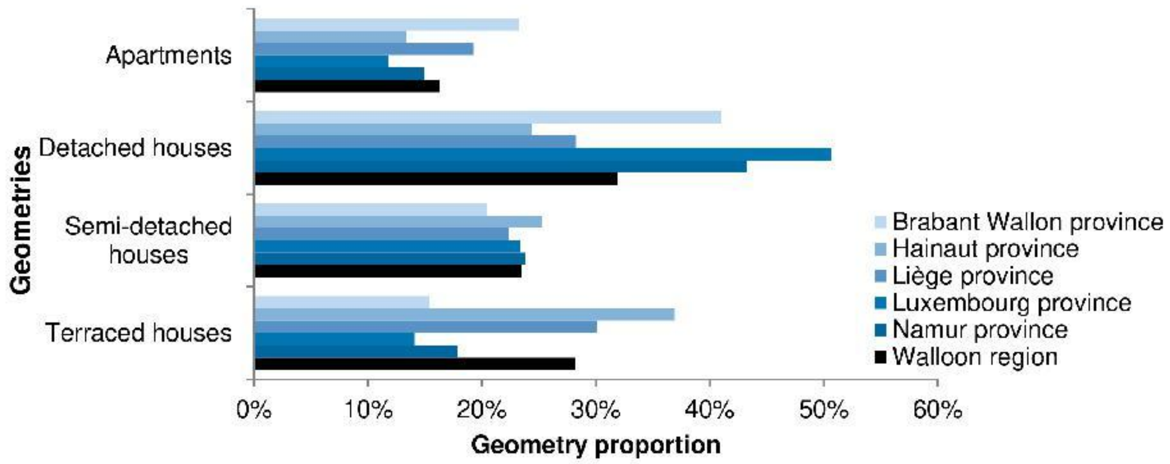

Figure 4. Geographical distribution of building type in the Walloon Region.

Figure 5 shows the characteristic homogeneity of the ownership rate distribution (62.25–68.63% owner-occupied houses). This homogeneity reflects the importance of regional and national policies in favor of homeownership. Liège and Hainaut have slightly more rented housing, whereas Namur, Luxembourg, and Walloon Brabant have more owner-occupied housing.

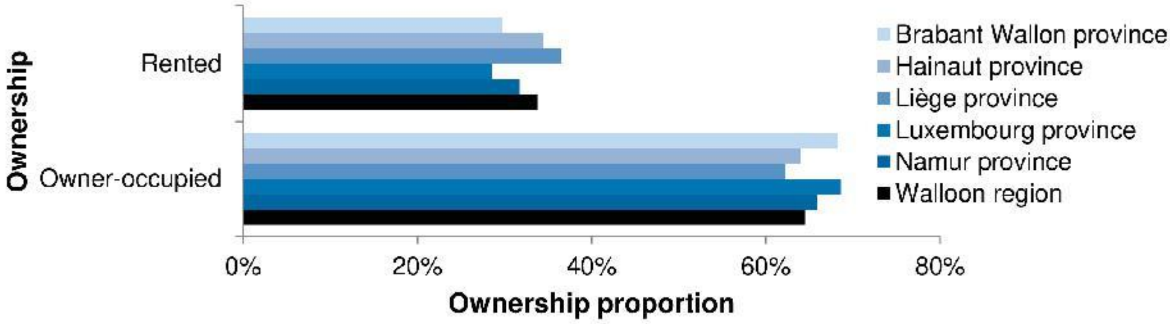

Figure 5. Geographical distribution of property title.

The income distribution in Figure 6 shows more marked variations, particularly in categories 2 (low income) and 6 (high income). Thus, Hainaut (33.27%) and Liège (30.20%) have a large low-income population. Conversely, Brabant-Wallon (21.75%), Luxembourg (17.77%), and Namur (16.25%) have a large high-income population. Category 1 (income of 1000–10,000 EUR) represents special occupants, such as students.

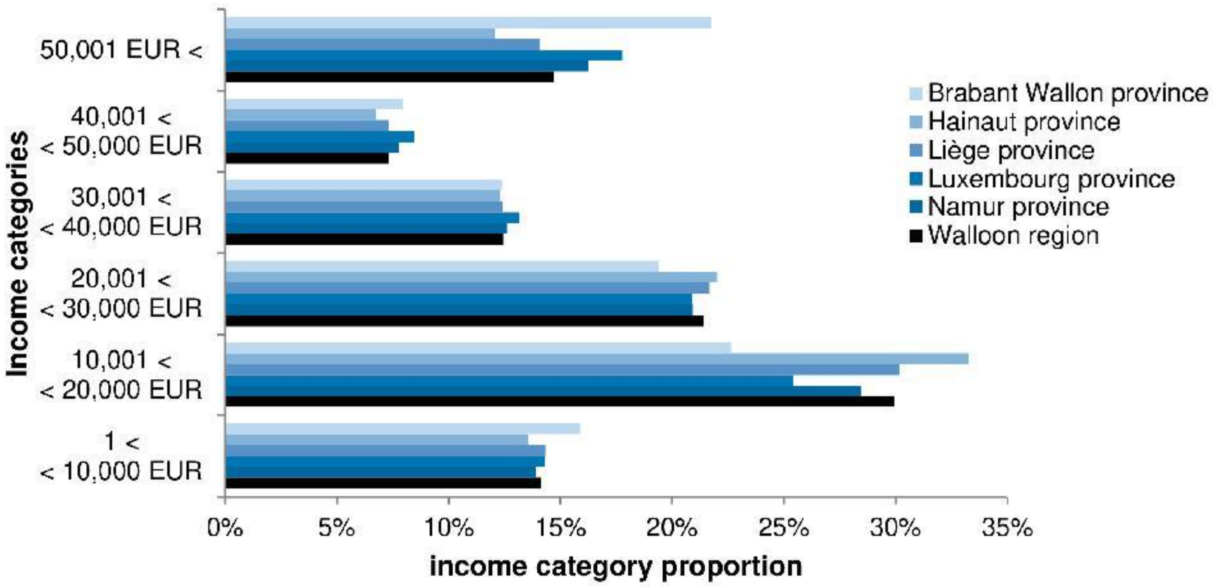

Figure 6. Geographical distribution of income categories.

Finally, the history of the Walloon region is well-reflected in the different characteristics studied. Liège and Hainaut have significantly suffered from deindustrialization. They have dense built-up areas (attached houses and apartments); low-quality (EPC F and G), less well-off populations; and more tenants. Luxembourg and Walloon Brabant were urbanized more recently. Walloon Brabant benefits from its proximity to Brussels, and the province of Luxembourg benefits from its proximity to the Grand Duchy of Luxembourg. These poles of activity lead to the arrival of new occupants with higher than average incomes. New dwellings that meet the latest energy standards are then built to accommodate them, allowing for greater penetration of four-sided houses and built stock efficiency.

3.2. Correlation between Walloon Built Stock Characteristics

Figure 7 shows the Spearman correlation results in matrix form. Larger circles denote higher correlations, and lighter yellow circles indicate more positive correlations.

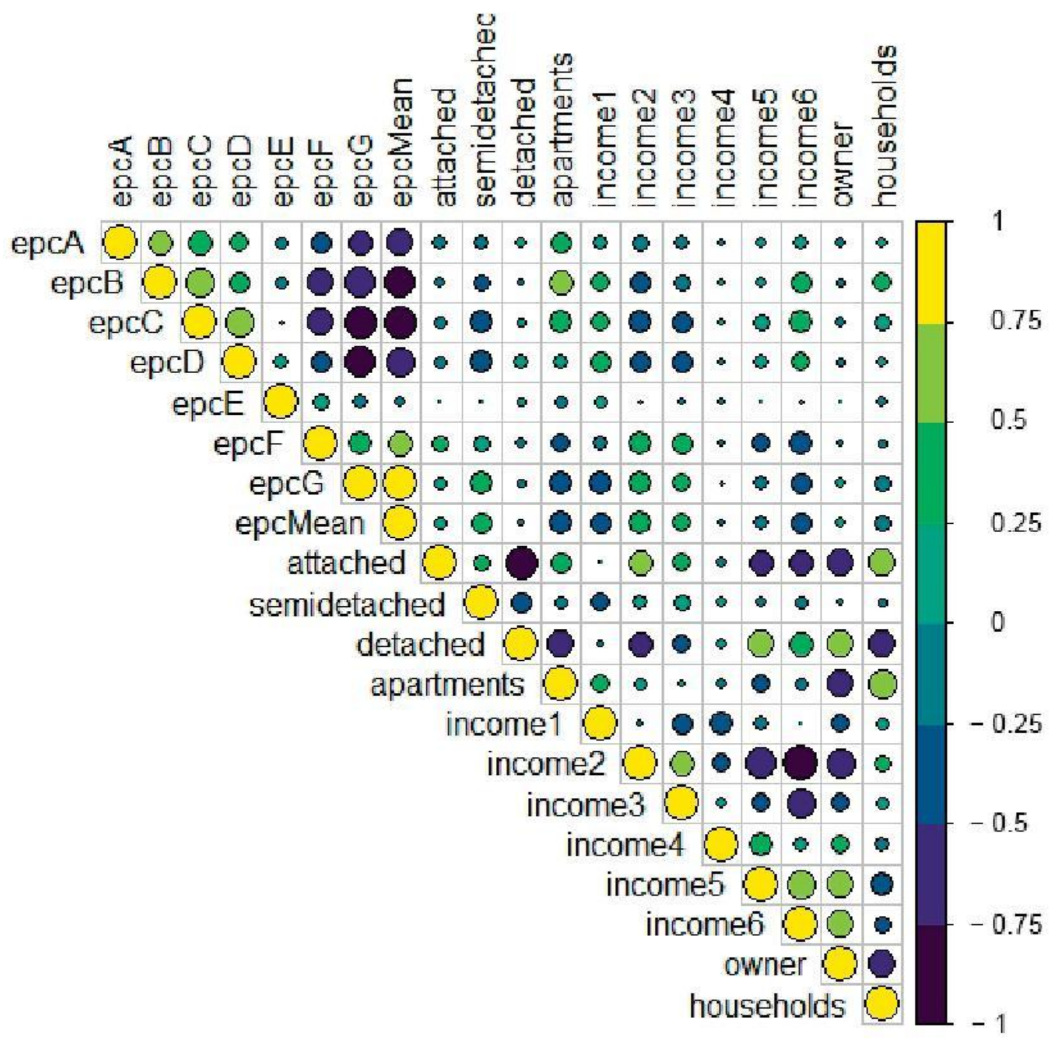

Figure 7. Spearman correlation between technical and socioeconomic characteristics of the Walloon built stock.

The proportions of EPC A, B, C, and D are positively correlated with each other and negatively correlated with EPC F and G's ratios and with average energy efficiency values (epcMean). These correlations confirm that the geographical distribution of EPC certificates is not random. The low correlation between the proportion of EPC E and other parameters indicates its independence. These certificates can be found in all the configurations.

The proportion of apartments is positively correlated to EPC A, B, and C and negatively correlated to EPC F and G. In contrast, the proportion of semi-detached houses is positively correlated to EPC F and G and negatively correlated to EPC B, C, and D. The proportion of attached houses was also positively correlated with the proportion of label E. No significant correlation was found between the proportion of detached houses and the EPC labels. The greater compactness of the apartments partly explains their better energy performance. A higher proportion of apartments in newly built dwellings meet existing energy standards, and attached and semidetached houses (although more compact) are significantly less efficient than detached houses. Attached and semi-detached houses often encounter difficulties in insulating specific walls, such as street fronts or shared walls. Some attached and semi-detached houses are older dwellings of lower quality—called worker houses in Belgium.

Low-income categories 2 and 3 are positively correlated with EPBD certificates F and G. High-income categories 5 and 6 are positively correlated with EPBD certificates A, B, C, and D. Income category 1 appears to be a special category (students), insofar as it presents correlations opposite to that of income 2/3. One hypothesis is that the highest income earners live in recently built or renovated housing. Another hypothesis is that higher-income earners live in larger areas, increasing energy efficiency per square meter. A third hypothesis is that low-income earners are more likely to perform energy retrofits themselves and would not provide proof of insulation during the certification process.

The rate of ownership is positively correlated with high income (categories 5 and 6) and detached houses and negatively correlated with the rate of apartments, attached houses, and low income (category 2). Numerous studies have found a negative correlation between the rate of ownership and the city population and a weak correlation between the rate of ownership and the rate of different energy labels. A higher ownership rate can explain the negative correlation for geometries with lower compactness (detached houses) and more energy efficiency work performed by the owners (without a contractor).

In summary, the correlations reveal three typologies that are widely represented in the Walloon region:

- Old worker houses in the industrial valley are more present in big cities. These attached or semi-attached houses are of lower quality and energy efficiency. Lower-income households occupy these houses; more than the average number of such houses are rented.
- Newer and more efficient apartments are primarily built in large cities and rented more than average.
- Four-sided houses in small towns are mostly owner-occupied by higher income.

3.3. Multiple Linear Regression between Walloon Built Stock Characteristics

An analysis of the MLR results highlights the simultaneous impact of the selected explanatory variables on each city's built stock's average energy efficiency. The model studied for the MLR can be summarized as follows in Equation (1).

$$\begin{array}{c}\text{epcMean} \sim \text{apartments} + \text{attached} + \text{semidetached} + \text{income1} + \text{income2} \\ + \text{income3} + \text{income4} + \text{income5} + \text{owner} + \text{households}\end{array} \quad (1)$$

The dependent and independent variables used for this MLR are described in more detail in Table 2, with their minimum value, mean value, and maximum value.

The results of the MLR are presented in Table 3. The first results are the model quality and have a multiple R-squared = 0.6194. The independent variables explain almost 60% of the dependent variable's variance, which is higher than that of other similar studies [15,19,26,27]. This shows the interest of the chosen parameters for explaining the average energy efficiency of the built stock. Each estimator can be interpreted as the share of energy efficiency (kWh/m^2·y) of the built stock induced by a 100% increase in this variable.

Table 3. Synthesis table of the separate results for each part.

	Estimate	Standard Error	*p*-Value
intercept	90.31	116.78	0.440021
apartments	−274.71	53.64	6.07×10^{-7}
attached	−26.59	23.65	0.261872
semidetached	141.27	39.12	0.000368
income1	−492.34	244.31	0.044952
income2	721.83	93.64	3.00×10^{-13}
income3	19.82	171.57	0.908130
income4	232.70	306.46	0.448383
income5	117.75	372.37	0.752103
owner	235.08	61.17	0.000154
relativehouseholds	59.81	27.03	0.027791
Residual standard error: 34.07 on 250 degrees of freedom			
Multiple R^2 = 0.6194		Adjusted R^2 = 0.6041	

Interestingly, the most precise estimates concern the proportion of apartments, semi-detached houses, income category 2 (income of 10,000–20,000 EUR), and owners. The proportion of income category 1 and the number of households in the city also have a p-value of less than 0.05, indicating that further analysis of the coefficients relating to these explanatory variables can be performed.

The variable relating to the proportion of apartments has a largely negative estimator (-274.71 kWh/m^2·y). The proportion of semi-detached houses has a largely positive estimator (141.27 kWh/m^2·y), confirming that more semi-detached houses decrease energy-efficiency. Conversely, more apartments seem to produce more energy-efficient housing stock.

The variable with the most important estimator is the proportion of income category 2 (from 10,000–20,000 EUR), strongly correlated (estimate = 721.83 kWh/m^2·y) with poor energy efficiency. Each percent increase in this category corresponds to an increase of 7.22 kWh/m^2·y in the built stock's average energy efficiency. Additionally, this correlation is not linear, as household income increases. From income categories 3–5, the estimator remains very insignificant (p-value > 0.4). The variable corresponding to the proportion of income category 1 confirms that it is a special category (estimate = -492.34 kWh/m^2·y). The negative estimator can be explained, among other things, by students living in apartments or by assisting spouses. The cases that correspond to this income category must be identified in future studies.

The ownership rate variable provides more information than the rest of the analysis. There was a weak correlation between the share of ownership and the share of different energy labels; the MLR indicates that the ownership rate and average energy efficiency vary in a similar way (estimate = 235.08 kWh/m^2·y). The lack of direct correlation in the previous analyses can be explained by considering that an increase in the ownership rate in a city is correlated with a decrease in the proportion of income category 2.

Finally, the number of households also has a positive impact (estimate = 59.81 kWh/m^2·y) on estimating the energy efficiency of buildings. Large cities have denser buildings (apartments and semi-detached houses). However, they also have older buildings and households with lower incomes. The city's density favors building compactness and complicates insulation from the outside (external boundary wall, street alignment, etc.).

Figure 8 summarizes the mean and confidence interval of the regression model coefficient estimates obtained on R more visually.

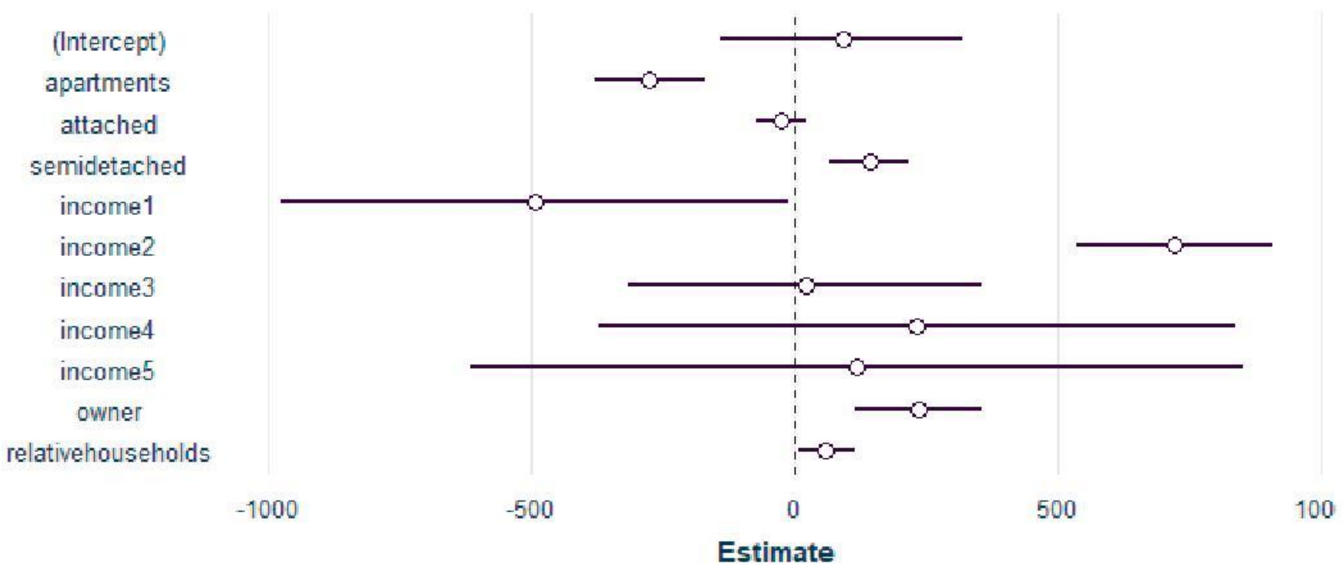

Figure 8. Mean and 95% confidence interval of regression model coefficient estimates.

The MLR is preceded by a test step, allowing the exclusion of outliers. The calculation of the Mahalanobis distance highlights Ottignies-Louvain-la-Neuve. We calculated a Mahalanobis distance of 94.67 with a chi-square of approximately 18.31 with 95% probability for this city. The city has undergone profound changes following the relocation of the French-speaking part of the University of Louvain, leading to thousands of new apartments between 1973 and 1980. These outliers were removed for MLR. The MLR study was then performed on 262 Walloon cities.

Tests applied to the model verify that it meets the statistical assumptions. The null hypothesis of normality of the residuals was accepted according to the Shapiro–Wilk normality test, with a p-value of 0.056. The null hypothesis of homoscedasticity was accepted according to the studentized Breusch Pagan test, with a p-value of 0.222. The magnitude of multicollinearity was low, considering that the variance influence factor was less than 5.5 for all explanatory variables.

3.4. Results Extrapolation

3.4.1. Cross-Analysis

The concomitant analysis of the results of the three methods makes it possible to refine their learning. The main results of these analyses are summarized in Table 4. In this way, correlations that are confirmed throughout the entire study can be distinguished. Table 4 also shows some different results between the methods, which deserve a separate explanation.

Table 4. Synthesis table of the separate results for each part.

	Energy	Geometry	Income	Ownership
Characterization	Extensive inefficient habitat. Very few efficient dwellings. Geographical heterogeneity	All categories are well-represented. Geographical heterogeneity	High rate of low income (between 10,000–20,000 EUR) Geographical heterogeneity	High rate of owner Geographical homogeneity
Correlation	The EPC mean is highly dependent on the percentage of EPC G (positive correlation) and EPC A/B/C/D (negative correlation) label.	Apartments are quite efficient, primarily occupied by tenants in large cities with little correlation to income. Semi-detached houses seem to be the more inefficient. There is little correlation between energy and attached or detached houses, which tend to be occupied by wealthier owners in smaller cities. Terraced houses appear to be occupied by more precarious households in large cities.	Category 1 appears to be a specific category, such as students, who live in reasonably efficient apartments. Categories 2 and 3 seem to rent more low-quality semi-detached houses. Categories 5 and 6 are more likely to be homeowners living in more efficient four-sided houses in smaller towns.	There is little correlation between ownership and energy efficiency. Rented properties seem to be more likely to be flats or semi-detached houses, occupied by low-income occupants in large cities.
Linear regression	Linear regression highlights geometry's importance in determining energy consumption, with more efficient apartments and very inefficient semi-detached houses. Household income is only important for income group 1, who live in more efficient housing, and income group 2, who live in very inefficient housing. Paradoxically, homeownership has a negative effect on energy efficiency.			

Concerning the analysis of the distribution of energy labels, it is possible to distinguish an important stratification of labels according to the city. The most efficient dwellings are not spread evenly over the entire region. According to the MLR, cities with more apartments have more energy-efficient stock. Conversely, the number of semi-middle-sized houses and households and the number of homeowners are correlated with a decreased average efficiency of built stock. Therefore, one way to increase the built stock's efficiency would be to make targeted proposals aimed at these categories of housing or households.

By studying the distribution of geometries, we see great variation from one region and city to another. The correlation between the number of households in the city and the proportion of different geometries responds to densification logic. The different correlations reflect the impact of the history of urbanization in the Walloon region. Some more compact geometries, such as apartments, are also more efficient. However, this is not true when comparing attached, semi-detached, and detached houses. The latter are less compact but more energy efficient than the first two. The MLR confirms that apartments are more efficient than average buildings and that targeting semi-detached houses is essential. This may lead to questions about why semi-detached houses are so different from attached and detached houses.

Income category 2 includes all households with a net taxable income from 10,000–20,000 EUR. All analyses show the particular importance that must be given to this part of the population to improve the built stock's efficiency. Characterization shows that the most represented segment of the population lives in less efficient housing than average and, according to the MLR, is the primary indicator of the low energy efficiency of the built stock. This also implies a higher exposure to fuel poverty risk and fewer means of improving the situation.

The analysis of the results on the ownership rate is more ambivalent. The characterization highlights the homogeneity of the ownership rate, and the correlation confirms little direct relationship between the efficiency of the built stock and ownership rate. However, the MLR shows that increased ownership rates correspond to a significant decrease in the built stock's energy efficiency. Other characteristics correlated with ownership rate tend to weaken the direct correlation. An increase in the number of high-income households is accompanied by a parallel improvement in energy efficiency and increased ownership rate. This correlation is significant as it is the opposite of the expected results. The tenants were assumed to live in less efficient dwellings because of split incentives, but this is not the case.

3.4.2. Prospective Simulation

Obtaining a model from MLR allows for analysis of the estimators. It can be directly applied to other statistical individuals (e.g., other sets of buildings) or on a regional scale to calculate the different explanatory variables' total impact instead of the relative impact. Therefore, the average number of households (rather than the total) in the Walloon municipalities is considered.

For example, different model variables can be applied to the values corresponding to the Walloon Region's different provinces. We obtained a prediction range that can be compared with the observations in Table 5.

Table 5. Predicted value of the model with a 95% confidence interval and observed value.

	Lower Value (kWh/m^2·y)	Mean Value (kWh/m^2·y)	Upper Value (kWh/m^2·y)	Observed Value (kWh/m^2·y)
Walloon Brabant province	330.16	343.14	356.12	349.53
Hainaut province	441.73	450.03	458.33	454.64
Liège province	390.64	400.32	410.01	434.69
Luxembourg province	400.94	408.09	415.25	405.68
Namur province	409.63	416.59	423.56	420.35
Walloon region	407.32	415.02	422.72	427.50

This comparison logically allows us to obtain very close results because they come from the same databases. Nevertheless, Table 5 shows that the model could explain the significant variations in the built stock's average energy efficiency between provinces.

4. Discussion

4.1. Findings and Recommendations

This research aimed to characterize Walloon's energy efficiency and to quantify the existing correlations with the socioeconomic factors that influence the renovation decision-making of house owners. The overall aim is to help policymakers propose long-term-renovation strategies adapted to both the buildings and their inhabitants.

The building stock characterization revealed the heterogeneity of building energy efficiency among the Walloon region's municipalities, with more than 45% of energy-inefficient houses (labels F and G) in Liège and Hainaut and more than 35% of energy-efficient homes (label A, B, and C) in Walloon Brabant. The correlation analysis shows that apartments, overall, are more energy-efficient. Semi-detached houses are correlated with lower energy efficiency compared to detached and terraced houses.

The MLR provides more novel results. The literature on split incentives suggested that owned residences were on average 6% more efficient than rented homes [33] due to the split incentive [31]. On the contrary, the MLR highlights the correlation between increased ownership rate and decreased energy efficiency. Each percent increase in the ownership category corresponds to an increase of 2.35 $kWh/m^2{\cdot}y$ in the built stock's average energy efficiency. Even if the owner–tenant dilemma exists [31], it is not currently a determining factor in the energy efficiency of the Walloon built stock. The landlord/tenant dilemma occurs when tenants are not allowed to own the building services [32].

Furthermore, the study confirms the positive correlation between some household income categories and housing energy efficiency. Very low-income groups (10,000–20,000 EUR of net annual taxable income) occupy much less efficient housing than the rest of the population. Each percent increase in this category corresponds to a rise of 7.22 $kWh/m^2{\cdot}y$ in the built stock's average energy efficiency. Nevertheless, this correlation between income and energy efficiency is not linear at all, contrary to the results obtained in other studies [25]. The differences observed between the middle and high-income groups are not very significant. Thus, there is a real threshold effect.

Therefore, a targeted renovation policy needs to be established with a particular focus on low-income households (from 10,000–20,000 EUR of net taxable income). These households must be the subject of complementary studies to characterize them deeper and to identify the effective actions to be implemented. Heavy renovation scenarios should be studied specifically for less energy-efficient building archetypes. Demolition/reconstruction scenarios could be proposed for these lower-quality archetypes. Energy regulations for buildings should be established on a broad geographical scale to subject everyone to the same rules and to close the disparity gap. Therefore, it is essential to adapt local policies in favor of renovation according to building owners and tenants' built and socioeconomic contexts.

4.2. Strength and Limitations

This study's principal contribution is cross-referencing buildings' technical data (energy performance and archetypes) with socioeconomic data of the inhabitants (income and property title). An increasing number of studies found in literature analyzed the social aspects of the inhabitants and the technical aspects of buildings separately—the two determining factors in improving the built stock. However, we could not find a building stock model that integrates the inhabitants' social aspects and to couple them such as our work on the national level [22,36,37]. Simultaneously, statistical models and studies that study these correlations at the international level rely on aggregated data sets that are usually based on questionnaires, which require much time to collect [15,27]. More and more databases can be used to improve our understanding of the characteristics of the built stock. However, these databases are complicated to link because they do not always relate to the same statistical individual, whether it is a building, a person, a city, or a province. Therefore, this study succeeded in performing a unique statistical analysis that crosses different sets of data. The use of municipal data allowed us to correlate data on the individual level, resulting in an acceptable level of data quality.

Moreover, the MLR formula succeeded in explaining with 62% certainty the variation of the dependent variable (energy) concerning the independent variables (geometry, income, and ownership). Reducing the uncertainty to less than 50% is a significant contribution of this study because it allows us to explain the correlation between energy efficiency and the socioeconomic factors with high confidence. For example, similar studies in the Netherlands [15], USA [26], and China [27] investigated the correlation between the technical aspects of the building and the socioeconomic aspects of the inhabitant, but with lower certainty. They obtain an R^2 below 0.4 for their regression model.

In our case, the *income2* category (10,000–20,000 EUR of net annual taxable income) negatively correlates with energy efficiency, while the *apartment* category has a positive correlation with energy efficiency. Thus, these evidence-based results can help decision-makers set their priorities when designing short-term renovation strategies.

However, the study considers neither the building's age, which is an essential criterion for estimating buildings' energy efficiency in Belgium, nor the house size. Unfortunately, these data were not available in a reference frame similar to that of the study.

Finally, the study provides a better understanding of Wallonia's building stock, and the results help propose a data-driven adaptation policy in favor of energy renovation. Moreover, this study's statistical methods can be transferred or applied to other data sets or case studies.

4.3. Implication on Practice and Future Research

This study can enable policymakers and local authorities to understand better the interactions between the building's energy efficiency characteristics and socioeconomic factors. Those factors must be considered when developing and implementing renovation strategies for the built stock. Local governments will have better knowledge of buildings' stock in their city and may encourage targeted initiatives for the least efficient buildings.

However, this study needs to be completed and improved. The integration of new study parameters, such as the dwelling's age and size, will result in a better understanding of the interactions' between different factors. The age of the buildings provides plentiful information on the type of construction and the standards in force. Investigating the building vintage would deepen and clarify the study of correlations. Additionally, a clustering study should follow this work to categorize existing buildings better.

5. Conclusions

The presented paper characterizes the Walloon building stock and analyses the existing correlations between the building stock energy efficiency and its occupant socioeconomic factors. The overall aim is to guide policymakers, professionals, and scientists towards an effective renovation strategy that can better cater to occupants' socioeconomic conditions. In this context, the study succeeded in quantifying the correlation between household income and building energy efficiency states. The study combines four different databases on different scales and spatial levels, analyzing them using multiple linear regression. The building stock characterization allowed us to reveal the heterogeneity of building energy efficiency among the Walloon region's municipalities, with more than 45% of energy-inefficient houses (labels F and G) in Liège and Hainaut and more than 35% of energy-efficient homes (label A, B, and C) in Walloon Brabant. Conversely, the MLR highlights the positive correlation between increased ownership rate and decreased energy efficiency. Belgium underwent a massive suburbanization in the last 70 years, and homeownership has always been stimulated by tax incentives [48]. It is time to re-engineer the tax incentive system to encourage renovation strategies and accelerate its rate [9].

Furthermore, the study confirms the positive correlation between some household income categories and housing energy efficiency. Very low-income groups (10,000–20,000 EUR of net annual taxable income) occupy much less efficient housing than the rest of the population. Each percent increase in this category corresponds to a rise of 7.22 kWh/m^2·y in the built stock's average energy efficiency. This correlation between income and energy efficiency is not linear at all. Indeed, the differences observed between middle and high-income groups are not very significant. There is a real threshold effect. Therefore, a targeted renovation policy needs to be established, with a particular focus on low-income households (from 10,000–20,000 EUR of net taxable income). These households must be the subject of complementary studies to characterize them deeper and to identify the effective renovation measures to be implemented.

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Abbreviations

DG TLPE	Direction Général Territoire, Logement, Patrimoine et Environnement
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate (Performance Energétique des Bâtiments)
GIS	Geographic Information System
IWEPS	Institut Wallon de l'Evaluation, de la Prospective et de la Statistique
MLR	Multiple Linear Regression

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Part I - Chapter 3.2

Journal Paper: Clustering of Archetypal Building-Inhabitant Pairs to Improve Energy Efficiency: The Case of the Walloon Region in Belgium

RQ2. *Which representative dwelling–occupant clusters can be identified in the Walloon residential building stock based on integrated technical and socio-economic data?*
RQ3. *What are the patterns of geographical distribution of these characteristics across Wallonia?*
RQ6. *What differentiated renovation strategies and policy instruments can be derived from dwelling–occupant cluster analysis to effectively increase deep renovation rates?*

This second journal paper represents the culmination of the development of a mixed-methods model of Wallonia's building stock, based on the clustering of technical building data and socioeconomic data on residents, based on the findings of Chapter 01 and the state of the art.

To achieve this, the statistical analysis is enhanced by adding weighting steps, applying ILR transformation, and utilizing ordinal logistic regression and beta regression algorithms. This statistical analysis allows us to estimate the probability of a specific income category and property type for each energy certificate. The resulting model is simplified using k-means clustering to identify two sets of six and ten clusters. A PCA completes the analysis to better examine the distribution of these clusters across the provinces and municipalities of Wallonia.

Two clusters stand out from the analysis: a low-efficiency cluster consisting of low-income households and a low-efficiency cluster consisting of high-income households. These clusters require different approaches to promote energy-efficient renovation. The study also highlights the significant differences in the geographical distribution of these clusters.

At the conclusion of Part I, it seems necessary to compare the theoretical results of the Regional Statistical Analysis with field research on the actual correlations between technical and socioeconomic characteristics. This comparison could be supplemented by a study of the strategies to be implemented to specifically target the clusters identified as priorities.

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Clustering of archetypal building-inhabitant pairs to improve energy efficiency: The case of the Walloon region in Belgium

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ABSTRACT

Considering the pressing need to renovate existing buildings across Europe, there exists a shared consensus on the importance of developing targeted strategies. Despite research, regulation and action in all the countries of Western Europe, the rate of energy renovation is stagnating. Turning this consensus into effective action requires models that accurately represent the diverse building stock and its inhabitants. This article focuses on Wallonia, aiming to identify typical combinations of buildings and inhabitants representative of the region's situation. The methodology employs ordinal logistic regression and beta regression algorithms to analyze correlations, leveraging extensive databases encompassing technical and socio-economic data. Subsequently, K-means clustering is utilized to distill the building stock into several characteristic typologies, offering insights into the diversity of the region. Notably, our findings highlight certain underestimated building types, constituting a significant portion of the Walloon building stock. Firstly, a typology of low energy performance houses, mainly attached and semi-detached, inhabited by low-income households makes up more than 17% of Walloon housing. More unexpectedly, a type of low energy performance house, mostly 4-fronted, inhabited by high-income households, still makes up more than 11% of the built stock. These results underscore the efficacy of our methodology in harmonizing disparate datasets and provide novel insights into the building stock and its occupants. Furthermore, the identified typologies empower researchers and policymakers to address the renovation challenge by directing targeted actions at appropriate scales, whether regional or local. Overall, this article contributes to a deeper understanding of the complexities surrounding building renovation and offers practical implications for policy formulation and implementation.

1. Introduction

1.1. Background

The war in Ukraine and the subsequent rise in energy prices (Fig. 1) have brought a fresh look at the issue of energy savings, particularly building renovation. According to Ari et al. [5], "By the end of the first quarter of 2022, crude oil prices had doubled, coal prices tripled, and natural gas prices increased more than five-fold relative to early 2021". This inflation has also affected the cost of materials and loan rates [17]. This is happening in a context that has been largely disrupted by COVID-19 and the increase in teleworking, which have already had a profound effect on housing market prices [31,80]. In the space of a few months, Europe has found itself faced with the dual urgency of having to continue to combat the climate crisis while at the same time redirecting a large part of its energy supply [32,61].

In the short term, the energy crisis has become priority number one. In the medium term, however, it has put the spotlight back on

Abbreviations: CEHD, Centre d'Etudes en Habitat Durable (Centre for Sustainable Housing Studies); CREG, Commission de Régulation de l'Electricité et du Gaz (Belgian Electricity and Gas Regulatory Commission); CWaPE, Commission Wallonne Pour l'Energie (Walloon Energy Commission); DG TLPE, Direction Général Territoire, Logement, Patrimoine et Environnement (Walloon Administration for Land, Housing, Heritage and the Environment); EPBD, Energy Performance of Buildings Directive; EPC, Energy Performance Certification; GDPR, General Data Protection Regulation; GHGE, Green House Gas Emissions; ILR, Isometric Log Ratio; IWEPS, Institut Wallon de l'Evaluation, de la Prospective et de la Statistique (Walloon Institute of Evaluation, Foresight and Statistics); LCA, Life Cycle Assessment; LCC, Life Cycle Cost; PEB, Performance Energétique des Bâtiments (Walloon EPC); PCA, Principal Component Analysis; SPF, Service Publique Fédéral (Belgian Federal Public Service); STATBEL, Belgian Statistical Office.

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commitments already made by the European countries and regions. The 55 % reduction in GHGEs (Green House Gas Emissions) by 2030 goes hand in hand with a reduction in energy demand [18,32]. Among the various options considered, the efficient energy renovation of the built stock would make it possible to reduce both the amount of energy consumed and dependence on Russian gas [80]. In this respect, the particularly old Belgian buildings are both a difficulty and a major challenge [18,70].

Energy renovation was sometimes considered primarily through the prism of the environment [26,65] or even solely in terms of the climate. However, given the urgency of the situation, governments have remembered that the issues of political and diplomatic independence and maintaining social peace must also be considered [14,31,82,83].

The rise in energy prices has had a direct impact on the moderation of energy consumption and the increase in energy efficiency work [75]. But this increase has also had a direct impact on public finances through the subsidies introduced to protect a growing proportion of the population. In Belgium, the CREG (Belgian Electricity and Gas Regulatory Commission) estimates the cost of the social tariff at €1.7 billion in 2021, 2022 and 2023, including €1 billion in 2022 alone [19]. Similar policies have been implemented throughout Europe. This makes it more important to transform this lost expenditure into a longer-term investment in building stock, regardless of the geopolitical situation in Eastern Europe. Regulations would benefit from being more geared towards renovation [102]. While renovation remains a costly policy, both on a household and national scale, it is even more important to compare it with the expected savings [102].

One of the main challenges is to gain a better understanding of the building stock and its behavior. For the moment, we can see a correlation between interest in renovation work and energy prices (Fig. 2) while observing a stagnation in applications for renovation permits [29]. This is proof of the reluctance of private individuals to commit themselves to cumbersome administrative, technical, and financial procedures. For similar reasons, the Walloon Region has decided to return to a simplified system of grants for energy-saving work [90]. This is a long-standing debate between better control of the work carried out to improve quality, and simplification of the procedures for renovation work to improve quantity. For the moment, renovation work that generates energy savings of over 60 % only concerns 0.2 % of projects [31].

A previous article has already assessed the statistical correlation between the technical characteristics of the home and the socio-economic characteristics of its occupants[84]. This article complemented other studies which had looked at these aspects but did not attempt to correlate them[4]. But this better understanding of the link between technical factors in the building and socio-economic factors in the inhabitant still needs to be refined to propose policies in favor of renovation that activate the right levers.

1.2. *Determinants of energy consumption and renovation*

There has been a significant increase in the number of articles devoted to sustainable renovation over the last few years [42]. At the same time, political and legislative tools are being put in place to accelerate the rate of major renovation. Article 23 of the Belgian Constitution defines the right to decent housing. However, Belgian efforts are mainly focused on the technical aspect of building, with the regional integration of the EPBD (Energy Performance of Buildings Directive) standard. Scientific publications show that passive renovation of buildings is possible [33]. Questions are being raised about the optimum level to be reached [102] and the right scale of intervention [64], about heritage issues [78] and workforce skills [52]. All these studies approach the building as a technical object whose performance must be optimized. At the same time, there is a lack of research [73] into renovation strategies and their social sustainability [49,94].

Yet there are important links between the energy and social characteristics of the residential sector [79,85], even if "connections between energy, housing affordability and well-being are still under-researched" [17]. In the Walloon region, for example, the weighted average annual bill has risen sharply (58.9 % for electricity and 63.8 % for gas). [21]. The various types of energy insecurity (measured, hidden, perceived) [68] will now affect 20.6 % of Belgian households in 2021 and 28.8 % of Walloon households [67]. There is considerable heterogeneity between and within municipalities, while housing inequalities are still relatively low in Belgium. [25]. Fuel poverty exacerbates poverty levels and disparities in well-being [96]. In the long term, housing inequalities may be associated with 18.5 % of deaths. [74]. Acting solely on energy prices can also be counter-productive: a reduction in VAT on electricity was accompanied by an increase in consumption. [45]. Occupant behavior plays an important role in the risk of the rebound effect [11,40,43], which has been much discussed recently [76]. It is important to note, however, that this Energy Performance Gap is due not only to the rise in temperature but also to the improvement in air quality [100]. Whatever the method used to define and calculate a rebound effect [38], it is undeniable that it tends to

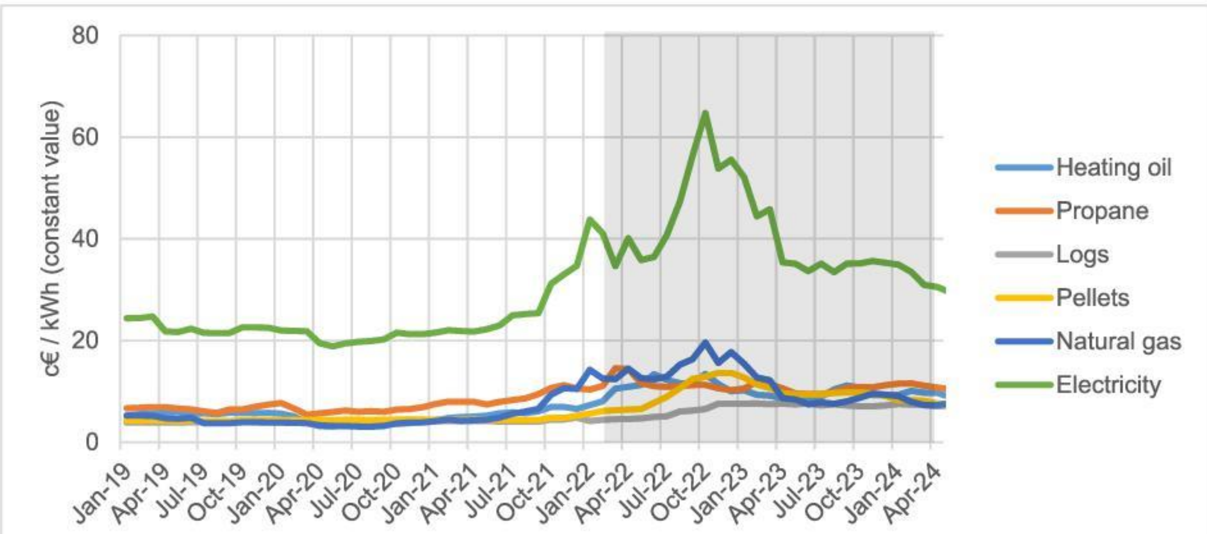

Fig. 1. Evolution of the price of energy purchased by households in recent years in Belgium. Value at constant currency. Source CREG, SPF économie, ValBiom; Statbel, 2024.

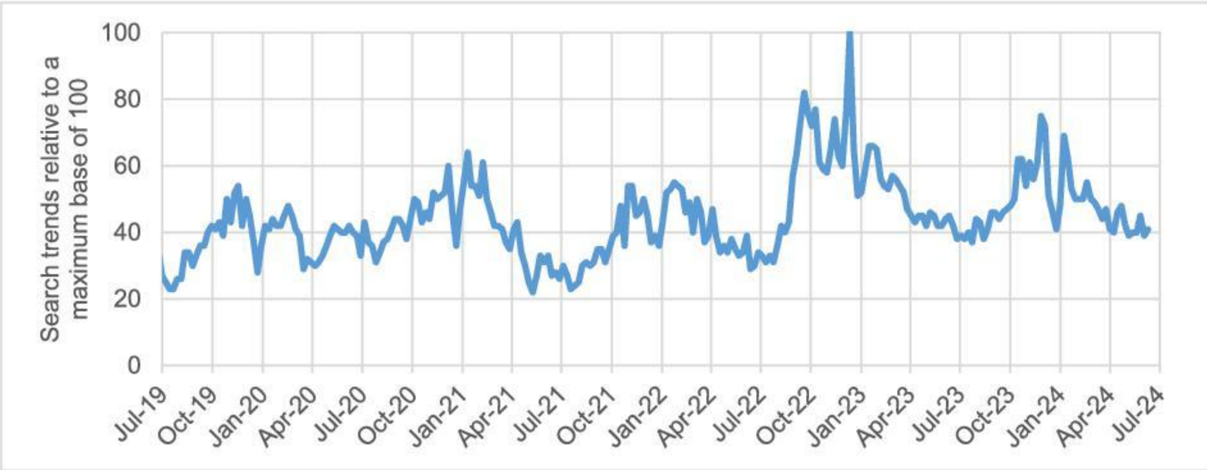

Fig. 2. "Building Thermal Insulation" research trends on Google in Belgium. . Source: *trends.google.com*, 2024

reduce the results of energy efficiency work [7]. All the more so, the inhabitants of low energy performance buildings are already tending to adopt energy-saving behaviors [92].

The occupant is also a determining factor in the decision to renovate [82]. For example, reducing carbon emissions is rarely a factor in the decision to renovate. Would-be renovators are motivated by aesthetics, comfort or energy savings[52]. Despite this, the role of residents remains largely unintegrated in policy initiatives[9]. Although financial tools [12]) have been put in place to reach the various profiles, they are not very effective for certain profiles. [57]. Private rental housing is a poor relation when it comes to financial aid.[13,59,62], because of the gap between the objectives of owners and tenants[6]. Rising house prices also contribute to widening existing gaps[80]. The economic issue remains the main obstacle to renovation work[2,52], even though such work would be cost-optimal from a macro-economic point of view[18]. More progressive work could help to broaden the target audience[69]. More generally, far-reaching renovation must no longer be the sole objective; we need to multiply strategies and approaches [50]. It is, therefore, essential to integrate the social aspects of the inhabitant into the article of the evolution of the built stock through its renovation.

1.3. Built stock modeling

Among studies of energy in buildings, modeling the built stock is one of the proven techniques [18,42]. There are two main families of residential energy consumption models [93]. Top-down models are based on macro-economic variables, which estimate the breakdown between different sectors. These models do not consider possible improvements at the end-user level. Bottom-up models construct and extrapolate end-user consumption. They are better suited to estimating political measures and energy renovation strategies [72].

Table 1 summarizes the main bottom-up models developed for Belgium and the Walloon region. In 2001, Hens et al. [44] proposed 960 typologies representative of the built stock, classified according to several criteria (age, type, surface area, primary energy, central heating or not) to article the energy-saving potential of the Belgian built stock. The same team of researchers considered 5 individual references separated according to architectural criteria (classic villa, typical Flemish rural house, modern commissioned house, small working-class terraced dwelling, large upper-class terraced dwelling) houses to articulate the financial viability of renovation [99]. Kints and De Herde [54] used a matrix of 28 typologies classified by age and typology based on the results of the 2001 Census [97]. They combine them to distinguish 8 priority architectural typologies in terms of renovation for the Walloon region. The Low Energy Housing Retrofit (LEHR) article [70] proposes 11 architectural typologies representative of the stock of buildings in need of renovation in Belgium. Allacker et al. [3] used 16 typologies representative of the existing Belgian building stock, according to age and type, for the SuFiQuaD project to evaluate LCAs and LCCs. Based on the previous work, the TABULA article [22] proposes a mixed classification of 25 typologies based on 5 construction periods and 5 types of housing units. Monfils and Hauglustaine use the same typologies as Kints for their article on the Walloon region, with 8 representative typologies [41]. The first cost-optimum article COZEB 1 [71] studies a large number of building archetypes, but focuses on 4 typologies of existing dwellings among those proposed by Kints to set the optimal energy performance of these dwellings. Gendebien et al. [39] rely heavily on the above work. The tree-based approach creates 992 building typologies to analyze the impact of different renovation scenarios on a national scale. The second cost-optimum article, COZEB 2 [60], studies 40 building typologies, including 22 typologies of existing housing, to refine and update the results of COZEB 1[71]. The TIMES model [18] has been developed for the Walloon region, including 20 categories of building typologies depending on the period of construction and the number of facades. TIMES models are general bottom-up energy system models based on a set of criteria. These typologies are mainly based on the COZEB 2 dataset. In addition, it should be noted that some studies focus on a single typology [8] to specify its characteristics.

Two approaches can be distinguished in the creation of typologies, according to Cyx et al. [22]. The representative approach creates simulated buildings based on technical characteristics (age of the building, type of dwelling, surface area, etc.), which are aggregated into matrices. The typical approach uses existing buildings that are representative of the built stock. This approach is often based on architectural archetypes: mansions, workers' houses, and four-fronted villas.

Table 1
Belgian and Walloon built stock models.

Sources	Dwelling typologies	Geographic area	Approach
[44]	960	Belgium	Representative
[99]	5	Belgium	Typical
[54]	8	Walloon region	Mixed
[70]	11	Belgium	Typical
[3]	16	Belgium	Representative
[22]	25	Belgium	Mixed
[41]	8	Walloon region	Typical
[71]	4	Walloon region	Typical
[39]	992	Walloon region	Representative
[60]	42 (22 existing)	Walloon region	Mixed
[18]	20	Walloon region	Representative

However, the two approaches tend to merge, with typical buildings being selected based on representative criteria and vice versa.

The quality and availability of the data studied is a key issue in data analysis [25,53,77]. While more and more data are being collected in our societies, the question of how to aggregate it is an unavoidable problem. It is necessary to standardize and improve methodologies and datasets to obtain more robust findings [58].

The transposition of the EPBD [24]/91/CE sur le performance énergétique des bâtiments, 2002) provides a large amount of information on the composition of the Walloon building stock [15,47]. These data can be used to describe energy use and renovation potential [35,56], by statistical analysis [91] or linear regression [84,101]. Clustering improves the use and cross-referencing of these data [86] while maintaining a reasonable number of representative typologies.

The models by Hens [44] and Gendebien [39] are designed for algorithmic use, which explains the large number of typologies (~900). The other models are less precise but allow us to work on a few typologies (from 4 to 25) that are easier to identify.

The 2001 Census [97] and the 2011 Census [66] provide the other major databases on which most of these studies base their models. They also offer the advantage of providing information on both the composition of the built stock and the socio-economic aspects of the population.

A review of the literature shows that the integration of socio-economic data into building stock modeling is still in its early stages [42,53]. The social factors that are essential for understanding the decision to renovate are not considered [10]. "Building stock modeling has so far focused on modeling technological aspects of the development of energy use in the stock and neglect complex interactions between technology, economics and policy when modeling the development" [72]. Sartori et al.[87]go even further in Norway by estimating the renovation rate based on population statistics alone.

A few studies nevertheless include technical and socio-economic factors based on surveys[63]. In the Walloon region, in particular, the CEHD (Centre for Sustainable Housing Studies) produced a report on housing quality in 2014 [16]. A new report is expected for 2024. This article combines socio-economic data on the occupant (age, tenure status, socio-economic status, nationality, household composition, household size, length of tenure, rent or credit, occupation of the dwelling) and technical data (type of dwelling, period of construction, surface area, heating method, energy consumption, wall insulation, condition of the building, building environment). The main drawback of this extremely comprehensive article is that it does not provide a representative typology of the built stock. However, it does offer the most detailed view of the link between technical and socio-economic characteristics in the Walloon region. In the models of the built stock studied in Table 1, only Verbeeck and Hens [99]make slight mention of this criterion by distinguishing two models of terraced dwelling: lower class and upper class.

As far as geographical delimitation is concerned, there are as many Belgian models as there are regional models. However, it seems simpler and more coherent to create a regional model. From a practical point of view, building and population databases are mainly regionalized. From a political point of view, building, energy and climate policies are largely regionalized in Belgium [18]. This probably explains the predominance of Walloon models in recent years. In any case, while there are significant differences between regions, spatial disparities in the built stock go beyond the north–south divide [98]. The European Commission also recognizes the importance of regions and cities in defining appropriate energy-saving solutions [32].

1.4. Objectives

This article aims to help increase the renovation rate by enabling policies to promote the energy-efficient renovation of housing in the Walloon region to be better targeted. Prior to this article, several factors were identified as playing a major role in the decision to renovate or not to renovate a dwelling.

The first objective of the article is to cross-reference technical data on the building with socio-economic data on the residents. The inclusion of socio-economic data enhances the understanding of occupant behavior, financial capacity, and decision-making processes related to building renovations. This information is critical for identifying barriers to energy efficiency, such as financial constraints, knowledge gaps, or behavioral tendencies. By clustering building-inhabitant pairs based on both technical and socio-economic attributes, the study identifies typologies that allow for tailored interventions. For example, low-income households in low energy performance buildings may require targeted subsidies or simplified renovation processes, while high-income households might benefit from tax incentives or stricter regulations. This alignment ensures that renovation strategies are not only technically sound but also socio-economically feasible, thereby increasing the likelihood of adoption and achieving significant energy savings. The second objective is to use the results of this cross-referencing to create clusters of building-individual pairs. These clusters will enable a new analysis of the composition of the built stock.

The third objective is to examine the distribution of these clusters. Their distribution across the Walloon region and the different municipalities will already provide keys to understanding the actions that can be envisaged at the different levels of government.

This research holds broader significance beyond the Walloon Region, offering a replicable methodology for integrating socio-economic and technical building data to identify actionable renovation strategies. European countries share similar challenges with aging building stocks and diverse occupant profiles, complicating the implementation of effective energy renovation policies. By demonstrating a scalable approach that aligns building typologies with resident characteristics, this study provides insights that can be adapted to other regions facing the dual pressures of climate commitments and energy crises. The findings emphasize the importance of localized interventions that balance technical efficiency with social equity, reinforcing the utility of this framework for advancing renovation strategies across Europe.

This article is innovative in two ways. First, it presents a solution for crossing datasets by using regression models to predict missing socio-economic information based on technical building data and vice versa, followed by clustering to group building-occupant pairs into representative typologies. This approach harmonizes distinct datasets, allowing for the extraction of actionable insights that connect occupant characteristics with building energy performance. The same methodology can be applied to other regions with similar databases, such as all European countries with similar EPC [1] and census data [95]. This methodology is also not limited to the proposed characteristics; it is easily possible to subsequently integrate other information that could have been collected. This methodology also has the advantage of avoiding problems related to the privacy of individuals because the criteria studied are all anonymous. This methodology also has the advantage of avoiding issues related to the privacy of individuals, as the criteria studied are all anonymous.

Regarding the results, this article offers a new perspective on the constitution of the built stock. It focuses on the correlations that exist between the building and its occupant. This building-occupant couple is essential to understanding the response of the built stock to the challenges of energy renovation. While the numerical results are specific to the Walloon case study, the methodology provides a framework that could potentially inform renovation strategies in other regions with comparable challenges, such as aging building stocks and the need for policies integrating socio-economic and technical data [27,34,36,37,89].

This article relies on a large amount of data already available. On the one hand the data from the PEB certification, result of the implementation of the EPBD policy. On the other hand, the statistical data collected by the official institutes. It should be noted that the everincreasing amount of data generated is leading to an interest in how to exploit them to understand the dynamics of many issues better. Once this data has been selected, cleaned, and sorted, it is possible to cross-reference it statistically to deduce potential correlations and extrapolate general profiles. The result is not only the classification of the Walloon building stock into some major archetypes. But also, the possibility to article the different Walloon municipalities according to the distribution of these archetypes to better understand their composition and to better target energy efficiency policies.

After this introduction, the methodology section allows us to go into more detail on the different steps of data processing. This part will explain how the databases were identified, collected, and cleaned. Then how different regression algorithms crossed the different databases. Finally, the clustering methods were used to simplify the expression. The result section will present the main results of the article. We will first focus on the clustering result. But we will also detail the implications of these results on the assumed energy efficiency of the built stock and the distribution of the clusters in the different Walloon municipalities. Finally, some validation steps will confirm the quality of the obtained results from a statistical point of view. These results will then be exploited through a discussion part that will highlight them with respect to what is already known about the Walloon building stock. We will also take the opportunity to broaden the conclusions and propose new avenues for the article.

The issue of energy renovation is of particular concern to the countries of Western Europe. The Netherlands, the United Kingdom, France, Denmark, Belgium and others are all characterized to some degree by a building stock that largely pre-dates the first energy regulations and by slow growth. Despite a great deal of research and regulation at the national and European level, as well as numerous awareness-raising, funding and training initiatives, the rate of energy renovation is growing slowly. Of all the obstacles that have been identified, this article focuses on improving knowledge of the composition of the housing stock and its occupancy applied to the Walloon region. This should enable more effective renovation strategies to be designed.

This article proposes a new model of the Walloon housing stock, in 6 or 10 clusters in this case. This model is based not only on the geometry and assumed energy efficiency of the dwellings. Above all, it incorporates certain occupant characteristics that are essential for understanding the decision to renovate, such as income and whether they are homeowners. This study, therefore, fills a research gap between a highly technical approach to the composition of the built environment and housing policies geared towards residents or homeowners. This article proposes a new methodology. By drawing on existing databases in all the countries of Western Europe that are subject to the same difficulties, it promotes a result that is both robust and reproducible. It is also easy to improve the model by integrating new databases using tools like those used or by updating the databases already in use. Finally, the results provided by this article make it possible to approach the question of renovation strategies in the Walloon region differently. By way of example, the cluster representing very energy-intensive housing occupied by low-income households represents more than 17 % of the built stock. This represents almost 1 household in 5 at high risk of fuel poverty. In contrast, the cluster representing very energy-intensive housing occupied by high-income households represents more than 11 % of the built stock. Renovation strategies for this cluster are totally different from those for the first group.

2. Methodology

2.1. Tools

The entire statistical processing work was done with the R programming language version 4.2.1. The programming interface is RStudio. Table 2 presents the packages that were used during this article in addition to the libraries natively present in R.

Table 2
Extra packages use.

Library	Use	Version
"readxl "	read excel table	1.3.1
"compositions"	isometric log ratio (ILR) transform	2.0–4
"VGAM"	logistic ordinal regression	1.1–5
"lmtest"	likelihood-ratio test	0.9–38
"betareg"	beta regression	3.1–4
"ggplot2"	plotting	3.3.5
"Hmisc"	weighted statistics	4.7–0

The developed code is available on Zenodo (https://doi.org/10.5281/zenodo.7708755) under the GPL-3 license.

2.2. Methodology flow chart

The article's methodology is based on several successive statistical operations, the general structure of which is shown in Fig. 3. This flow chart highlights the link between databases relating to cities to the left and databases relating to energy certificates to the right. The methodology is divided into three main stages, each requiring several substages: data collection and treatment (2.3), data crossing (2.4) and clustering (2.5). The first part of the work involves identifying 'individuals,' which, in the statistical sense, refer to data points representing specific entities within the datasets. In this study, 'individuals' correspond to building units associated with socio-economic data at the household level. These data points are aggregated and expressed at the level of 'individual-cities,' meaning that all data within a given city are pooled to form representative values for that city. This allows the methodology to connect the characteristics of the building stock with socio-economic variables at the municipal scale rather than focusing on individual buildings or households. These correlations are used to deduce the probable missing information on the second type of "individuals": for each energy certificate, probable socio-economic data are predicted. If these "individual-certificates" do not have value independently of each other, they can, on the other hand, draw trends by grouping them by cluster. The distribution of these clusters can then be studied at different territorial scales, either directly to highlight specific clusters or through a PCA to highlight specific cities. The various stages and the results obtained are described in greater detail below.

Data collection and treatment.

Data Collection

The article relies on existing databases. Table 3 summarizes references of the different databases used. Most of this data is published by public institutions. The data is then freely available. The energy data is directly taken from the PEB (Performance Energétique des Bâtiments) database. The PEB is the application for the Walloon region of the European EPC (Energy Performance Certificates) rating scheme. In the rest of the article, this database will be referred to as EPC. To respect the GDPR (General Data Protection Regulation), the EPC data collected are anonymized by the absence of any precise information (names, exact addresses).

All the data collected are compiled in two tables. The CITY table (Table 4) compiles all known data (typology, income, ownership, households) on the constitution of Walloon cities (268 cities). For each city is indicated the name of the city, the name of the province, the number of inhabitants and the proportion relative to the Walloon population, the proportion of owners, the proportion of each housing typology (apartments, 2, 3 and 4 facades) and the proportion of the different income categories.

The EPC table (Table 5) compiles data from the EPC database (632,833 certificates) that will be used in this article. For each certificate is indicated the name of the city, the specific primary energy consumption, the energy label, the destination (public, apartment, single-family house) and the number of free facades. The EPC data are corrected so that the city names are written the same in both databases. The

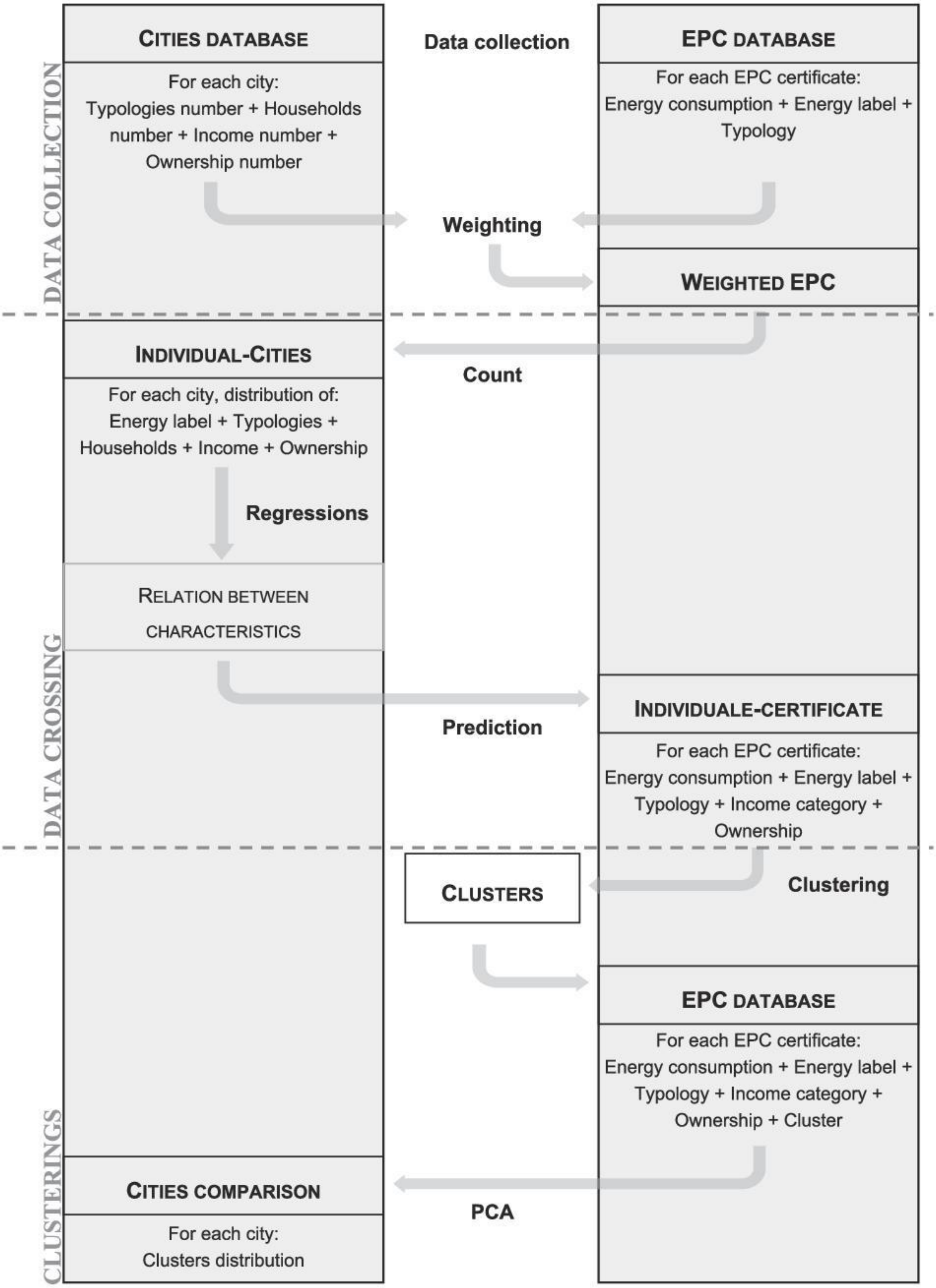

Fig. 3. Methodology framework for the cross-exploitation of technical data from energy certificates and socio-economic data from official databases.

Table 3
Summary table of the dataset.

Category name	Data name	Source	Data year
Energy	EPC label and consumption	DG TLPE	2020
Geometry	Type of building in housing	STATBEL	2018
Income	Categories of income	IWEPS	2016
Ownership	Property title	Census	2011
Households	Number of households	STATBEL	2018

A, A + and A++ labels are combined.

The EPC data are also cleaned of some unnecessary or unusable data:

- 1,522 certificates for municipal buildings.
- 1,012 certificates without geometry details.
- 3 certificates with a specific consumption lower than -100 kWh/m^2.year. Buildings with renewable energy production (such as photovoltaic panels) can achieve negative energy consumption. However, a production value that is too high is difficult to explain in terms of energy logic.
- 8 certificates with a specific consumption higher than 10,000 kWh/m^2.year. If there are very energy-intensive buildings, the analysis of certificates presenting such extreme values shows inconsistencies between the quantities of heated surfaces and loss-producing surfaces.

The EPC table finally consists of 630,278 certificates representing a built stock of 1,749,879 dwellings in the Walloon Region.

Weighting.

The weighting process ensures the representativeness of the EPC data relative to the Cities Dataset. This was checked by comparing the distributions of building typologies (e.g., apartments, attached houses) in both datasets using chi-square tests ("chisq.test" function in library "stats").

Discrepancies were corrected by applying proportional weights to the EPC data.

2.3. Data crossing

Count.

The matching of datasets was conducted by linking municipal-level data from the Cities Dataset with the geographic identifiers in the EPC data.

This weighting step allows us to obtain information on the corrected distribution of the certificates and to calculate a weighted energy efficiency ("wtd.mean" function in library "Hmisc") of the Walloon building stock.

At this stage, all the data collected was therefore pooled at the same scale, that of cities.

Regressions.

The new combined database contains the following data for each city: income, geometry, energy label, ownership, province, and city size. The interest of this first pooling is to be able to calculate the correlations that exist between the different characteristics studied.

Income, geometry, and energy labels are expressed as percentages of representation of different categories. The sum of these categories is equal to 1 (100 %). It is not possible to use a traditional regression model on this type of redundant data. Applying an Isometric Log Ratio (ILR) transformation [28] on these distributions ("ilr" function in library "compositions") allows for use in a regression model while reversibly keeping all the information [46].

The first regression model looks for explanatory variables for the distribution of income categories. The specificity of this regression is the existence of a hierarchy between the different income categories (from lowest to highest). Ordinal logistic regression [88] ("vglm" function in library "VGAM") takes this hierarchy into account during the statistical

Table 4
CITY table structure.

City	Typology				Income						Owner	Households	City size	Province
262 Walloon cities (name)	attached (%)	semidetached (%)	detached (%)	apartments (%)	Cat. 1. (%) inc. < 10.000€	Cat. 2 (%) 10.001€ < inc. < 20.000€	Cat. 3 (%) 20.001€ < inc. < 30.000€	Cat. 4 (%) 30.001€ < inc. < 40.000€	Cat. 5 (%) 40.001€ < inc. < 50.000€	Cat. 6 (%) 50.001€ < inc.	(%)	(number)	relative city size (%)	(name)

Table 5
EPC table structure.

Certificate	City	Destination	Free Facade	Specific primary energy	Energy label
630,278 certificates	(name)	(public / apartment / single family)	(detached / one free / two free / three free)	($kWh/m^2.an$)	(A / B / C / D / E / F / G)

treatment. Different explanatory variables are tested to find the best formula using several likelihood ratio tests [30] ("lrtest_vglm" function in library "VGAM"). The full model with non-proportional odds performs better than other models. The most efficient model (modINCOME) explains the ordered income variable with typology, energy label, province, and city size.

The second regression model looks for explanatory variables for the distribution of ownership rates in different cities. The ownership rate must be between 0 and 100 %. The use of a beta regression algorithm [20] ("betareg" function in library "betareg") allows to maintain this requirement of a response variable between 0 and 1. Different explanatory variables are tested to find the best formula using several likelihood ratio tests ("lrtest" function in library "lmtest"). The most efficient model (modOWNER) explains the ownership variable with typology, energy label, income, and province.

Prediction

These two regression models (modINCOME and modOWNER) allow income and property to be deduced based on typology, energy label, province and city size. They can be used to complete the characteristics of the EPC certificates. For each certificate, we can deduce a probability of belonging to the different income ("predictvglm" function in library "VGAM") and ownership categories ("predict" function in library "stats").

2.4. Clusterings

Certificates clustering.

For certificate clustering, the specific primary energy consumption of each certificate will be considered rather than the energy label. This makes it easier to differentiate between certificates. All certificates are considered, regardless of their location (province or city). These choices allow us to consider only quantitative variables in the clustering.

The main objective of this article is a better understanding of the composition of the built stock to renovate it. The A, A + and A++ energy certificates can be considered outliers. They are few, and might require one or more clusters to represent them. Consequently, it is decided to remove them during the clustering.

At this point, each certificate has a probability of being attached to each income category. In practice, each certificate is occupied by a single income category. A draw determines which income category each certificate belongs to, considering the probability of belonging to each category. The income category is drawn at random 10 times. This allows us to check that this draw has no effect on their distribution within the built stock. A slight variance appears after clustering on the distribution of the different clusters: a change in cluster size of up to 5 % of the total population may be observed. However, the other characteristics of the clusters show variations in values of less than 1 %, making their analysis identical.

To ensure that each criterion has the same weight when clustering, the energy, ownership, and income categories are standardized: distribution of mean 0 and standard deviation 1.

The first method for estimating the number of clusters [55] to be created is to look for an inflection in the within groups sum of squares. This inflection is between 2 and 11 but needs to be refined. The "NbClust" function in the library "NbClust" compares different ways to obtain the optimal number of clusters but can only be used on small databases for hardware reasons. The function is used on samples drawn from our database, but the results vary from one test to another between 3 et 10. Based on these initial results, it was decided to limit the number of clusters tested to 10. The minimum number of clusters tested is set in accordance with the state of the art (Table 1), in which no study proposes fewer than 4 clusters. Clustering will, therefore be tested from 4 to 10 centers.

A k-means clustering method is used [48] ("kmeans" function in library "stats"). This is a clustering method that allows to manage of large numerical databases in a reasonable amount of time. Multiplying the iterations (200 maximum iterations) and testing different numbers of centers (from 4 to 10) reduces the known drawbacks.

The cluster results are corrected by de-standardizing the variables and calculating the representativeness (see Weighting) of each certificate in the cluster. A quick analysis of the distribution of cluster centers enables the clusters to be sorted according to the most explicit distributions. In the results section, we will look at the two clusters that seem most interesting to analyze from a technical and socio-economic point of view.

Cities PCA.

Once each certificate has been assigned to a cluster, it is possible to calculate the distribution of these different clusters in each city in proportion to their representativeness. We can see that certain specific clusters are more represented in certain cities, while other clusters correspond to a different type of cities.

In this case, we will try to identify general trends rather than focusing on specific clusters. To do this, we run a Principal Component Analysis (PCA) [51] of these distributions ("prcomp" function in library "stats"). PCA is a way of reducing the number of dimensions in a database while limiting the loss of information. In our case, the number of dimensions is 6 or 10, corresponding to the number of clusters chosen during clustering. PCA is used to obtain new dimensions chosen to represent the variability of the old dimensions best. The representation of the first two dimensions of these PCAs allows us to highlight in a 2D-plot the cities with the most distinctive k-means cluster distributions, considering a maximum of information present in the 6 or 10 initial dimensions.

This type of representation should allow highlighting groups of cities with a similar composition or, on the contrary, to highlight cities with a very different composition from the majority group.

2.5. Validation

The entire data collection and statistical processing process was subject to various validation stages. We have already explained in the previous sections how the databases were processed and corrected, as well as the various stages that led to the calibration of the different algorithms used to obtain the most accurate results.

However, to ensure the validity of the regression algorithms, it is also necessary to ensure that the results are statistically exploitable. For the ordinal logistic regression model, the Pearson distribution of residuals highlights potential outliers that could call into question the validity of the model. For the beta regression model, the calculation of the generalized leverage [81] allows us to identify the individuals having the most influence on the regression.

Robustness and Limitations.

On one hand, the article relies on well-known and validated databases of large size to maximize their representativeness. A cleaning step allows to removal of outliers, and a calibration step enables to correction of some of the known biases of the EPC database. Moreover, the open access code allows everyone to verify it and reproduce the experiment with other databases.

On the other hand, the article is based on databases collected at different times. Not only is there a gap of several years between the different databases, but also within the same database (EPC certificate).

This limitation must be put into perspective because the characteristics of the buildings – particularly the Walloon buildings – change slowly. The differences generated affect the accuracy of the results but do not compromise the conclusions drawn. The proposed methodology also leads to several simplification steps (sampling, drawing) whose impact has been verified but which reduce accuracy.

Furthermore, energy certificates are widely considered to be imprecise tools for measuring energy performance [23] for two main reasons: the lack of precise knowledge of existing buildings, which implies many default values, and the lack of consideration of user behavior. However, these very real weaknesses are moderate for the use made of them here. Even if the performance of a certificate can be largely underestimated or overestimated, analyses on large samples will smooth out the most significant errors. Furthermore, what interests us is not so much the actual consumption as the hierarchy of these consumptions between high energy performance, moderate energy performance and low energy performance buildings. Finally, if user behavior can indeed have a large impact on energy performance, the very idea of the article to jointly study socio-economic data makes it possible to integrate, in a very simplified way, a first behavioral issue.

3. Results

3.1. Certificates clustering and built stock characterization

The main result of the article is the characterization of the built stock by clustering the aggregated data. Two sets of clusters are kept. These two sets represent different characteristics of the built stock. Two digits number each cluster obtained: the first corresponds to the importance of this cluster in the clustering and the second corresponds to the number of clusters in the clustering. For example, cluster 1/6 is the cluster with the most individuals out of 6 clusters. The first set of 6 clusters (Table 6) is characterized primarily by its energy performance, ownership rate, and income. One of the most interesting clusters is Cluster 5/6, which contains 12 % of the housing stock. It gathers houses with low energy performance occupied by high-income owners. We also notice that one of the clusters with the highest rate of home ownership (Cluster 3/6) is also characterized by low energy performance for low-income households. This typically represents households in potential fuel poverty.

On the other hand, clusters 4/6 and 6/6, which contain the highest energy performance housing (excluding label A), are mainly occupied by households with higher incomes. From this first clustering, we can deduce the importance of accentuating renovation aids for low-income households in clusters 1/6, 2/6 and 3/6, which group ~ 63 % of the dwellings, mainly with average and low energy performances. But it is also necessary to put in place more restrictive regulations to push cluster 5/6 to invest in energy efficiency. Following this analysis, each cluster can be designated not only by a number but also by its main characteristics.

The representation of clusters (Fig. 4) by province highlights the similarities between some provinces. On the one hand, the former industrial provinces of Hainaut and Liège, which are home to the two largest agglomerations, are more likely to be made up of clusters 1/6 “mid performance – compact – renter” and 3/6 “low performance – low income – owner”. In contrast, the provinces of Walloon Brabant, Namur and Luxembourg are composed of more 4-front and semi-detached houses with moderate (2/6 “mid performance – low income”) or high (4/6 “high performance – house – owner”) performances.

The distribution in Belgian municipalities of clusters 3/6 “low performance – low income – owner” and 5/6 “low performance – high income – owner”, which deserve particular attention, will be highlighted in Section 3.3.

The second set of 10 clusters (Table 7) completes the observations by highlighting characteristics specific to housing typologies. We observe 6 clusters specific to specific typologies (3 for apartments due to their over-representation in the certificates, 1 for each other typology) and 4 clusters with mixed typologies (2 high performance and 2 low performance).

Among the clusters representing specific typologies, we see that detached (5/10) and semi-detached (4/10) houses are more owner-occupied than attached houses (2/10) and apartments (8/10, 9/10 and 10/10). We also note that the most energy-intensive clusters are overwhelmingly owner-occupied. However, it constitutes only 2 % of the built stock, cluster 10/10 concentrates on the weaknesses with poor energy efficiency, low ownership rates and low-income categories. With cluster 1/10 much more owner-occupied, they constitute the two clusters at risk of fuel poverty. Following this analysis, each cluster can be designated not only by a number but also by its main characteristics.

This multiplication of clusters allows us to see more detail in the distribution by province (Fig. 5). For example, Walloon Brabant is characterized by its high rate of relatively high-performance dwellings (clusters 3/10 “high performance – high income – house – owner”, 7/10 “high performance – high income – renter”, 9/10 “high performance – low income – apartment – renter”), which is explained by its recent urbanization. Conversely, the province of Liège is characterized by its relatively high rate of low-performance apartments (cluster 10/10 “low performance – low income – apartment – renter”). The cluster 1/10 “low performance – low income – apartment –– renter” is particularly present in the provinces of Hainaut and Liège.

In the same way, as for clusters 3/6 “low performance – low income – owner” and 5/6 “low performance – high income – owner”, a more detailed analysis of the distribution of clusters 1/10 “low performance – low income – house – owner” and 6/10 “low performance – high income – owner” with similar characteristics will be carried out in Section 3.3.

3.2. Certificate distribution analysis

The weighting of the certificates before statistical analysis provides information on their distribution and the constitution of the built stock. The weighting correction of the certificates of the 4 typologies in each city (Fig. 6) highlights the lower weight of apartment certificates in all cities. Apartments are overrepresented in the certificates. All other typologies are given greater weight, which means they are under-represented. The attached houses have the greatest variability in their representativeness.

This is explained by Walloon legislation which requires the creation of certificates for new housing and rented housing. However, these are two categories of housing in which apartments are largely over-represented, while terraced houses are generally older and more occupied by owners.

Table 6
Centers characteristics of 6 clusters.

Cluster	Proportion	Specific primary energy	Apartment	Attached	Semidetached	Detached	Owner	Income
1/6 “mid performance – compact – renter”	~23 %	331	70 %	30 %	0 %	0 %	37 %	2.0
2/6 “mid performance – low income”	~23 %	361	0 %	7 %	50 %	43 %	67 %	2.2
3/6 “low performance – low income – owner”	~17 %	709	16 %	23 %	34 %	27 %	79 %	2.1
4/6 “high performance – house – owner”	~15 %	277	0 %	14 %	23 %	63 %	75 %	5.5
5/6 “low performance – high income – owner”	~12 %	702	4 %	21 %	29 %	46 %	84 %	5.3
6/6 “high performance – compact – renter”	~10 %	276	75 %	25 %	0 %	0 %	42 %	5.1

Income: average of income categories (from 1 to 6) of cluster members (see Table 4).

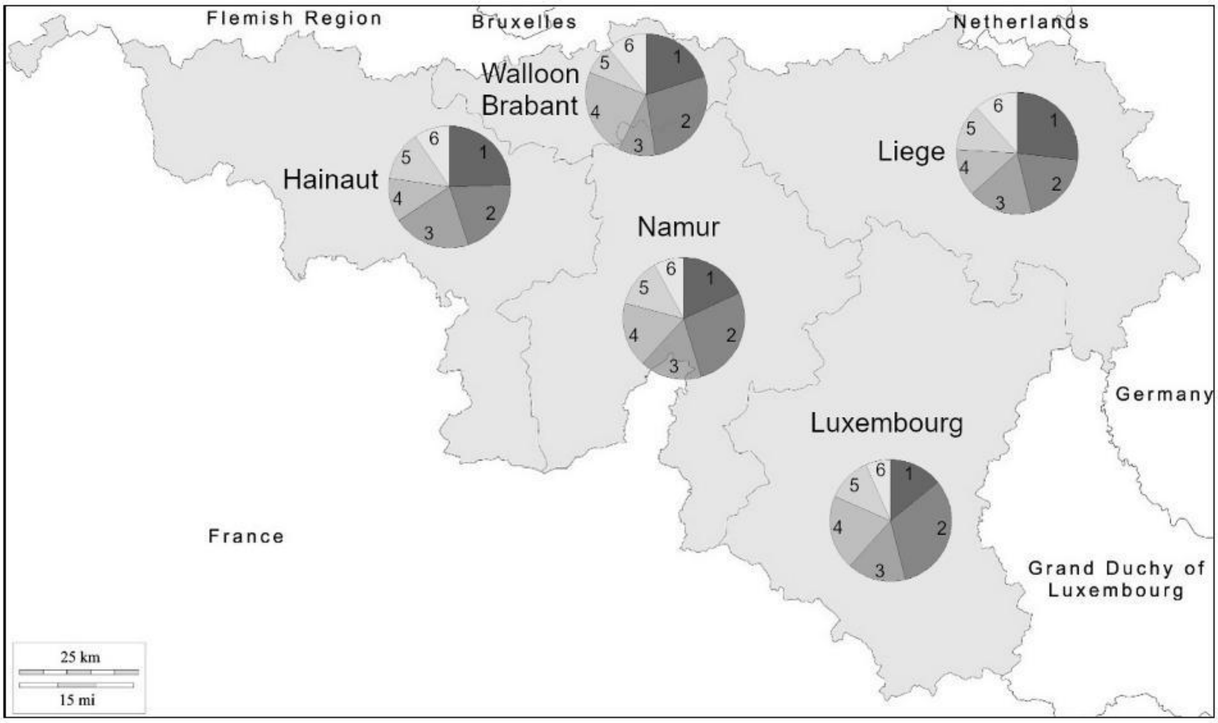

Fig. 4. Distribution of the 6 clusters by province.

Table 7
Centers characteristics of 10 clusters.

Cluster	Proportion	Specific primary energy	Apartment	Attached	Semidetached	Detached	Owner	Income
1/10 "low performance – low income – house – owner"	~16 %	705	0 %	29 %	43 %	28 %	85 %	2.1
2/10 "mid performance – low income – attached – renter"	~15 %	373	0 %	100 %	0 %	0 %	44 %	2.2
3/10 "high performance – high income – house – owner"	~14 %	265	0 %	15 %	25 %	60 %	75 %	5.6
4/10 "mid performance – low income – semidetached – owner"	~12 %	376	0 %	0 %	100 %	0 %	63 %	2.2
5/10 "mid performance – low income – detached – owner"	~11 %	397	0 %	0 %	0 %	100 %	73 %	2.2
6/10 "low performance – high income – owner"	~11 %	700	3 %	24 %	21 %	52 %	84 %	5.4
7/10 "high performance – high income – renter"	~7%	267	73 %	26 %	1 %	0 %	42 %	5.7
8/10 "mid performance – low income – apartment – renter"	~6%	372	100 %	0 %	0 %	0 %	22 %	2.2
9/10 "high performance – low income – apartment – renter"	~6%	173	100 %	0 %	0 %	0 %	48 %	2.5
10/10 "low performance – low income – apartment – renter"	~2%	704	100 %	0 %	0 %	0 %	55 %	2.5

Income: average of income categories (from 1 to 6) of cluster members (see Table 4).

An analysis of the specific energy statistics of the unweighted and weighted certificates according to the distribution of the typologies (Table 8) also highlights the overrepresentation of the best-performing certificates. The average consumption of the certificates is 417 kWh/m^2.an. After weighting, this average consumption becomes 437 kWh/m^2.an. In the same way, the different quartiles confirm that a certification of the whole building stock would probably lead to a decrease in the estimated performance of the building stock.

3.3. Cities distribution

During the clustering analysis (3.1), two typologies of clusters emerged: clusters of low performance buildings occupied by low-income households (3/6 "low performance – low income – owner" and 1/10 "low performance – low income – house – owner") and clusters of low performance buildings occupied by wealthy households (5/6 "low performance – high income – owner" and 6/10 "low performance – high income – owner"). The distribution of these clusters in the different communes of the Walloon region is shown in Fig. 7. The same representation can be used for the other clusters obtained in the cluster analysis. However, the choice has been made to concentrate here on those whose characteristics appear to be the most interesting in terms of the objective of improving energy efficiency. In addition, the representation of clusters with redundant characteristics makes it possible to check the homogeneity of the results between 6-clustering and 10-clustering.

For these two cluster typologies, 6-groups (top maps) and 10-group clustering (bottom maps) give practically identical distributions. It can also be seen that some municipalities concentrate high rates of these two clusters, reflecting an overall inefficiency of their built stock and, more generally, their older urbanization. Finally, while we might expect large towns (>50,000 inhabitants) to be poorly represented by clusters representing wealthy households, it is more surprising to find that this is also the case for clusters representing low-income households. This can be explained by the greater compactness of urban buildings (flats and terraced housing), which implies lower energy consumption, and which

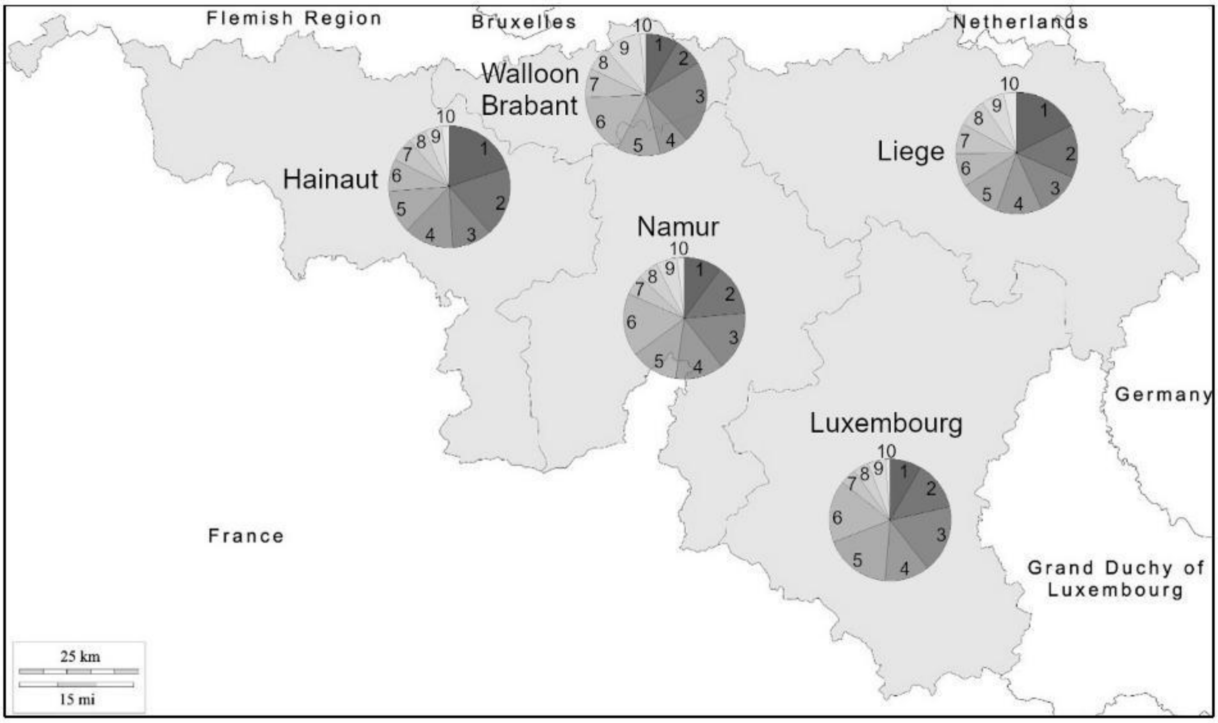

Fig. 5. Distribution of the 10 clusters by province.

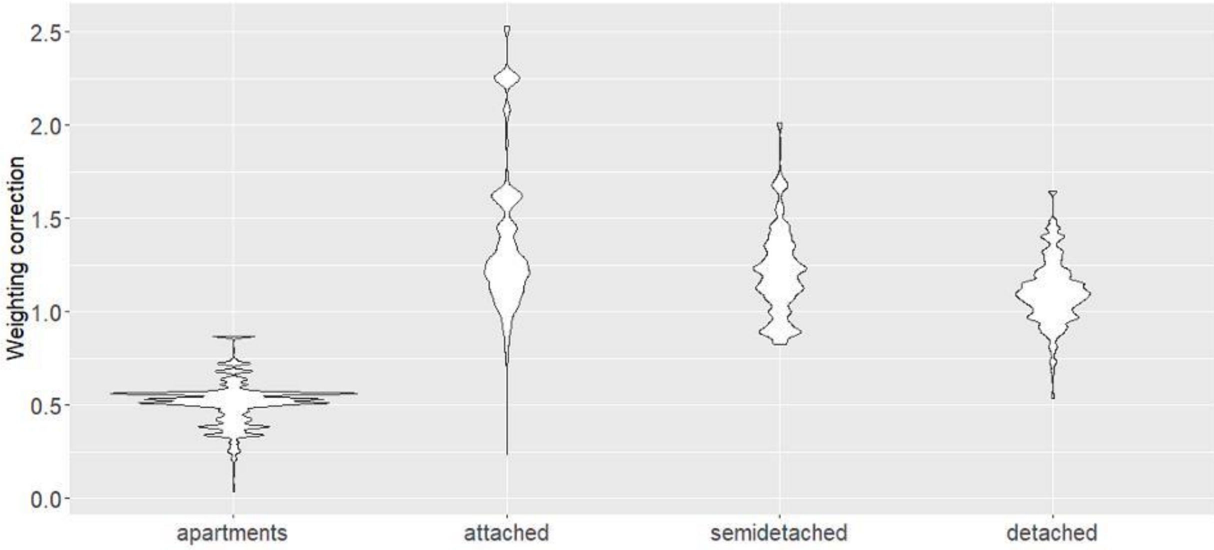

Fig. 6. Distribution of the certificate's weights depending on the typologies.

Table 8
Certificate and weighted certificate statistics.

	Q 25 %	Median	Mean	Q 75 %
Certificate	253	386	417	534
Weighted certificate	282	409	437	550

would be better represented by clusters 2/6 "mid performance – low income", 2/10 "mid performance – low income – attached –– renter", 4/10 "mid performance – low income – semidetached – owner" and 8/10 "mid performance – low income – apartment –– renter".

More comprehensively, the PCA of the distribution of clusters in Walloon cities presented in Fig. 8 should be interpreted as the difference in the distribution of clusters in a city compared to an 'average' distribution in the Walloon region. The more peripheral the towns, the more the distribution of the clusters differs from this average distribution. First, it confirms the similarities between the two clusterings. Certain towns with compositions that merit closer articles are enhanced by their exterior positioning. We find the same cities as extreme cases, which means that the characteristics of the two clusters are homogeneous.

Dimensions 1 and 2 cannot be directly interpreted because they are the result of an integration of all the initial dimensions. The percentage on the graph represents the quality of these dimensions to represent the information. Thus, in the graph on the left concerning the cluster with 6 groups, dimension 1 represents 68.9 % of the initial data and dimension 2 represents 26.4 % of the initial data, for a total of 95.3 % of the initial data represented. On the graph on the right concerning the cluster with

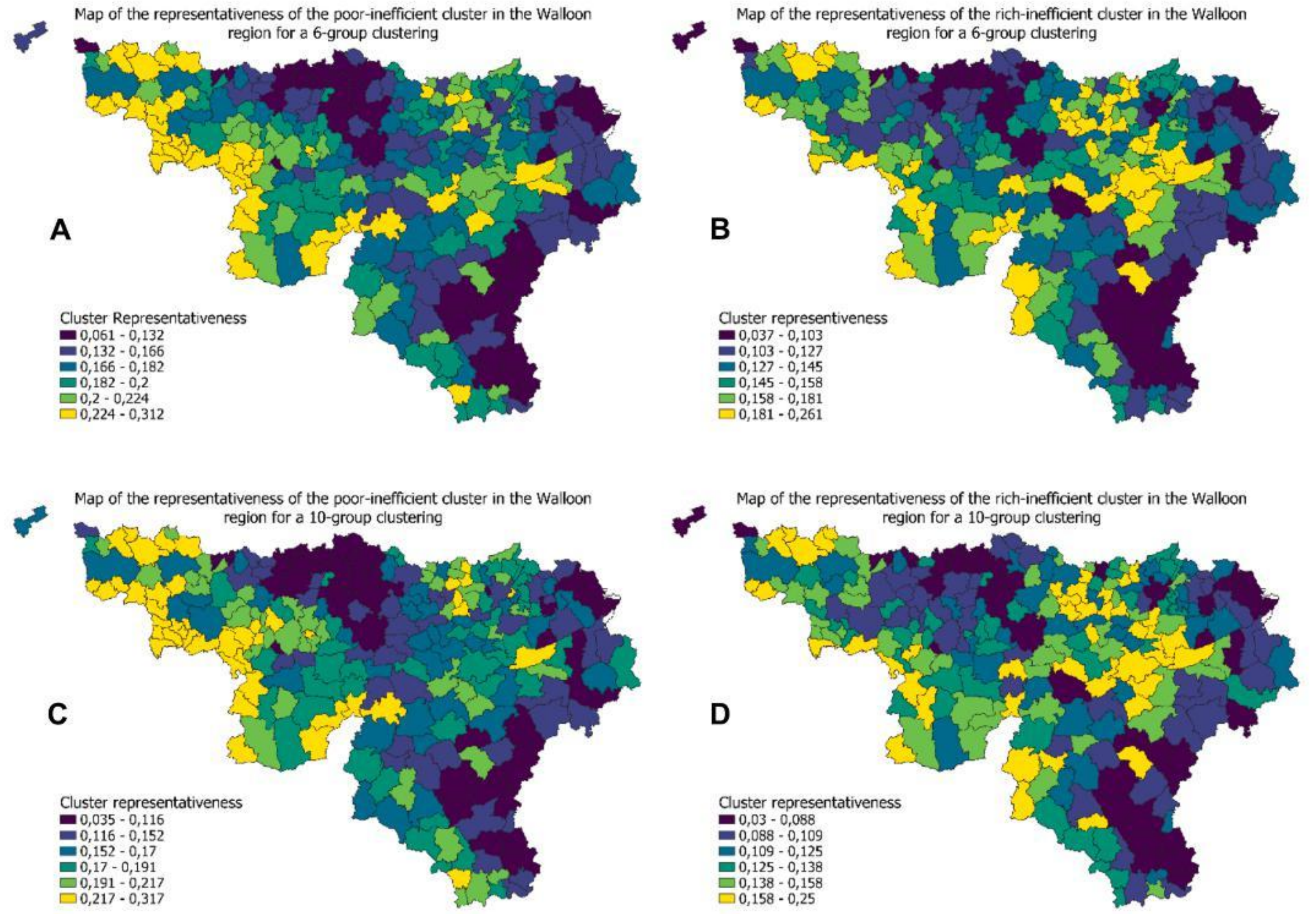

Fig. 7. Distribution in Walloon municipalities of clusters 3/6 "low performance – low income – owner" (A), 5/6 "low performance – high income – owner" (B), 1/10 "low performance – low income – house – owner"(C) and6/10 "low performance – high income – owner" (D).

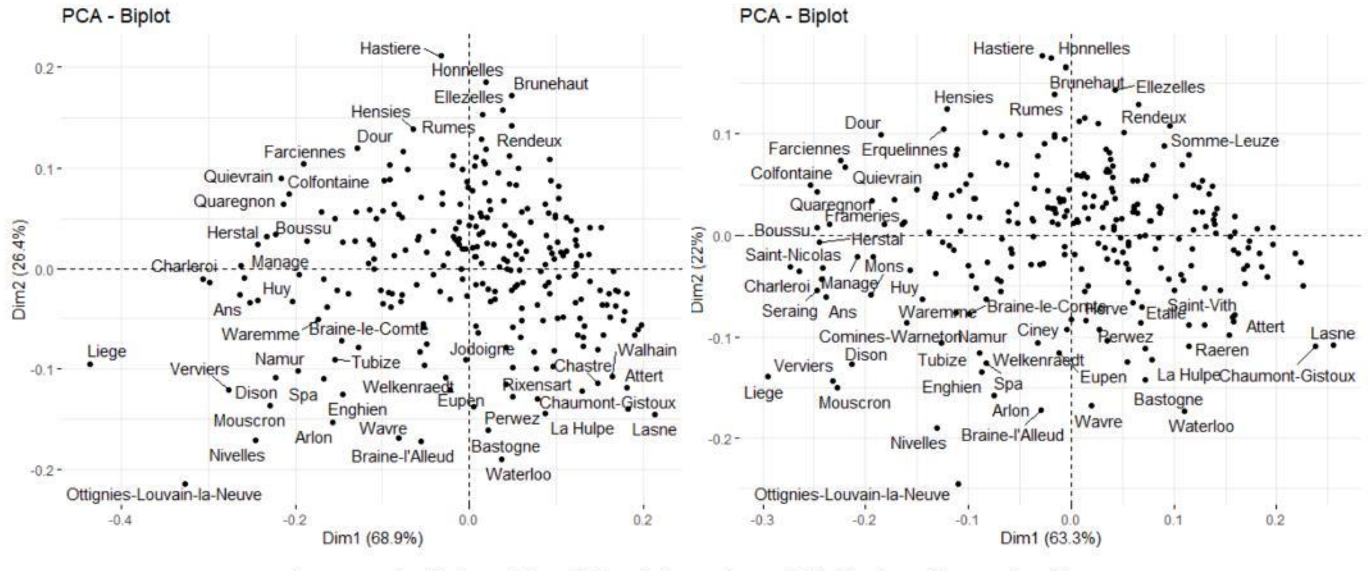

Fig. 8. PCA distribution of the 6 (left) and the 10 clusters (right) in the Walloon region cities.

10 groups, dimension 1 represents 63.6 % of the initial data and dimension 2 represents 22 % of the initial data, for a total of 85.3 %. We can, therefore, consider that these graphs highlight very well the individuals with the most remarkable distribution, even if this quality logically decreases with the increase in the number of initial dimensions. Despite this, we can hypothesize that the horizontal axes put forward information related to the distribution of geometries (more apartments and semi-detached houses on the left, more 4-front houses on the right). In contrast, the vertical axes seem to put forward information related to energy performance (better performances at the bottom). On the

diagonal, we find information related to income, with a higher proportion of high incomes on the bottom right.

What is most interesting is probably to highlight the cities that should rely on a differentiated approach to their building stock. Deux towns clearly have a very specific built stock, which is consistent with their size (Liège) and their history (Ottignies-Louvain-la-Neuve). Some towns, such as several former industrial towns in the Sambre et Meuse region (Charleroi, Ans, Manage, Herstal, Huy, Boussu, etc.), can be included in the same group. Other towns (Arlon, Braine-L'Alleud, Wavre, Waterlo, Bastogne, Enghien, etc.) are characterized by a more recent stock of buildings due to their location on the outskirts of Brussels or Luxembourg. This classification could be used to identify the most effective housing and building policies in similar towns. Policies that have proved successful in a specific city or region could be replicated in cities with a similar distribution of clusters. On the other hand, we must be careful not to generalize too quickly results between two entities with very different distributions.

3.4. Validation

Fig. 9 allows us to check the consistency of the logistic ordinal model's results used for the income regression. It can be noted that the majority of "individual-cities" have a similar weight in linear regression. However, the residuals of this model for the two metropolises of Liège and Charleroi are particularly high, but this is explained by the size of these two cities, which bring together 11 % of the region's households. From a statistical point of view, this check does not invalidate the results of the ordinal logistic model.

The representation of the fitted values according to the generalized leverage (Fig. 10) confirms a relatively homogeneous distribution of the individuals for the beta regression model. Even though some individuals logically have more influence than others, none of them stand out specifically. From a statistical point of view, this check does not invalidate the results of the beta regression model.

The various statistical validation tests carried out as the processing progressed ensured that the statistical regression models could indeed be used.

4. Discussion and conclusions

Previous research has already identified the potential of exploiting existing databases to build a mixed model of the built stock. This article succeeded in combining several databases from different sources and representing varied information (residents and housing). With the help of advanced statistical analysis involving regression and clustering techniques, the article managed to provide useful and insightful knowledge on the correlation between occupancy profiles and housing energy efficiency. The article could thus provide a methodological base on which future studies could rely to compile the multiple databases that exist on the composition of the built stock and the socio-economic characteristics of the population. The article's methodology results in the grouping of homes into several representative groups. Each group has its characteristics and its occupant profile. Thus, renovation policies can be adapted to match the characteristics of each group, particularly socio-economic characteristics. As the state of the art has shown, it is necessary to distinguish better and group the real estate stock to achieve high renovation rates. The analysis confirms what had already been envisaged by Cassilde [15], that we have more EPC certificates for high-performance housing and fewer certificates for low-performance housing. Consequently, the EPC database must be used with caution to characterize and improve the performance of low energy performance buildings, which constitute most of the Belgian and European building stock.

The article also revealed an interesting phenomenon among two groups of housing users. The first group, low-income people, with an ownership rate of 79 %, occupies 17 % of residential buildings in Wallonia. Unfortunately, they occupy the lowest energy performance housing with EPC F and G. This high level of ownership, which can be explained by Belgian housing policy, implies great difficulty in carrying out heavy renovation work. This group must become a priority in all renovation policies. The second group is high-income occupants, with a high property rate of 84 %, living in houses whose specific energy is, on average, 704 kWh/m^2.year. In other words, being rich and owner is not enough to ensure energy-saving work either. This result confirms one of the hypotheses of our study: the inclusion of socio-economic data enhances the understanding of occupant behavior, financial capacity, and decision-making processes related to building renovations.

Furthermore, any renovation strategies should be planned and

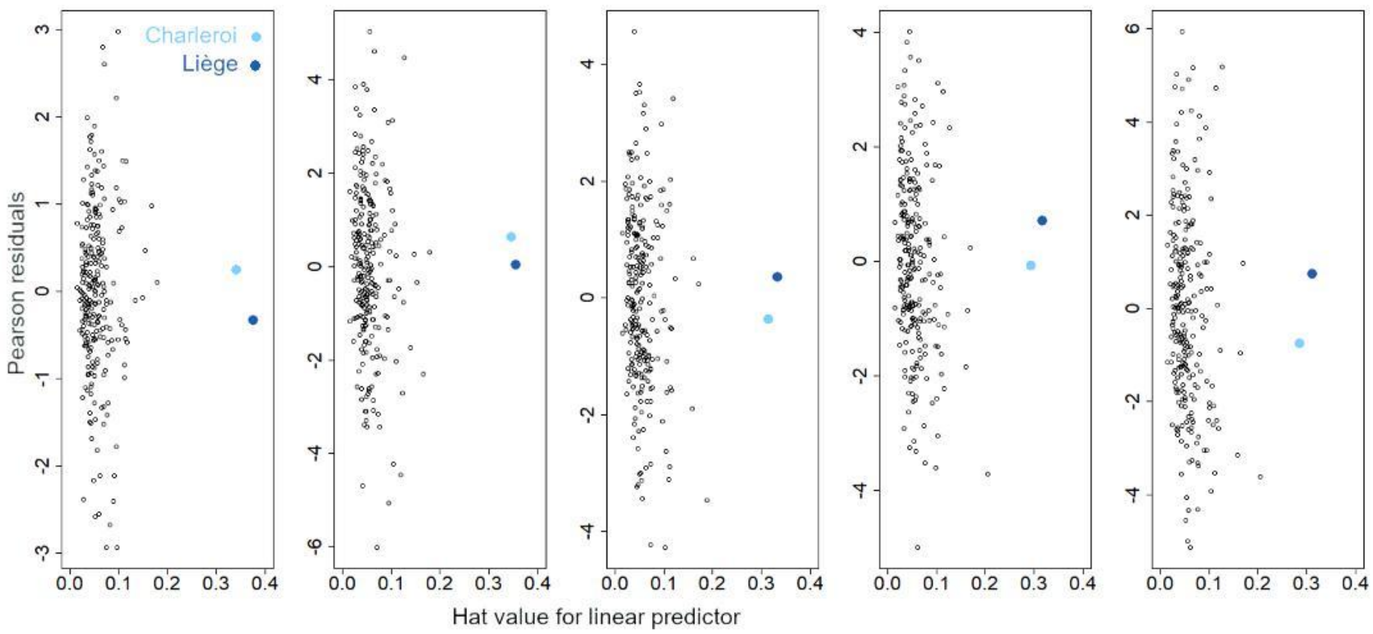

Fig. 9. Pearson residuals depending on Hat values of the income logistic ordinal.

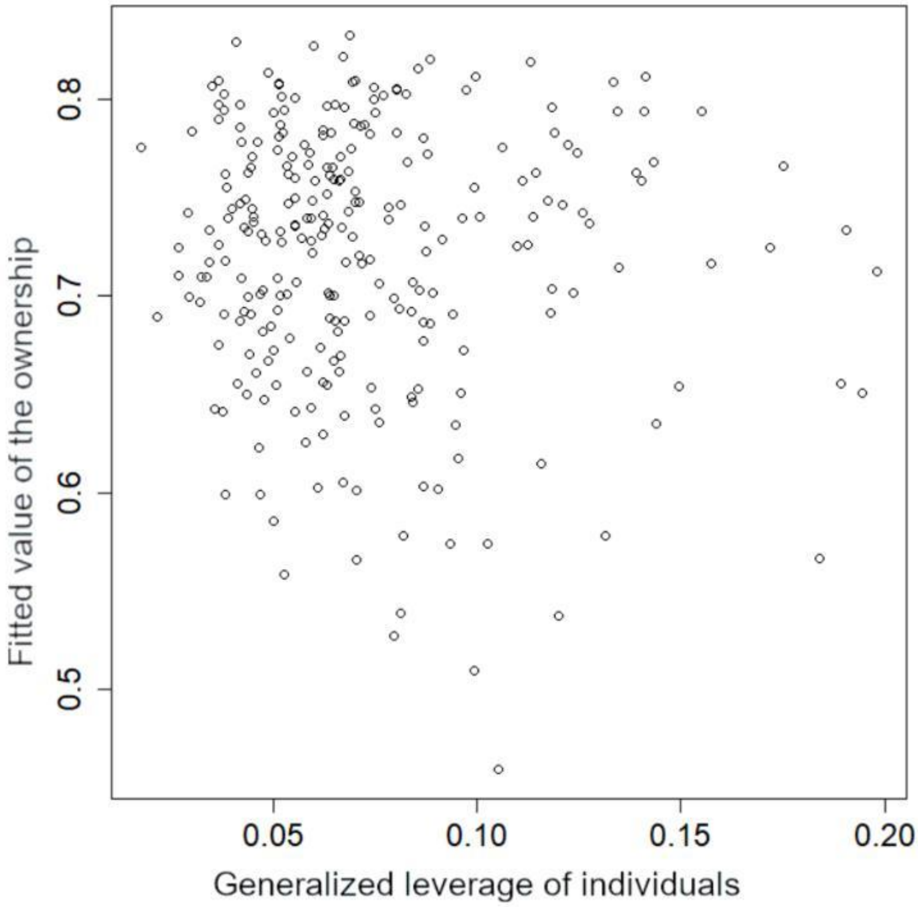

Fig. 10. Fitted values of the ownership beta regression model depending on the generalized leverage.

implemented on the city and municipal level and not only at the regional or national level, to achieve a breakthrough by increasing the renovation rate in the Walloon region. Our article confirms that only customized and tailor-made renovation strategies and plans can become effective. These targeted strategies will help to address the diversity of socio-economic profiles highlighted by the clustering, which is a determining factor in the decision to renovate [57,69,82]. These targeted strategies could be adapted to the heterogeneous distribution of these clusters across the territory highlighted by the PCA [25]. There is also an urgent need to create energy performance certificates for all existing buildings without certification. Without this step, any city or municipality will not have a complete picture of the energy efficiency and clusters of its residential stock. In the current socioeconomical context of Wallonia a fact check confirms the low progress of renovation ineffective subsidies program. The article revealed that the existing incentive program failed to support low-income households with significant renovation measures nor high-income dwellers. Therefore, we suggest revising the policy of support for property ownership for social classes and low incomes. Empowerment via ownership is not enough and must be coupled with proactive energy efficiency measures and incentives, at the risk of putting these households in a vicious circle of energy expenditure. For high-income house owners who live in low energy performance dwellings, a high taxation of greenhouse gas emissions could be an example of future reforms or regulations that should address this category.

The article succeeds in addressing the representativity problem by coupling different databases. This is unique and novel. Until now, similar models (Table 1) were built with homogeneous technical data whose distribution in the built stock is well documented. This method is transferable and reproducible and can be supplemented with additional data sets. This coupling of a data set on the energy efficiency of buildings with a socio-economic data set via regression and clustering techniques makes it possible to create completely new typologies. If we already knew the essential link between these two aspects [16], we now have a tool to put them together to propose appropriate policies. The influence of the variance of the dataset temporality might be significant but does not jeopardize the clustering results. The known limitations of the EPC database are specifically considered. Its representativeness is corrected, possible measurement errors and default values are smoothed by a large-scale analysis, and the introduction of socio-economic characteristics makes it possible to anticipate the real energy behavior of households better. The article requires several steps of simplification to perform statistical modeling and assure hypothetical values for each different calculation method. We consulted statistical experts to ensure that all our assumptions were within acceptable ranges and best practices. However, to increase confidence in this model, it would be interesting to validate the results with an in-situ survey that would confirm the results obtained.

The article's results implicate revising existing strategies in the European Union and elsewhere to make sure that they can be executed operationally on the city or municipal level. Without detailed classification and clustering of different archetypes, generic renovation programs will not be able to target priority households. There is a need to use real case studies in the form of neighborhoods or municipalities to test renovation strategies and implement our suggested clustering approach. Missing information on the EPC of existing buildings in those neighborhoods or municipalities will require targeted audits to complete the full picture of the building stock efficiency states. The impact of the new European carbon tax that will be implemented in 2027 needs to be well-studied. Also, the influence of the Ukrainian-Russian war and associated energy price increases require a detailed article. Between 2022 and 2023, the Belgian government will have paid out about 5 billion euros to protect households and businesses against price increases. It would be interesting to article other alternatives to use the money from this social protection in targeted renovation plans.

CRediT authorship contribution statement

Guirec Ruellan: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. Shady Attia: Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. Gentiane Haesbroeck: Writing – review & editing.

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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Data availability

EPC data is confidential. Other data is public and can be sent by the author on request.

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Part II - Chapter 3.3

Conference Paper: Integrating Statistical Data and Thermographic Survey for Assessing Energy Renovation Policies: A Review

RQ4. *To what extent can façade-based infrared thermography complement statistical datasets to improve the characterization of building performance and energy use at the neighborhood scale?*

This conference paper presents a discussion of the state of the art in IRT for energy audits and the potential of this technique to validate and supplement the statistical data analyzed in Chapters 3.1 and 3.2.

The methodology employed is based primarily on a condensed review of scientific review articles and state-of-the-art literature using the following keywords: "building infrared thermography review," with irrelevant results removed to retain only those directly relevant to our specific topic.

The results of this review are compared with the findings presented in Chapters 3.1 and 3.2. The discussion highlights the value of IRT for energy mapping and auditing while identifying clear limitations, particularly regarding accuracy, which necessitate combining it with other data sources.

This conference paper serves as the bridge between the presentation of the results in Part I and the methodological analysis in Part II, which concludes in Chapter 3.4.

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INTEGRATING STATISTICAL DATA AND THERMOGRAPHIC SURVEY FOR ASSESSING ENERGY RENOVATION POLICIES: A REVIEW

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Abstract

Despite extensive energy renovation policies implemented across Europe, the tangible improvement in housing energy performance remains slow, particularly evident in Wallonia, Belgium, used as a case study. Identified challenges include mismatches between existing renovation support mechanisms and target demographics, as well as discrepancies between diagnostic tools like the Energy Performance Certificate (EPC) and actual construction realities. This paper is a reminder of two established methodologies to explore their potential synergies in addressing these issues. Leveraging large-scale databases enables the assessment of the building stock's composition and the socio-economic characteristics of residents. Concurrently, thermographic surveys offer rapid identification of atypical cases. Cross-referencing these methodologies reveals their compatibility and complementarity, suggesting a promising avenue for future research to test their combined efficacy in addressing energy renovation challenges.

Keywords

behavior, energy audit, Wallon region,

Abbreviations

AI, Artificial Intelligence; BEM, Building Energy Model; EPC: Energy Performance Certificate; EN, European Norms; GPR, Ground Penetrating Radar; HFM, Heat Flux Meter; IRT, InfraRed Thermography; ISO, International Organization for Standardization; IoT, Internet of Things; LiDaR, Light Detection and Ranging; NDT, Non-Destructive Techniques ; TPC, Thermal Point Cloud; UBEM, TWIR, Through Wall Imaging Radar; Urban Built Energy Model; UHI, Urban Heat Island

Introduction

The need to renovate Europe's built stock to meet climate targets (Renovate Europe, 2020) is a widely shared consensus. This is all the truer given the many other advantages of energy renovation (Thuvander et al., 2012). Long focused on new buildings, legislation is taking an increasing interest in this significant part of the built stock (Directive 2010/31/UE on Energy Performance of Building, 2010; Directive 2012/27/EU on Energy Efficiency, 2012). Numerous strategies are being tested: incentives (Dubois & Allacker, 2015), tax incentives (Villca-Pozo & Gonzales-Bustos, 2019), rent controls (Bertoldi, Economidou, et al., 2021), the massification of programs (Brown et al., 2019), simplification of supply (Bertoldi, Boza-Kiss, et al., 2021), and so on. Despite these numerous and sometimes costly programs, the rate of energy renovation is not reaching the expected levels (Filippidou et al., 2017).

When we look at the reasons why a household decides to undertake energy renovation work, we can see that this choice depends on two main aspects, among others. On the one hand, the best way to renovate largely depends on the technical characteristics of the building (Nielsen et al., 2016), its basic condition, its dimensions, its organization, the physical characteristics of the materials used, etc. While it is possible to improve the energy performance of any building, the fact remains that the techniques to be adopted, and therefore their cost, vary drastically depending on the base case. On the other hand, the socio-economic conditions of its occupants and owners (Friege & Chappin, 2014) will largely define the actions that can be envisaged. Occupancy status (rental, shared ownership, sole ownership) (Ástmarsson et al., 2013) and income, which determine the risk of falling into fuel poverty (Meyer et al., 2018), the ability to invest and knowledge of subsidy mechanisms (Baek & Park, 2012) are essential determinants of the decision to act. However, these two aspects are still relatively compartmentalized, both in the scientific literature and in the initiatives targeting one or the other. If we look at Belgium, the articles that have been able to study them together (Anfrie et al., 2021; Ruellan et al., 2021) are still very patchy. The state of the energy efficiency of the built stock suffers from very fragmented, old knowledge that is subject to many approximations and which is not representative of the actual use of the building (Monfils & Hauglustaine, 2016).

This brief introduction leads us to the following research question: How can we gain a better understanding of the built stock based on both the physical characteristics of the building and the socio-economic characteristics of its occupants?

To answer this question, we will first look at how our laboratory's previous studies in the Walloon region have enabled us to establish the existence of correlations between these different criteria and the possibility of proposing a mixed socio-technical model of the housing-occupant relationship.

Then, based on a review of the literature on infrared thermography, we will analyze the way in which such a technique could potentially enable us to validate hypotheses about this dwelling-occupant pairing with a view to better guiding building renovation strategies.

Finally, we will discuss the possible implementation of such a scan to validate the various hypotheses and identify the strategies best suited to the various cases encountered.

Building/Inhabitant couple: data crossing

It is reasonable to ask what correlations exist between the different technical and socio-economic characteristics that are decisive in the decision to renovate. To this end, we have previously (Ruellan et al., 2021) used different independent databases representing the criteria we were interested in for the Walloon Region. Two databases were compiled to represent the geometry of the building (detached, semi-detached, attached, flat) and its energy efficiency based on the EPCs. Two other databases were compiled to represent household income and occupant status (owner or tenant). The correlations between the distribution of these characteristics in the various Walloon municipalities were studied using statistical tools (Spearman correlation, linear regression, multiple linear regression), some of the results of which can be seen in Figure 1. It has already been possible to observe that flats were, on average more efficient due to their compactness and, even though they were mostly occupied by tenants on lower incomes. Paradoxically, the increase in income is accompanied by a relative decrease in energy efficiency.

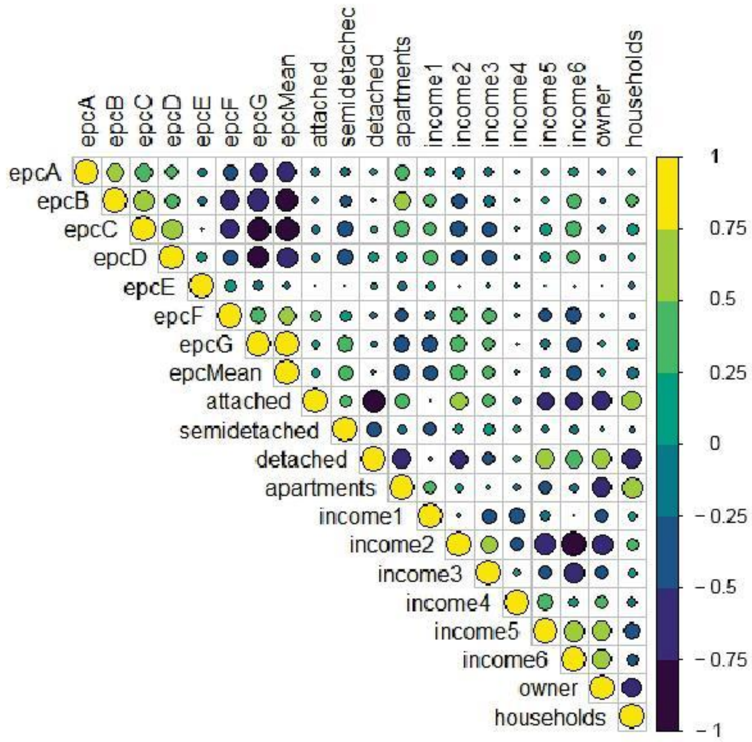

Figure 1. Spearman correlation between technical and socio-economic characteristics of the Walloon built stock (Ruellan et al., 2021).

Based on these initial results, it was possible to propose a clustering approach (Ruellan et al., 2025). Without going into detail - which is the subject of a dedicated article currently being submitted for peer review - the databases studied were weighted to take account of their representativeness. More specific statistical algorithms were then used to establish the correlations between these factors as accurately as possible. These correlations made it possible to construct statistically representative clusters of the different building/inhabitant pairs existing in Wallonia (Figure 2), composing a new model of the built stock capable of better anticipating the effectiveness of different building energy renovation strategies.

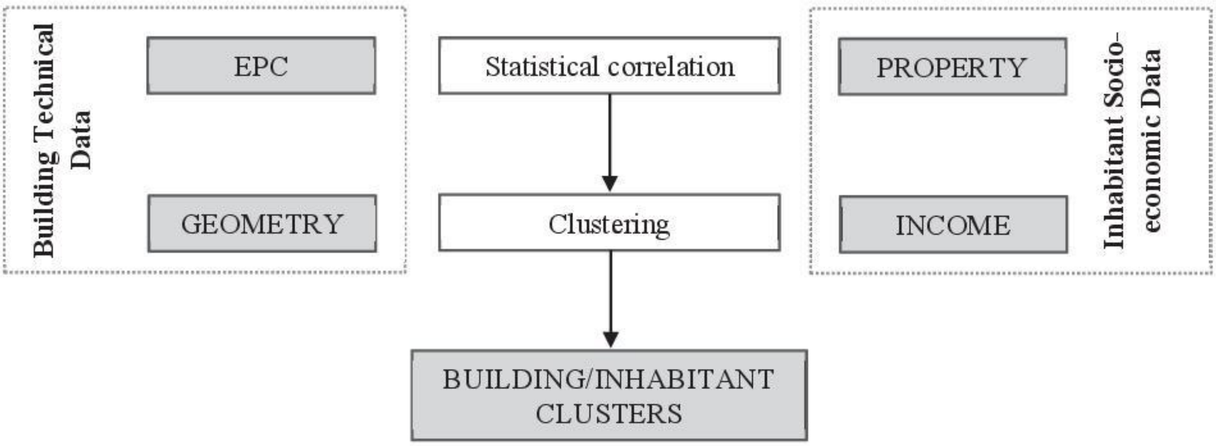

Figure 2. Conceptual framework on the correlations between the technical characteristics of the building and the socio-economic characteristics of the inhabitants.

This model of the built stock is based on many assumptions, each of which brings its uncertainties and approximations. At this stage, it remains largely theoretical. It is therefore necessary to compare it with a field study, the aim of which would be not only to validate or correct the model's initial conclusions. The field study could also make it possible to establish the link between the clusters identified and the renovation strategies to be implemented for each one. One of the techniques identified for this purpose is InfraRed Thermography (IRT).

Building Infrared Thermography: Process

Before going any further with a review of the literature, here is a reminder of the use of IRT in the energy analysis of a building. Without going into the details of the physical calculations, materials send out radiation in the infrared range in two components: the radiation emitted by the material as a function of its temperature and the radiation reflected by the surface of the object. Figure 3 illustrates the results obtained, as well as some of the difficulties associated with this measurement. The perimeter of window frames can be seen as a hot spot in the wall, compared with brick and stone, indicating the existence of a thermal bridge. On the other hand, glazing appears much cooler than brick, despite its lower thermal performance, because glazing reflects more radiation from the colder environment. As we shall see later, the results of an IRT can be used in many ways. However, this method also has its limitations and requires precautions to be taken when using it.

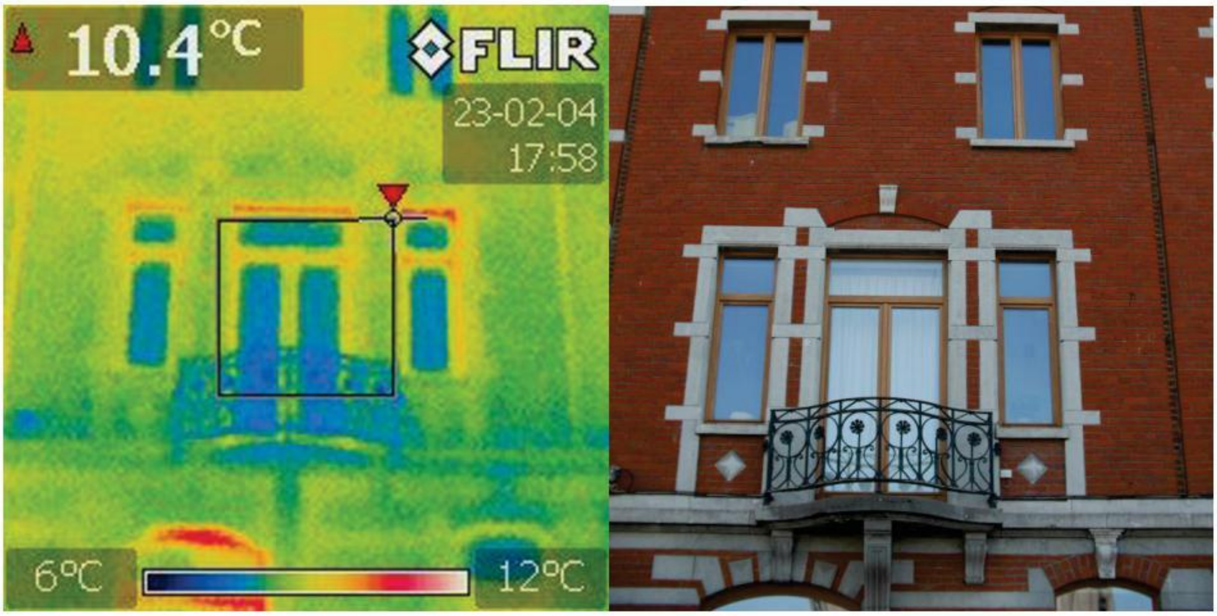

Figure 3. Comparison of infrared thermography and a visible image

Standards regulate these analyses ISO 6781 (*ISO 6781-1*, 2023) and EN 13187 (*UNE EN 13187*, 2000-11-01), which set out guidelines for detecting thermal defects in the envelope using the infrared method, and ISO 9869 (*ISO 9869-2*, 2018) for in-situ measurement of resistance and thermal transmittance using IRT, to limit the risk of errors in interpreting the results.

One of the rules to follow to ensure good quality IRT is that the temperature difference between inside and outside must be at least 10°C. And that this temperature difference is present long enough before the test to limit the impact of inertia. Similarly, it is preferable to have precise knowledge of emissivity and reflection temperature factors, which are common sources of error in IRT. In addition to IRT, it is necessary to take regular readings of the ambient temperature and relative humidity to ensure that they are relatively constant or to take account of any changes. The wind should be light (<5 m/s). Finally, it is not advisable to study a facade that is sunny or has recently been sunny. For all these reasons, the best time to survey in Europe is on a winter's morning, before sunrise and with plenty of cloud cover. However, it is also possible to survey the rest of the day, if you pay particular attention to the other criteria.

The reading distance should be as constant and as small as possible to minimize atmospheric noise and increase the resolution of the image obtained: between 5 and 20 meters is recommended for the thermography of a façade. While it is recommended to be perpendicular to the building, it should be noted that some sources (Kylili et al., 2014) recommend shifting slightly to avoid impacting the thermography with the reflection of the thermographer and equipment's infrared emissions.

Building Infrared thermography : A review of reviews

Now that the technique is known, it's worth asking how it can be used. What are the limitations, advantages and potential areas for improvement of IRT? To do this, we will conduct a literature review. To reduce the amount of text, we will concentrate on analyzing literature reviews that have already been carried out using the following keywords: "*building infrared thermography review*". Excluded are reviews that deal exclusively with fault detection, envelope damage, structural analysis and reviews that deal specifically with heritage buildings.
The ten studies selected are listed in Table 1, in order of publication and annotated with their number of citations according to google.scholar. The recent nature of this field of research can already be seen. Indeed, without any date criteria in our searches, the first literature review article on this subject only appeared in 2014. On the other hand, there has been a clear acceleration in this research since 2018 due to the clear material and treatment advances raised by these various articles (Lucchi, 2018).

Table 1. Literature reviews in the field of infrared thermography of buildings

Sources	Name	G.Scholar citation
(Kylili et al., 2014)	Infrared thermography (IRT) applications for building diagnostics: A review	576
(Lucchi, 2018)	Applications of the infrared thermography in the energy audit of buildings: A review	266
(Kirimtat & Krejcar, 2018)	A review of infrared thermography for the investigation of building envelopes: Advances and prospects	124
(Nardi et al., 2018)	Quantification of heat losses through the building envelope: A state-of-the-art analysis with critical and comprehensive review of infrared thermography	149
(Shariq & Hughes, 2020)	Revolutionising building inspection techniques to meet large-scale energy demandes: A review of the state-of-the-art	70
(El Masri & Rakha, 2020)	A scoping review of non-destructive testing (NDT) techniques in building performance diagnostic inspections	98
(Martin et al., 2022)	Infrared thermography in the built environment: A multi-scale review	51
(Ramón et al., 2022)	Thermal point clouds of buildings: A review	21
(Tardy, 2023)	A review of the use of infrared thermography in building envelope thermal property characterisation studies	6
(Kim et al., 2023)	Innovations in building diagnostics and condition monitoring: A comprehensive review of infrared thermography applications	10

In 2014, Kylili et al. published an article on the applications of IRT for building diagnostics. (Kylili et al., 2014). This article discusses the physical foundations and history of IRT. It also gives a broad overview of the many uses of IRT. There are two approaches to building and civil engineering thermography: passive thermography measures the temperature difference of a structure under normal conditions. In contrast, active thermography measures the temperature difference of a structure subjected to an external heat source. The passive approach is mainly qualitative, enabling anomalies such as thermal bridges or the presence of moisture to be located. However, passive quantitative approaches have been developed by controlling the climatic parameters on both sides of the wall. In this way, it is possible to quantify the value of a thermal bridge, calculate the U-value of a wall with a deviation of the order of 10 to 20%, or even cross-reference thermal and photogrammetric data to estimate the energy performance of an entire façade. The infrared active pulsed and active lock-in thermography are mainly used to detect construction defects in materials and very little for an overall analysis of the envelope due to the greater complexity of the installation. A paragraph is also devoted to infrared image analysis, highlighting the importance of considering the reflection of different materials.
Lucchi offers a comprehensive review based on 148 publications on the use of IRTs in building energy audits. Passive and active approaches are again distinguished. The passive approach remains the typical approach for energy audits. This approach is itself subdivided according to the method used to obtain it: "aerial, automated fly-past, street pass-by (or drive-in), perimeter walk around, walkthrough, repeat, time-lapse, and mock target" (Lucchi, 2018). These approaches progress from the fastest and

most inaccurate (aerial shots) to the most precise and time-consuming (time-lapse, mock target). The drive-in approach already appears to be an interesting compromise for studying the built stock on a large scale. Finally, the article concludes that qualitative approaches are already widely covered in the literature. By contrast, quantitative applications, such as insulation level detection and U-value measurements, require more research.

Based on the previous article, Nardi et al. (Nardi et al., 2018) published an article the same year focusing more specifically on the problem of determining U-value. An easy, quick and inexpensive method of determining the U-value is an important issue in building energy improvement strategies. Five methods can be used to determine the U-value of a wall: analogies with coeval buildings, calculation method, heat-flow meter measurements, laboratory testing and IRT measurements. IRT measurements to determine the U-value are the subject of 34 articles, classified according to whether they concern the façade, roof, glazing or thermal bridges. The study of façades is the most studied subject, while the study of glazing and roofs presents specific difficulties, such as reflection. The study concludes once again that this technique is effective and profitable on a large scale. However, it is necessary to use good quality instruments, and to ensure that the climatic conditions for the survey are maintained.

In parallel Kirimtat and Krejcar (Kirimtat & Krejcar, 2018) publish their own literature review on the field of infrared thermography in building envelope research. Sixty-two studies published between 1998 and 2017 are classified according to criteria similar to those already mentioned: the measurement method (quantitative or qualitative), the analysis scheme (active or passive), the type of analysis (thermal bridge, U-value, moisture, air leakage, heat loss, other problems), the component analyzed (exterior wall,, interior wall, floor, roof, ceiling, window, sample, junctions), the surface material, testing locations (in-situ and/or laboratory) and the type of study (experimental and/or numerical). The article's conclusions include the growing number of studies in the field. The IRT is a robust tool that can be used in many ways. They are particularly well suited to the study of buildings prior to renovation, provided that the data obtained is properly processed. Passive in-situ studies provide rapid and cost-effective results.

Shariq and Hughes (Shariq & Hughes, 2020) are interested in the detailed examination of large-scale building inspections and, in particular, study the feasibility of combining the latest hardware advances in terms of IRT, photogrammetry and drones. They highlight the potential for combining these different techniques, accentuated by rapid advances in Artificial Intelligence (AI) for combining and analyzing the results obtained. A simultaneous survey using monocular photogrammetry and IRT using a drone would enable 3D mapping to be produced quickly and efficiently. Lidar, on the other hand, is highly suitable for in-depth analysis of a façade but requires too much time to carry out this work on a large scale.

El Masri and Rakha (El Masri & Rakha, 2020) propose a literature review of six Non-destructive Techniques (NDT) for building performance inspections: Ground Penetrating Radar (GPR), Light Detection and Ranging (LiDaR), IRT, Ultrasound, Close range photogrammetry and Through Wall Imaging Radar (TWIR). No single NDT technique fulfills all the categories defined for a building energy audit as defined by the ASHRAE 211P standard. Among the various possible combinations of NDT, IRT and GPR offer interesting prospects. The article highlights the importance of rationalizing the combination of these tools, using hybrid hardware or software to process the results. In any case, these mixed, large-scale databases would be extremely valuable for assessing the validity of building energy policies. Finally, it is emphasized that most of these techniques, except for GPR, can be implemented on a drone to streamline the process further. The ability to automate the process and the possibility of connecting different tools to the drone are thus becoming priority areas for research into large-scale energy renovation of buildings.

In 2022, Martin et al. (Martin et al., 2022) carried out the same literature review of IRT on buildings, looking at the different scales of study through 197 articles. Meta-analysis tools were used to analyze this large body of text. Among the scales of study, they distinguish between the city-scale observed by satellite, the neighborhood scale observed from the air and the building-scale observed by drone or from the ground. Some specific studies have even chosen to combine different scales. Martin et al. in turn, raise the interest of cross-referencing infrared data with other data sources, not only other image sensors but also data from the Internet of Things (IoT), which could be used to produce a digital twin. Another area of exploration is the development of street thermography alongside new thermal image processing mechanisms. The analysis of urban heat flows to understand the Urban Heat Island (UHI) would also benefit from more detailed studies on small scales, as well as comparing estimates of urban heat flows on different scales. Finally, the authors also highlight the potential of infrared imagery used on a large scale to feed Urban Built Energy Models (UBEM) and reduce their uncertainties. These lines of research are all avenues for better analysis of how a city functions and strategies for energy improvements.

The literature review published by Ramón et al. (Ramón et al., 2022) focuses more specifically on Thermal 3D Points Clouds (TPC), with a review of 21 articles. This field of research is still in its infancy. Among the research gaps in this field, Ramon et al. show that most of the work is done outdoors. Surveys are generally carried out in a single pass without considering the temporal dimension that could be used to refine the results and limit uncertainties. The transition from a thermal point cloud to a semantic model and the format of these computer models are other major problems. Finally, the IRTs still need to improve the automatic calibration of temperatures according to exogenous criteria.

Tardy (Tardy, 2023) provides a literature review comparing U-value assessment techniques. ISO 9869-1 (*ISO 9869-1*, 2014) defines thermal resistance using Heat Flux Meters (HFM). ISO 9869-2 (*ISO 9869-2*, 2018) defines the definition of thermal resistance based on IRT but restricts it to steady-state lightweight structures. In the field of IRT, standards still need to be improved and clarified. Most of the research is based on the need to carry out several measurements over time. In theory, in-situ research should be based on resistance-capacitance models rather than resistance-only models, which is not the case for most of the research using IRT. In conclusion, there is still considerable improvement to be made in IRT surveys to offer more accurate results at the same time. With sufficient improvement, it would be possible to achieve results equivalent to those of an HFM in a simpler and less invasive way.

Kim et al. (Kim et al., 2023) reiterate many of the observations already made, such as the existence of passive and active methods or the effectiveness in detecting envelope defects. The emissivity and reflectivity of surface materials are crucial parameters for the accuracy of measurements. In the field of urban auditing and analysis, the use of AI and machine learning could lead to significant progress in terms of accuracy and speed of data processing.

At the end of this qualitative analysis of literature reviews on the IRT as an energy audit tool, several common lessons can be found summarized in Figure 4:

- The first point is the importance attached to the precision of the IRT. As mentioned above, the IRT must follow a rigorous protocol if it is to be usable. In addition, the quality of the equipment and the training of the technicians are just as important in ensuring the quality of the results.
- IRT can already provide a significant amount of information, both on building defects and on the general energy audit of the building.
- IRT must take advantage of its simple and inexpensive nature to increase the number of readings and thus reduce the intrinsic uncertainties.
- IRT must be accompanied by other surveys: weather conditions, photography, photogrammetry, Lidar, etc., which will be analyzed together, not only to limit errors of interpretation but also to identify new information.
- IRT can benefit greatly from advances in image processing, particularly in the field of automatic learning. One of the major challenges is to succeed in automating image processing to be able to take many readings in a short space of time.

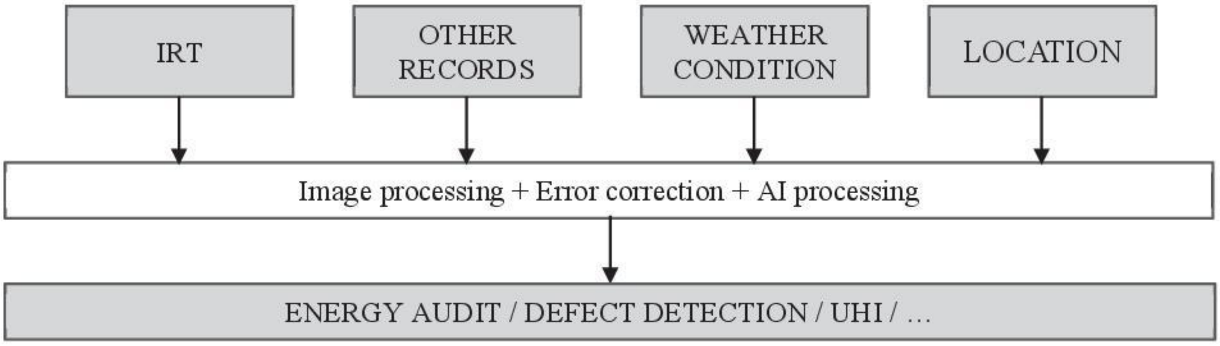

Figure 4. Conceptual summary of the main findings of the literature review on IRT of buildings.

Discussion

In the first part, we looked at how statistical analysis of databases on the built stock and the inhabitants enabled us to estimate the correlations that exist between certain technical data on the building and certain socio-economic data on the occupant. Clustering has enabled us to go even further by proposing building/inhabitant pairs that are representative of the composition of Wallonia's built stock. However, this approach has yet to be validated by field studies and currently remains a macro approach that does not tell us much about the occupancy of a specific building.

In parallel, the second part of this article has identified the strengths of the IRT to understand the specific characteristics of a building better. Not only is it a relatively quick and cheap technique to implement on a large scale. Would it then be possible to imagine that this IRT survey of a building, coupled with a statistical analysis of the building stock in which it is located, could give us relatively reliable hypotheses, not only on the technical composition of the building but also on the socio-economic characteristics of its occupant?

By cross-referencing the thermography results with knowledge of building occupancy, for example, based on energy consumption data, we could further refine the results. In parallel, as we have already shown, the location of the property itself provides us with estimated information on a whole range of parameters that play a key role in the decision to renovate. The IRT could, therefore, become the ultimate tool for refining these estimates and reaching out to a certain number of households that would benefit from support and personalized assistance to improve the energy performance of their homes (Figure 5).

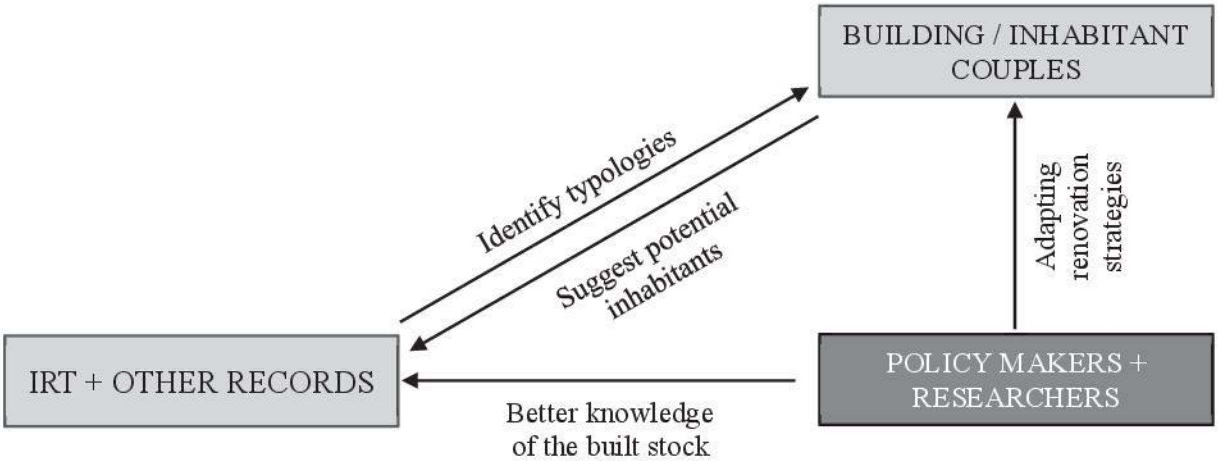

Figure 5. Crossing of IRT and statistical studies to target policies in favor of energy renovation

This cross-referencing of results between a scan of buildings based on an IRT and a statistical analysis of macro databases should make it possible to propose the most appropriate strategies for each building. However, given the many assumptions underlying the relationship between the IRT scan and the statistical analysis, it is advisable to validate it before extending it. We therefore propose to begin by validating these hypotheses through a survey carried out in the buildings subjected to the scan (Figure 6).

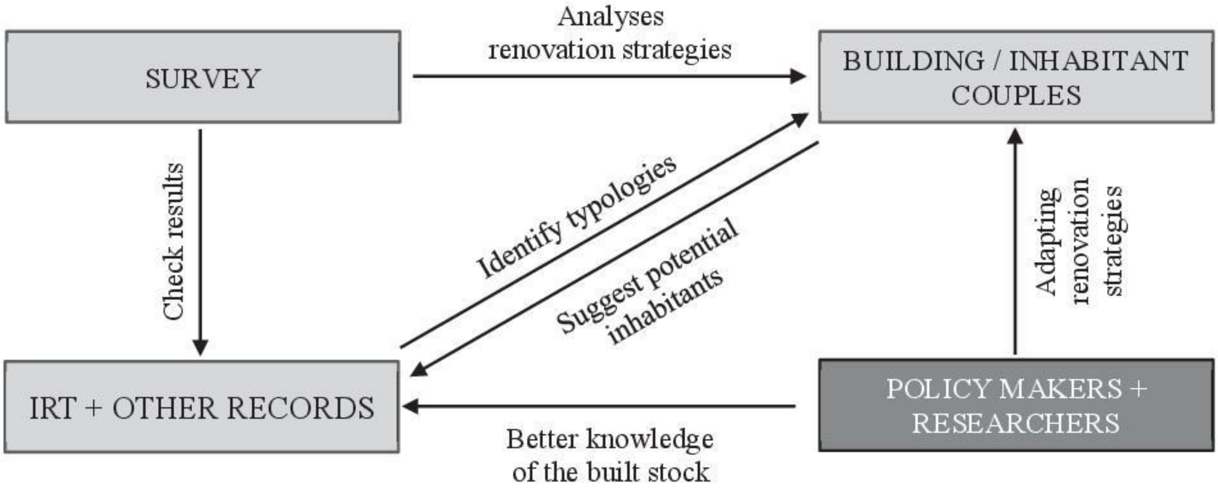

Figure 6. Conceptual framework for a future study linking the couples resulting from clustering to an IRT.

In order to verify all of these results, it is planned to carry out (i) a thermography and photographic survey of a group of buildings from the public space, (ii) an identification of the technical characteristics of the building and the socio-economic characteristics of the occupants based on the elements known and visible from the public space, (iii) and a door-to-door survey in order to compare the data obtained with the reality of the use of the building and to associate them with a set of questions on the possibility of carrying out energy improvement work on the building.

Conclusion

In this article, we first recall the importance of considering both the technical aspects of the building and the socio-economic aspects of the occupant and owner. We then demonstrated the existence of correlations between these different aspects. These correlations make it possible to pool the numerous databases that exist on these aspects. Following this logic, it has previously been possible to establish a mixed model of the built stock for the Walloon region of Belgium. However, this model remains largely theoretical to date. At the same time, a literature review on infrared thermography as a non-destructive energy audit technique gave us an idea of the potential of this technology for improving the energy efficiency of the built stock. While the accuracy of the measurements still needs to be improved, the possibility of combining IRT with other techniques and advances in automated processing are promising.

Ultimately, among the potential areas for future research identified, we believe that the possibility of combining the two techniques mentioned above offers unexplored potential for better-guiding renovation strategies towards effective, efficient approaches. To confirm this intuition, we propose to complement the macro study of the built stock and the IRT survey with a survey that will not only validate the assumed link between these two parts but will also be able to provide more information on the strategies to be adopted.

For researchers in the field of energy efficiency in buildings and for policymakers, this article not only proposes a new way of integrating technical and socio-economic issues. It also proposes a new methodology that still needs to be tested in situ.

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Part II - Chapter 3.4

Journal Paper: Linking Building Conditions and Household Realities for Neighborhood-Scale Residential Energy Renovation

RQ1. *What statistically significant relationships exist between the technical characteristics of dwellings and the socio-economic characteristics of their occupants in the Walloon Region?*
RQ2. *Which representative dwelling–occupant clusters can be identified in the Walloon residential building stock based on integrated technical and socio-economic data?*
RQ4. *To what extent can façade-based infrared thermography complement statistical datasets to improve the characterization of building performance and energy use at the neighborhood scale?*
RQ5. *How do dwelling–occupant clusters contribute to explaining observed renovation behaviors and renovation inertia?*
RQ6. *What differentiated renovation strategies and policy instruments can be derived from dwelling–occupant cluster analysis to effectively increase deep renovation rates?*

This journal paper compares the theoretical results previously obtained in Chapters 3.1 and 3.2 with on-site experiment. Its objective is to consolidate the results previously obtained, but also to use them to produce a set of recommendations that can be utilized by the various stakeholders.

The methodology employed draws heavily on the discussion presented in Chapter 3.3. The journal paper relies on three qualitative tools which results are triangulated: IRT, door-to-door survey, and focus group.

The results highlight the poor energy performance of the built stock. This performance is widely accepted and normalized, particularly among low-income households in a situation of energy poverty. Current energy renovation policies have not succeeded in radically improving this performance. And there appears to be an increase in inequalities based on the level of knowledge on the subject.

Beyond its intrinsic value, this article represents the culmination of a discussion on the Local Case Study initiated in Chapter 3.3. It also complements the thesis's overall analysis of the determinants of energy renovation and the recommendations that can be made to improve the situation.

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Article

Linking Building Conditions and Household Realities for Neighborhood-Scale Residential Energy Renovation

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Abstract

Residential energy renovation remains a central pillar of climate mitigation and social sustainability strategies, yet renovation rates persistently lag behind policy targets, particularly in older urban neighborhoods. This study investigates the underlying causes of renovation inertia using a neighborhood-scale mixed-methods approach that combines door-to-door household surveys, façade infrared thermography, and expert focus groups. Using a post-industrial residential district in Liège, Belgium, as an exploratory case, the study jointly analyzes building conditions, household characteristics, and renovation contexts. The results reveal that renovation failure cannot be explained solely by technical deficiencies. Instead, three interacting socio-technical mechanisms emerge: adaptive occupant behaviors that mask poor building performance, a constrained renovation agency shaped by tenure and income asymmetries, and the stratification of energy awareness along social lines. Together, these mechanisms reinforce a form of renovation lock-in in which technical degradation, behavioral adaptation, and institutional fragmentation mutually sustain inaction. By integrating physical diagnostics with social and experiential data, the study explains why conventional incentive-based renovation policies systematically underperform in comparable urban contexts. Rather than treating energy renovation as a purely technical or economic decision, the findings highlight the need for policy instruments that explicitly address agency constraints, behavioral compensation, and unequal exposure to energy-related risks. The proposed mixed-method framework is transferable to other urban neighborhoods and offers a replicable approach for diagnosing renovation barriers, supporting more socially sustainable energy transition strategies.

Keywords: energy renovation; infrared thermography; energy poverty; neighborhood-scale analysis; socio-technical factors; residential buildings

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1. Introduction

The European Union (EU) [1] has committed to reducing its emissions by 55% in 2030. European countries are expected to achieve net-zero greenhouse gas emissions by 2050. However, 40% of the energy consumed in the EU is used in buildings. The revised EPBD [2] places particular emphasis on implementing an ER plan tailored to each country's building stock, aiming to renovate the 26% worst-performing buildings by 2033. This objective has been transposed in the Stratégie Wallonne de Rénovation à Long Terme (Walloon Long-Term Renovation Strategy) [3]. But despite long-standing announcements, the average and deep ER (>30% energy savings) rate is stagnating at around 1% in Europe [4].

The Walloon region, in particular, shows little sign of an acceleration in ER rates despite its many benefits [5]. This can be explained, among other things [6], by an old building stock (77% constructed before 1981) and a significant proportion of single-family homes (76%) [7]. The wide variety of building types makes it difficult to implement industrialized ER programs such as EnergieSprong in The Netherlands [8]. And while city centers can rely on a more compact building typology, with more apartment buildings and terraced houses, they have a particularly old building stock and a higher concentration of vulnerable populations [9]. These densely populated dwellings must also address specific technical issues, such as interior insulation [10]. The risk of overheating after renovation work is also greater [11].

However, barriers to ER—high initial investment costs, uncertain profitability, administrative difficulties, and lack of knowledge [10–12]—depend as much on the building as on the occupant. This interaction between technical and socio-economic characteristics is central to the definition of an effective strategy. It has been the subject of two studies aimed at clarifying its distribution [9,12].

At the same time, the 2022 energy crisis highlighted the vulnerability of the entire European energy system and of the most vulnerable households. The Energy Poverty (EP) barometer [13] estimates the EP rate in Wallonia at 29.2%. This EP has significant effects on the ability to heat homes, physical health, mental well-being, and social integration of the households concerned [14,15]. It has been proven that effectively combating EP requires major ERs to be brought to their homes [14,16,17]. Socio-economic aspects can therefore be considered both determinants and objectives of ER.

Several studies have already raised the relevance of examining these ER dynamics at the local level [18–20]. A smaller scale allows us to validate and refine conclusions drawn at the regional level regarding the joint distribution of technical and socio-economic characteristics. It paves the way for a more detailed analysis of motivations and obstacles as a function of these characteristics. It enables the proposal of strategies adapted to this urban and social context. It is therefore worth considering using a tool such as IRT to enable a socio-energy diagnosis at the neighborhood level [21]. In this study, infrared thermography (IRT) is not considered as a substitute for detailed energy audits or building-level diagnostics. Rather, it is mobilized as a rapid, non-destructive screening and mediation tool at the neighborhood scale, capable of highlighting relative thermal weaknesses, usage patterns, and socio-technical contrasts between dwellings. When combined with household surveys and qualitative insights, IRT contributes to the prioritization of intervention areas and the support of locally adapted renovation strategies. Despite extensive research on building energy performance and on socio-economic determinants of renovation, few studies explicitly integrate building conditions, household realities, and energy poverty within a single neighborhood-scale analytical framework. Existing approaches often rely on either technical diagnostics or socio-economic surveys, limiting their capacity to inform locally actionable renovation strategies.

Through a specific analysis of an old neighborhood in the city of Liège, we therefore seek to (a) understand the dynamics of ER at work in this neighborhood based on its specific technical and socioeconomic characteristics, (b) understand how these ER dynamics relate to the specific issue of EP, and (c) assess the relevance of the IRT for quickly estimating these technical and socio-economic characteristics.

The corresponding research questions are as follows:

1. What are the technical characteristics of the housing and the socio-economic characteristics of the inhabitants in a former urban suburb in the Walloon region? And what are the links in between?

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2. What are the motivations and obstacles to ER based on these technical and socio-economic characteristics?
3. What are the specific risks associated with EP in this neighborhood, and how can ER strategies address them?
4. How does the IRT contribute to our understanding of ER dynamics?

The results enable us to identify dominant building/occupant profiles that require locally adapted ER strategies. These results also highlight the need to integrate the issue of EP directly into ER strategies, not only as an objective but also as a determinant of these strategies. Finally, the IRT demonstrates its capacity for rapid neighborhood-scale screening while also revealing its technical limitations.

Against this background, this paper addresses a critical gap in current research on renovation and policy practice. While most studies focus either on building performance metrics or on household socioeconomic characteristics in isolation, fewer investigate how technical conditions, lived experiences, and institutional contexts interact at the neighborhood scale to produce persistent renovation inertia. This study adopts a mixed-method diagnostic approach that combines infrared thermography, household surveys, and expert focus groups to examine these interactions in an integrated manner. Rather than aiming for statistical representativeness or predictive modeling, the objective is to identify the socio-technical mechanisms that prevent renovation policies from translating into action in real residential contexts. By doing so, the paper moves beyond a local case description and contributes to a broader understanding of why energy renovation strategies repeatedly underperform in older urban neighborhoods across Europe.

2. State of the Art

Technical characteristics primarily determine the need to renovate a building to improve its energy efficiency. The EPC [2] models these characteristics to estimate energy use under specified technical and behavioral assumptions. More precise energy audits or renovation passports [22] are available to better target interventions. These audits go further in analyzing the building and make specific proposals regarding the work to be undertaken [23] and, at their command, to respect the Trias Energetica and avoid the lock-in effect [24,25]. They are also responsible for adapting energy renovation solutions to the specific technical characteristics of the building in question. Managing the hygrothermal behavior of walls—particularly those insulated from the inside [10,26]-and the installation of suitable ventilation [27] requires special attention. The risk of increased summer overheating must be properly taken into account [11]. While it is possible to limit its effects, the lack of appropriate measures leads to a significant increase in the risk of overheating and the energy requirements for air conditioning [28]. EPC and audits serve as the basis for regulations, communication on sales and rentals, and future performance requirements. They could also be used to determine eligibility for loans or subsidies. They may even offer an estimate [29] on the profitability of the proposed works. They are, therefore, key elements in defining and promoting energy renovation strategies [30]. But actual energy use may differ significantly from estimated use [29,31,32] due to simplifying assumptions about behaviors and technical characteristics that are unknown. These simplifications lead to both overestimating energy use in inefficient buildings and underestimating it in high-performance buildings [33]. This performance gap must be considered to estimate the financial profitability of an energy renovation project accurately [31]. These assessment tools must also go beyond energy use to analyze the entire life cycle [34–36]. A more comprehensive assessment of sustainability is even desirable. [37]. While certification and auditing are useful steps in guiding ER [23,30]. They should be improved [29,31] and cannot be the sole determinants of a strategy for widespread ER.

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> "The Energiesprong business model instead offers an integrated approach based on an energy performance guarantee, industrialised supply chain, simple customer journey and self-sustaining financial model." [8].

Following Energiesprong's business model, several initiatives are being implemented across Europe to promote large-scale, high-performance ER programs [38,39]. The Walloon Region has thus incorporated a massification plan into its ER strategy [40], yet this has not been reflected in an increase in the renovation rate. Pellegrino identifies six major obstacles to this widespread adoption: (i) Regulatory and urban planning constraints that limit projects; (ii) Significant initial costs coupled with uncertainties regarding return on investment; (iii) The multiplicity of actors involved in renovation markets; (iv) The small size of projects and the inertia of large companies; (v) Inadequate performance assessments, no verification of performance after work is completed, no consideration of the life cycle, and little consideration of occupant comfort [39]. Taking these obstacles into account requires identifying the appropriate scale of intervention, which enables pooling of study costs inherent to this type of market, offers solutions optimized for the geophysical characteristics of the territory, and considers the needs and capacities of the households concerned. Several studies have thus highlighted the importance of developing strategies adapted to a more local context, at the city or neighborhood level [9,19,40–44]. While the success of the Energiesprong approach is based on the industrialization of solutions, the approach was designed as a one-stop shop [45] that primarily meets the needs of occupants: "energy performance guarantee, industrialised supply chain, simple customer journey and self-sustaining financial model." [8].

In fact, the decision to renovate depends less on a dwelling's energy efficiency than on the occupant's ability and willingness to undertake the renovation. In Belgium, ER activities depend largely on household age, region, education level, type of ownership, and construction period [46]. The economic aspect—the need for initial funding or the work's uncertain profitability—is the primary barrier to ER [47]. Subsidies should therefore target major energy-efficient renovations rather than minor works [48]. Administrative difficulties and a lack of knowledge among stakeholders also constitute significant barriers. [47,49]. At the same time, thermal [49] and acoustic comfort [47] are recurring motivations for renovation, as important as purely financial gain. The occupants' commitment and support are important. We are already seeing that the people most sensitive to energy issues, who might be interested in ER work, are also, in part, those who already adopt energy-saving behaviors [49,50]. This paradoxical observation underscores that the economic profitability of the works is highly dependent on user behavior and inevitable rebound effects [51]. However, financial gain is not the main driver behind home renovation. Currently, the primary motivations for prospective renovators are: (i) rational use of living area, (ii) quality improvement, (iii) comfort improvement, (iv) higher quality of life [52]. Communication campaigns that focus heavily on energy savings should perhaps draw more inspiration from what residents are looking for. Nevertheless, involving residents early on in ER projects ensures that their needs are taken into account [15], while raising awareness leads to better use of buildings after ER, and limits the rebound effect [53]. ER programs must therefore take these socioeconomic factors into account [49] in addition to the technical characteristics of the built stock.

Taking these socioeconomic factors into account enables us to consider specific yet common situations arising from their diversity. The renovation of condominium buildings, for example, is a well-known issue. Each occupant of the building has their own interests, needs, and financial capabilities [44,47]. The ER of a building does not have the same financial benefit for the occupant of the first floor as it does for the occupant of the top floor. Nor does ER confer the same benefit on an owner-occupier as it does on a landlord [54]. The situation in which the landlord finances major works while the tenant reaps the primary benefits in terms of comfort and lower energy bills is known as a split incentive [55,56]. A future carbon dioxide (CO_2.equiv.) emissions tax (GHG emissions equivalent) could therefore impose an additional burden on tenants [57]. Among tenants, households experiencing EP are overrepresented and therefore more likely to face split incentives [57]. These households generally live in substandard housing but lack the means to finance ER work [58]. This EP has direct impacts: some households significantly reduce ancillary expenses to pay their energy bills, while others significantly reduce heating energy use [15]. These impacts then reverberate throughout society, which bears the costs directly (e.g., energy subsidies) or indirectly (e.g., declines in physical and mental health, social isolation) [59,60]. All these situations must be incorporated into renovation strategies in three ways: (i) adapting regulations to both facilitate the work and enforce energy performance standards for the housing in question; (ii) raising awareness among various stakeholders by developing training courses and information tools focused on energy renovation; (iii) implementing viable financial solutions that correspond to each individual's economic capacity [42,57,61].

Thermography appears here as an interesting tool for specifying the technical characteristics of the building stock and user behavior, while raising awareness of their energy use. Infrared thermography measures the temperature of the target object by analyzing its infrared radiation. When applied to the exterior surfaces of a building, infrared thermography can generally be used to assess the heat loss from these surfaces and identify specific defects (thermal bridges, water infiltration) that cause greater losses [62–67]. This rapid, non-destructive assessment has established itself as the preferred solution for building energy audits. It is a solution attracting growing interest for auditing entire neighborhoods [66,67], particularly through aerial thermography [65,68,69]. The IRT only evaluates the performance of the part of the envelope that is surveyed. However, part of the envelope can be used as a proxy for the overall performance of buildings at the neighborhood level [68]. The results of infrared thermography are even more accurate and informative when combined with other sources, such as photographs, LiDAR, and EPC. [66,70–72]. To process the large volume of data generated, deep neural networks, LVM, and LLMs show promise for improving the speed and quality of IRT data interpretation [62,73,74]. A previous review of the literature allows us to define the advantages and disadvantages of IRT more extensively [21]. Thermography results are also powerful educational and awareness-raising tools for promoting energy savings [75,76]. However, the results remain limited by the definition of thermography, the lack of information on lower floors, and the dissemination of information to the affected populations. To our knowledge, there are no studies on the impact of internal temperature variation on external infrared thermography, even though a building's heat loss is logically dependent on user behavior. This state-of-the-art underscores the interest in large-scale facade thermography as an assessment and awareness-raising tool, even though a better understanding of the impact of user behavior is necessary, and clearer communication with users is required.

Given the reviewed literature, a more detailed examination of energy renovation (ER) dynamics at the neighborhood scale is necessary to better capture the interactions among building conditions, household characteristics, and local implementation constraints. Such an approach enables analysis of socio-technical mechanisms that are insufficiently addressed in studies at broader spatial scales, particularly in relation to rental housing and energy poverty. This study adopts an integrated perspective that combines technical assessment and socio-economic analysis to examine how ER strategies may influence the evolution of the energy performance of the residential building stock. Infrared thermography (IRT) is employed in this approach to assess its capacity to support an initial neighborhood-scale diagnosis when combined with social inquiry. The analysis is applied

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to an old urban neighborhood in the Walloon Region, providing empirical insights of scientific and policy relevance for the design of locally adapted ER strategies in similar urban contexts. These proposals must be adapted to the context in which they are applied. Climatic conditions, construction methods, building types, urban organization, socio-economic characteristics of residents, cultural habits, available budgets, and political dynamics are all factors that influence energy renovation strategies.

3. Methodology

This study uses a convergent mixed-methods design at the neighborhood scale to examine how building envelope conditions and household socio-economic realities interact in the context of residential energy renovation. Three complementary sources of evidence are collected in parallel and then integrated during interpretation: (i) a door-to-door household survey, (ii) façade infrared thermography (IRT), and (iii) a professional focus group. The overall conceptual logic and data flow are summarized in Figure 1. Triangulation is applied to enhance credibility by examining convergence and divergence across methods while giving comparable interpretive weight to each stream [77,78].

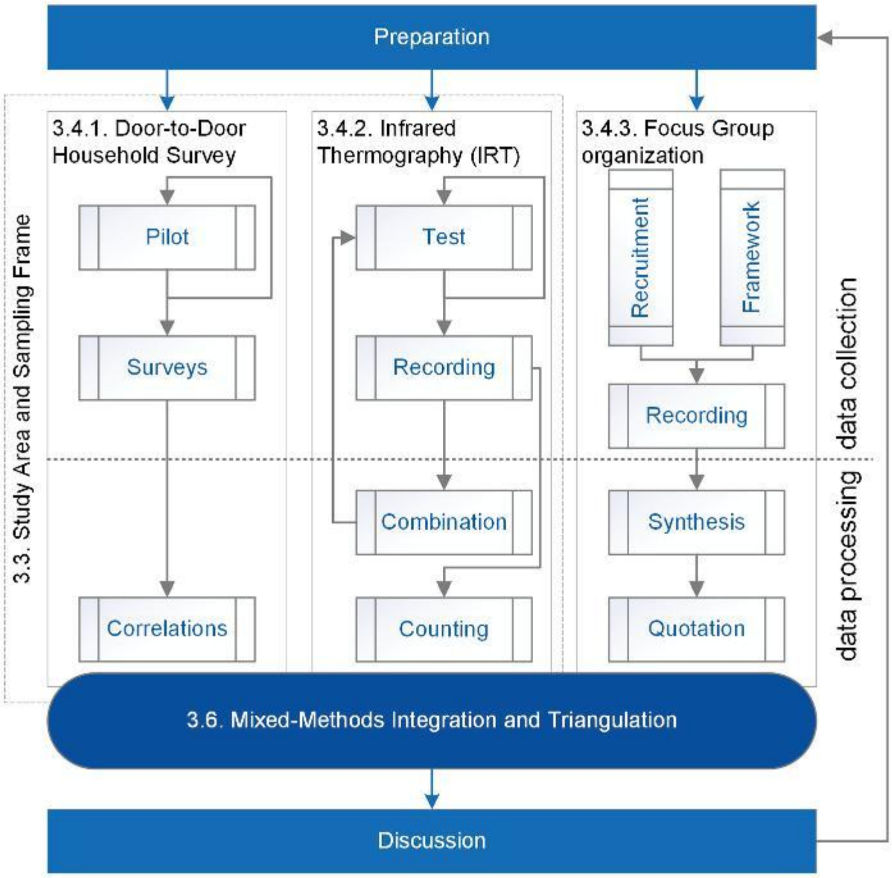

Figure 1. Study Conceptual Framework.

The approach is exploratory and diagnostic, not predictive. Its objective is to identify structural patterns, barriers, and mismatches between the technical performance of residential buildings and the socio-economic realities of households, rather than to estimate energy performance indicators or simulate renovation outcomes. This positioning is consistent with neighborhood-scale studies of energy renovation and energy poverty, in which heterogeneous household conditions interact with relatively homogeneous building stocks.

The overall research design, data flows, and integration logic are summarized in Figure 1, which illustrates how the three methods inform each other during the interpretation phase. All primary quantitative and qualitative data generated in this study are documented and shared through an open mixed-methods dataset hosted on Harvard Dataverse [79].

3.1. Research Design and Conceptual Framework

The methodological framework is structured around the complementarity of three empirical tools that capture different dimensions of residential energy renovation. Household surveys provide self-reported information on socio-economic conditions, dwelling characteristics, energy use, comfort, and renovation status. Infrared thermography of façades offers systematic, instrument-based observations of relative heat-loss patterns at the building level, independent of occupant perception. Focus group discussions with professionals and stakeholders yield contextual and interpretive insights into renovation barriers, energy poverty dynamics, and policy implementation challenges.

Each method has intrinsic strengths and limitations. The survey enables direct linkage between household characteristics and dwelling attributes, but is non-representative and subject to self-reporting bias [80]. IRT provides comprehensive spatial coverage of the neighborhood and allows comparison across buildings, but does not deliver calibrated thermal performance metrics and must be interpreted qualitatively through relative temperature contrasts [21]. Focus groups generate rich, in-depth qualitative information but are limited in generalizability and sensitive to group dynamics [81].

The integration of these three methods compensates for individual weaknesses while strengthening analytical robustness. Equal analytical weight is given to each data stream, in line with triangulation principles [77]. Convergences across methods are interpreted as reinforced findings, while discrepancies are treated as analytically valuable signals that may reveal perception gaps, measurement limitations, or socio-technical tensions. This integration strategy underpins all subsequent analysis and interpretation.

The complete structure of the mixed-methods design, including survey instruments, infrared imagery, focus group transcripts, and synthesized integration outputs, is documented in the associated Harvard Dataverse dataset [79].

3.2. Variables, Indicators, and Operationalization

The analytical framework is built on the explicit operationalization of technical building variables and household socio-economic variables, allowing their joint examination at the dwelling and neighborhood scales. Variables were selected based on their relevance in the literature on residential energy renovation, energy poverty, and building performance, as well as their feasibility for collection through non-intrusive field methods.

3.2.1. Technical Building Variables

Technical characteristics of dwellings are described using six primary indicators:

1. Construction period, expressed as building age in years.
2. Building typology and geometry, distinguishing apartments and single-family dwellings and the number of exposed facades.
3. floor area (m^2).
4. Energy performance certificate (EPC) label, reported on a categorical scale from A to G.
5. Reported annual energy use, expressed either in monetary terms or technical units and subsequently harmonized.
6. Relative façade heat-loss patterns, derived from infrared thermographic imagery and interpreted through surface-temperature contrasts.

IRT indicators do not represent absolute thermal transmittance values but provide qualitative diagnostics of envelope performance, such as wall insulation continuity, window and frame losses, thermal zoning, and signs of non-occupancy. These indicators are used comparatively across buildings rather than as calibrated performance metrics.

3.2.2. Household Socio-Economic Variables

Socio-economic characteristics of households are captured through the survey and include:

1. Net household income category.
2. Tenure status (owner-occupier or tenant).
3. Household composition, including the number and age of occupants.
4. Education level of adult household members.

Additional variables describe energy-related practices and perceptions, such as reported energy expenditure, heating setpoints, ventilation practices, perceived comfort, satisfaction with dwelling performance, and attitudes toward energy renovation and regulatory instruments.

3.2.3. Analytical Intent

The analytical focus is placed on relationships and patterns between technical and socio-economic variables rather than on causal inference or prediction. Correlations and associations are examined to identify recurring configurations of building conditions and household circumstances that may explain differences in renovation behaviors, comfort outcomes, or vulnerability to energy poverty. These relationships form the basis for the subsequent mixed-methods integration and interpretation.

All variable definitions, coding schemes, and anonymized survey responses are provided in the associated open dataset [79], enabling transparency and reuse.

3.3. Study Area and Sampling Frame

The empirical investigation is conducted in the Saint-Léonard district of Liège, Belgium (Figure 2). This neighborhood was selected because it combines a relatively homogeneous residential building stock with a high diversity of socio-economic household profiles, making it suitable for exploratory analysis of the interactions between building conditions and household realities.

The building stock is largely composed of terraced houses and small apartment blocks constructed more than 50 years ago, typically featuring masonry façades, wooden floors and frames, and limited or absent thermal insulation. These characteristics are representative of the former working-class neighborhoods found in many Belgian and North-Western European post-industrial cities [82]. A check in the Walonmap database [83] confirms that no heritage-protected buildings are located within the study area. Two dwellings are listed in the heritage inventory but are not subject to any special protection measures. The residents of these two buildings did not respond to the survey. From a methodological perspective, this relative homogeneity reduces structural variability in envelope performance and allows greater analytical focus on differences related to occupancy, socio-economic status, and renovation trajectories.

At the same time, the Saint-Léonard district exhibits pronounced social heterogeneity, simultaneously housing low-income and energy-vulnerable households alongside higher-income residents attracted by proximity to the city center and housing quality, reflecting early stages of gentrification [84]. This combination makes the area particularly relevant for studying energy renovation and energy poverty in parallel.

The study focuses on a contiguous subset of the neighborhood comprising 288 street-facing buildings. Buildings located within inner courtyards were excluded because their facades were not accessible for infrared thermographic observation from public space.

21 additional buildings were identified in these courtyards using satellite imagery. Three of the 288 buildings are not aligned with the road frontage, which constitutes a major technical constraint, strongly encouraging interior renovation for all the others. Based on doorbell counts, letterbox numbers, and survey observations, these buildings are estimated to contain approximately 522 individual dwellings. For data protection reasons, the precise geographic delineation of the study area is not disclosed.

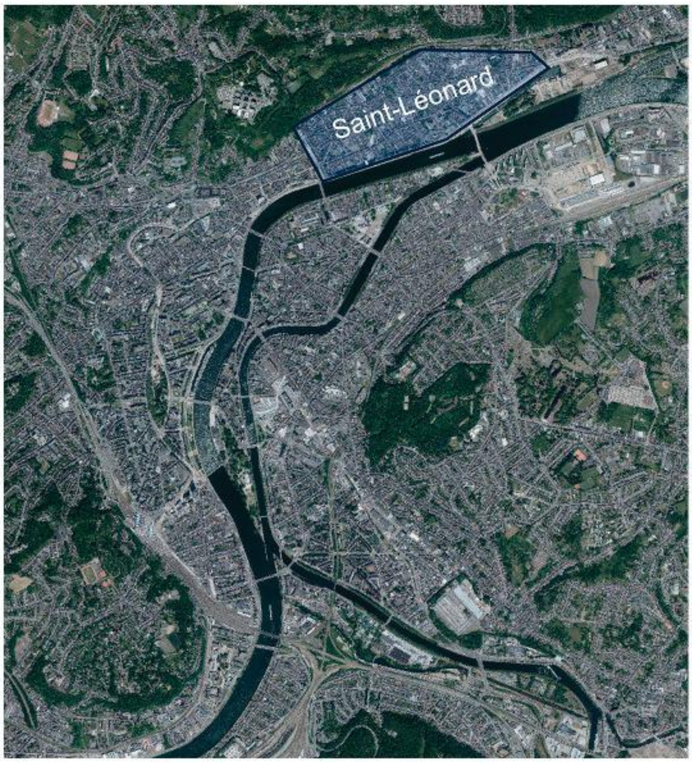

Figure 2. Map of the city of Liège and the location of the case study "https://geoportail.wallonie.be/walonmap (accessed on 12 December 2025)".

The selected area does not aim to be statistically representative of the city of Liège, the Walloon Region, or the Belgian housing stock. Instead, it constitutes a purposeful sampling frame designed for neighborhood-scale diagnostic analysis, where depth of information and methodological triangulation take precedence over representativeness. Institutional collaboration with the City of Liège and academic-stakeholder platforms facilitated access to the field and informed the design of the study's qualitative components.

All spatial descriptors and anonymized contextual information related to the study area are documented in the associated Harvard Dataverse dataset [79].

3.4. Data Collection

3.4.1. Door-to-Door Household Survey

A door-to-door household survey was implemented to collect detailed socio-economic, technical, and behavioral information directly from residents. This approach was selected to ensure access to population groups that are often underrepresented in online or self-selected surveys, including older residents, low-income households, and households with limited digital access [85]. These groups are particularly relevant in the context of energy renovation and energy poverty. Door-to-door surveys also allow the interviewer to explain the meaning of questions if necessary, particularly technical concepts that could be misunderstood, such as the EPC label or the presence of insulation.

The survey instrument was designed based on the research objectives and a review of comparable questionnaires in the literature. It is structured into two main parts. The first part collects descriptive and status information to characterize respondents and their dwellings, including socio-economic profile, household composition, dwelling typology, construction period, floor area, energy systems and reported energy use, setpoint temperatures, EPC label, insulated parts of the envelope and ventilation and air conditioning systems. This section supports comparison between the survey sample and broader population statistics and enables linkage between household characteristics and building attributes. Several questions have a "Don't know" answer option in order to reduce the risk of false positives (people who answer without really knowing the answer), even though this answer also increases the risk of false negatives (people who do not answer even though they know the answer) [86].

The second part is tailored according to tenure status (owner or tenant) and renovation status (renovated or non-renovated dwelling). It focuses on any ER work that has been carried out, perceived thermal comfort, energy affordability, renovation decisions, motivations, barriers, satisfaction with renovation outcomes, and attitudes toward energy performance regulations. Opinion-based questions predominantly use Likert-scale response formats to facilitate response consistency and subsequent analysis [87].

A pilot survey was conducted with 11 volunteer households, who were chosen for the diversity of their profiles, including people with no knowledge and people who had carried out energy renovations with significant knowledge. Respondents were asked about the relevance of the questions (apparent validity), the completeness of the questions (content validity), logical flow, length, and respondent burden (construct validity) [88]. Based on feedback from this phase, questions were reworded, reordered, or removed to reduce ambiguity and limit completion time to approximately 15 min, which is considered optimal for maximizing response rates in face-to-face surveys [89]. The finalized questionnaire is provided in the associated dataset [79].

The main survey was conducted between February and April 2025, concurrently with the infrared thermography campaign. Residents were informed in advance through notices distributed in letterboxes. Surveyors systematically visited all dwellings in the study area, briefly explained the study objectives and data protection measures, and invited residents to participate. Surveys were primarily self-administered, with researchers providing clarification when needed. In cases of language barriers or respondent preference, questions were administered orally by the researcher.

A total of 67 households completed the questionnaire. Paper questionnaires were digitized and checked for completeness and legibility. In line with established methodological recommendations, questionnaires with excessive missing data (more than 5% of unanswered items) were excluded from analysis [90]; no complete questionnaires met this exclusion criterion. Among these respondents, two households responded twice. One person responded twice, while a couple responded separately several days apart. This test–retest allows us to verify the reliability of the survey. The responses are broadly similar, although there is greater variability in the responses on energy consumption ("I don't know" on the first test, specific response on the second) and comfort (in the case of the couple). The motivations on the Likert scale show similar results, with one level of difference.

Reported energy use values were expressed in monetary units (€) or physical units (kWh, m^3, liters, steres) according to the respondents' preference, to improve the response rate. Most questionnaires were completed in €, with only 7 respondents using one or more physical units. None of these 7 respondents benefited from a social energy tariff. As a result, these physical units were harmonized by converting them into monetary equivalents using average regional energy tariffs provided by the Walloon energy regulator (CWaPE). This standardization enabled comparison across households reporting different energy vectors and units. The decision to favor monetary units over physical units in the analysis of the results meets three objectives. (i) As noted, energy consumption was mainly expressed by respondents in euros, as this is the unit they are most familiar with. Some respondents also benefit from a social tariff, which makes it more complex to estimate the quantities of energy consumed. (ii) The objective of the study is to examine renovation dynamics, which we believe are more dependent on energy expenditure than on energy consumption. (iii) The calculation of standardized primary energy, which is the most relevant in terms of environmental impact, requires the integration of a coefficient that leads to a significant loss of meaning in relation to the perception of the public.

All anonymized survey responses, variable coding, and documentation are included in the Harvard Dataverse dataset [79].

3.4.2. Infrared Thermography (IRT)

Façade infrared thermography (IRT) was conducted to obtain systematic, non-intrusive observations of relative heat-loss patterns across the residential buildings in the study area. Unlike indoor monitoring or invasive diagnostics, facade IRT enables neighborhood-scale coverage from public space and supports comparative analysis between buildings and dwelling types.

Thermal images were acquired using a FLIR TG267 (Teledyne FLIR LLC, Wilsonville, OR, USA) infrared camera. This handheld device has significantly lower resolution and thermal sensitivity than higher-quality instruments. That is why a preliminary test survey was carried out in December 2024 on buildings with similar characteristics to assess image quality, operational constraints, and protocol adjustments prior to the main campaign. This test phase highlighted the importance of allowing sufficient camera warm-up time to stabilize automatic calibration and ensure consistency across recordings. The test also highlights the camera's limitations in terms of the accuracy of absolute temperature measurements. The absolute temperatures measured will therefore not be used in the rest of the study, and only relative temperature differences will be examined. The main IRT campaign comprised five recording sessions conducted on 23 January, 5 February, 6 February, 13 February, and 14 February 2025. Sessions were scheduled under meteorological conditions aligned with established IRT guidelines and literature recommendations: outdoor air temperatures below 5 °C, overcast conditions, and absence of direct solar radiation to minimize thermal disturbance of façade surfaces [21,91,92]. For each session, recording times and corresponding dry-bulb temperatures measured at the Bierset meteorological station were documented [93].

Images were captured from the opposite pavement to maximize the field of view and reduce perspective distortion. Obstacles may have interfered with the shooting by obscuring part of the facade. As all facades face the street, these obstacles are mainly vehicles (Figure 3). Cars only obscure the lower part of the facade and do not constitute a significant loss of data, as shown in the qualitative analysis below. Of the 1209 images produced for the IRT of the 522 facades in the case studies, only six images were affected by the presence of a van significantly obscuring the ground floor. Nevertheless, it should be noted that these obstacles pose three problems: (i) they could be much more numerous for other urban typologies, (ii) they constitute a significant loss of data in the case of a more precise analysis of the thermal characteristics of the walls, and (iii) in the event of automated image processing, it will be necessary to integrate these obstacles, in particular vehicles with hot engines. Due to the camera's limited angular coverage, multiple images were taken per facade and subsequently assembled using image-processing software (Gimp 3.0.6-1) to reconstruct complete façade views (Figure 3). These reconstructions facilitate comparative analysis across buildings but are not strictly required for single-building interpretation.

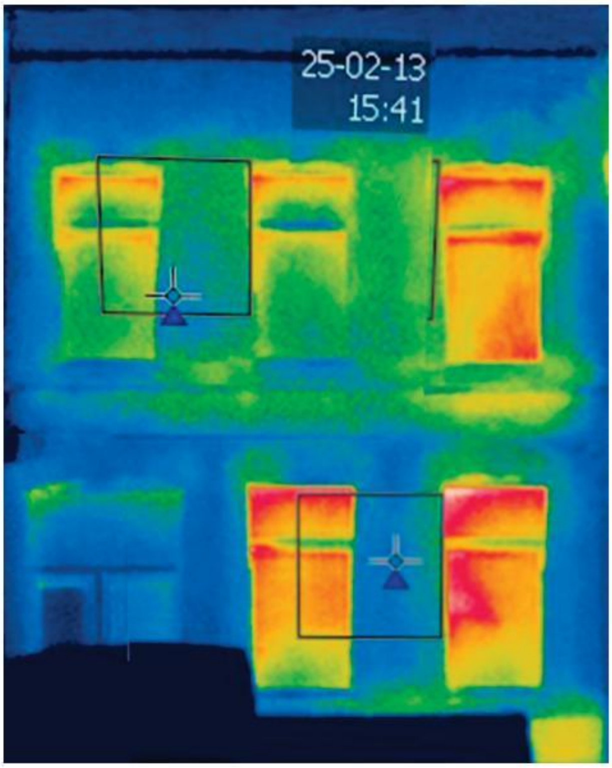

Figure 3. Reconstruction of a thermal photograph of a facade (here with 4 source photos).

Given the camera's resolution-inspection-oriented design and the losses of information related to the shooting method, thermograms were interpreted qualitatively, focusing on relative surface-temperature contrasts rather than absolute temperature values. Observations targeted recurring envelope features, including wall insulation discontinuities, window and frame heat losses, apparent thermal zoning, open windows, and apparent non-occupancy (Figure 4). These indicators were used comparatively across the building sample to identify dominant heat-loss patterns at the neighborhood scale.

All thermal images, acquisition metadata, and qualitative interpretation notes are provided in the associated Harvard Dataverse dataset [79], enabling transparency and reuse.

3.4.3. Focus Group Organization

In parallel with the survey and infrared thermography, a focus group study was conducted to capture qualitative insights from professionals, institutional actors, and civil society stakeholders involved in housing, energy renovation, and energy poverty. This qualitative component was designed to contextualize and interpret the quantitative findings and to explore mechanisms, barriers, and policy-related dynamics that cannot be observed solely from household-level data.

The focus group was organized within the framework of the UNIC CityLabs initiative, which promotes collaboration between academia, public authorities, and societal actors in post-industrial urban contexts [94]. The session's thematic focus was energy poverty and residential energy renovation in the city of Liège. The discussion framework and guiding questions were jointly developed by the research team and UNIC organizers, drawing on established focus group methodologies [95].

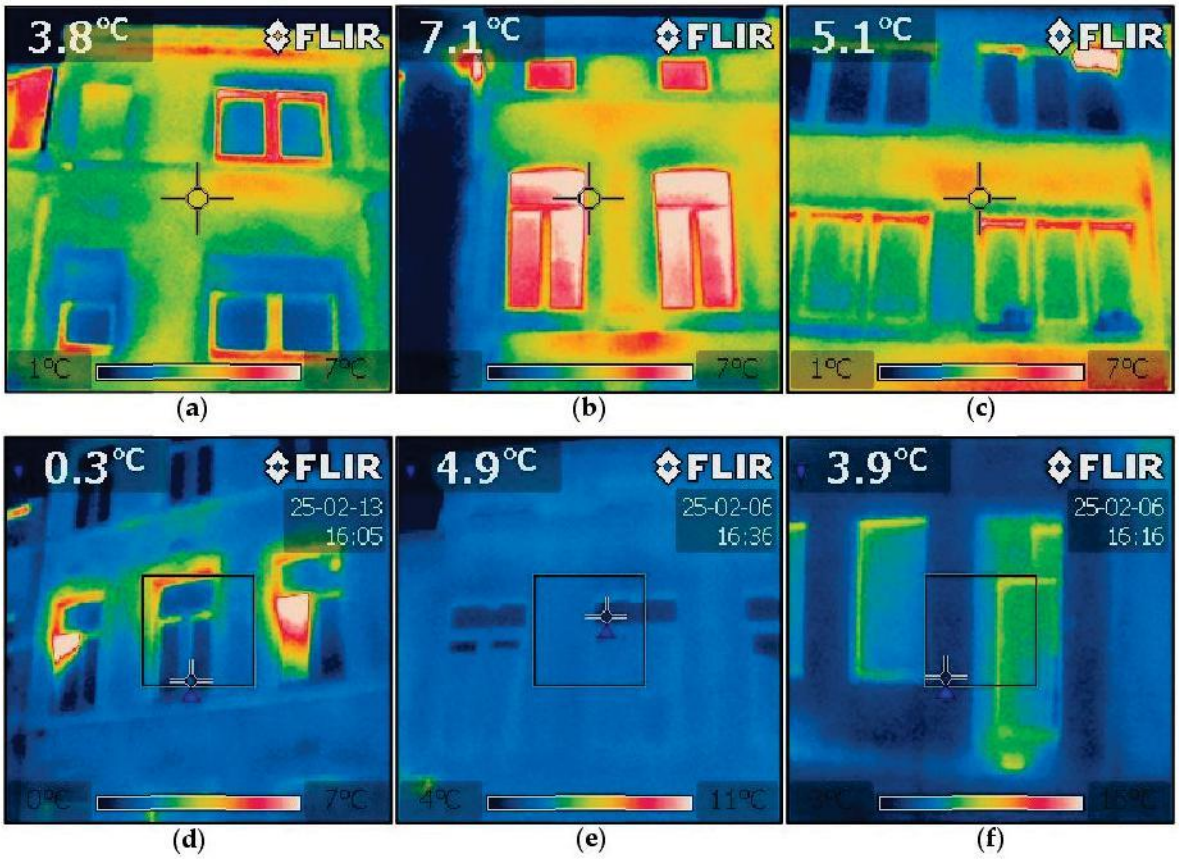

Figure 4. Infrared image of buildings with (**a**) suspected low wall thermal insulation, (**b**) suspected low thermal resistance windows/glass, (**c**) apparent thermal zoning, (**d**) two open windows, (**e**) presumed unoccupation, and (**f**) presumed good insulation.

Participants were recruited through purposive sampling to ensure a diverse range of perspectives and expertise. Invitations were sent to researchers from the University of Liège, representatives and employees of the City of Liège, and professionals and stakeholders from civil society organizations and associations active in the housing and energy domains. In total, 25 participants took part in the focus group exercise, including researchers and academics, municipal staff, and civil society representatives. Participants were distributed across three parallel discussion groups, each comprising approximately eight participants, a size consistent with recommended focus group practices to encourage balanced participation and limit dominance effects [81,96]. The composition of stakeholder categories is illustrated in Figure 5.

The focus group was structured in two discussion rounds. In the first round, participants discussed the determinants, manifestations, and recent evolution of energy poverty in Liège, guided by semi-structured questions introduced by moderators. Following a short break and a presentation of preliminary survey and IRT observations, a second round focused on potential responses, including behavioral strategies, renovation barriers, financing mechanisms, and priority policy measures at the local level.

Each discussion session was moderated by a trained facilitator and documented with dual audio recordings, complemented by handwritten notes from designated rapporteurs. All participants provided informed consent prior to recording. At the end of the sessions, rapporteurs presented preliminary syntheses of the discussions to verify the accuracy of the recorded content and to enable immediate clarification or correction.

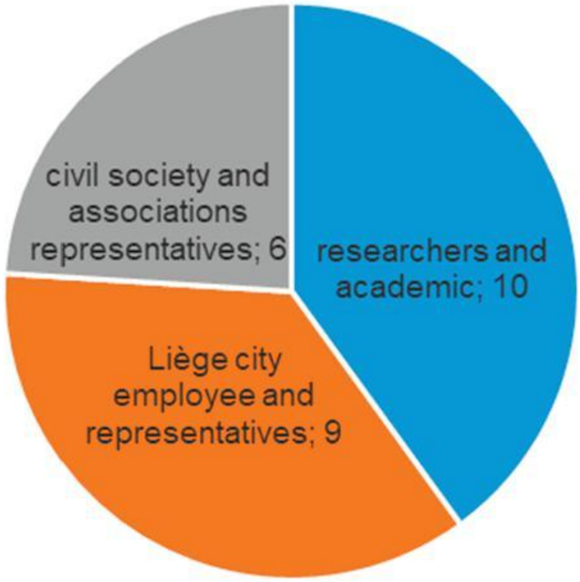

Figure 5. Distribution of the different focus group stakeholders.

Audio recordings were transcribed verbatim, with filler words and repetitions removed to facilitate analysis. Rapporteurs reviewed transcripts for verification. The three group transcripts were then jointly analyzed using a structured thematic extraction aligned with the guiding questions, enabling the identification of recurring themes, points of consensus, and divergent viewpoints across groups. An anonymized synthesis of the focus group findings was produced and shared with participants for feedback.

All anonymized transcripts, thematic syntheses, and supporting documentation are included in the associated Harvard Dataverse dataset [79].

3.5. Data Processing and Analysis

Data processing and analysis were conducted separately for each empirical component prior to mixed-methods integration, following a sequential but complementary logic. This approach ensured methodological rigor within each data stream while preserving the analytical independence required for triangulation.

3.5.1. Survey Representativity, Data Processing and Analysis

Survey responses collected on paper were digitized and encoded into a structured database. Data cleaning involved checking for completeness, internal consistency, and legibility. In accordance with established methodological recommendations, questionnaires with more than 5% missing responses were considered inadmissible and excluded from analysis [90]; no questionnaires met this exclusion criterion.

The study of the distribution of respondent categories in comparison with their actual distribution in the city of Liège (Figure 6) reveals any categories that may be underrepresented. We find that respondents with a higher education degree (a) and a high income (b) are overrepresented. Conversely, people with low levels of education and low incomes are underrepresented, as are older people (c). There are several reasons for these differences. Households with a high level of education are proportionally more open to responding to these surveys. In addition, as we will see in the results, high-income households tend to live in single-family homes, while low-income households tend to live in apartments, which are more difficult to contact due to the barrier represented by the intercom. All types of households are represented (d) despite an underrepresentation of single-person households and single-parent families, which is consistent with previous observations.

Overall, our sample is composed of varied profiles, even if it is not fully representative of households in Liège and Wallonia.

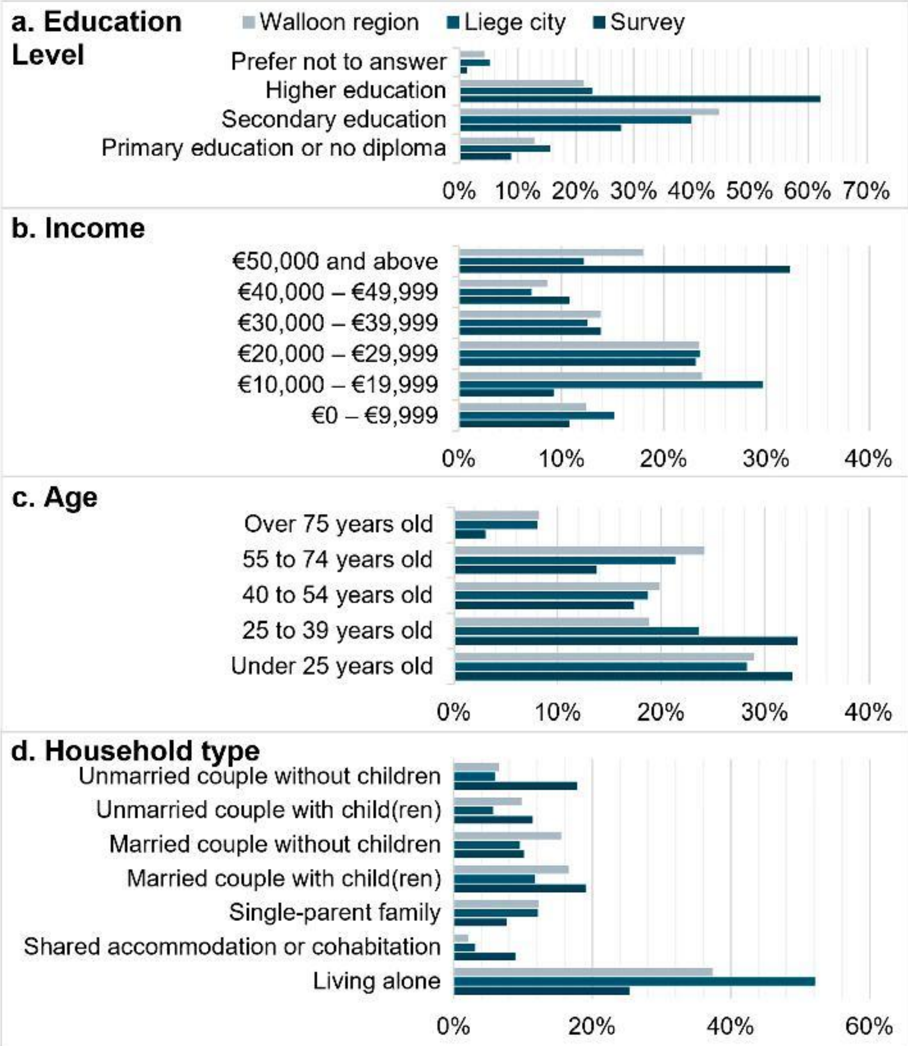

Figure 6. Comparison of the distribution of (**a**) maximum level of education, (**b**) net household income, (**c**) age of household members and (**d**) household type, between survey respondents, residents of the city of Liège and residents of the Walloon Region.

Descriptive statistical analysis was conducted in three stages. First, univariate descriptive analysis was applied to all variables to examine distributions, frequencies, and central tendencies, and to identify potential anomalies [97]. This stage also enabled characterization of the survey sample and comparison with reference population data for the city of Liège and the Walloon Region.

Second, bivariate descriptive analysis was performed using contingency tables to explore associations between technical building variables and socio-economic household variables [98]. This approach is well-suited to mixed data types, including nominal, ordinal, and discrete quantitative variables. Third, for selected contingency tables with notable patterns, Cramér's V was calculated to assess the strength of the association between variables. This statistic is particularly appropriate for small sample sizes and categorical data [99].

3.5.2. Infrared Thermography Analysis

Thermal images were processed and examined using a qualitative diagnostic approach. Individual thermograms and reconstructed façade images were reviewed to identify recurring heat-loss features, including wall insulation discontinuities, window and frame losses, thermal zoning, open windows, and signs of non-occupancy. Interpretation focused on relative temperature contrasts between facades rather than absolute surface temperatures, in line with the equipment's limitations and the neighborhood-scale scope of the study.

Observations were systematically coded into predefined diagnostic categories to support comparisons across buildings. To ensure the robustness of the observations, a single person was responsible for systematic co-coding. Coding was carried out in a single day for the entire batch. Coding was repeated a second time on another day to identify any images that were open to debate and make a final decision on the choices. These codes were then linked to survey variables for dwellings where both survey and IRT data were available, enabling joint interpretation of envelope performance and reported occupancy or usage patterns.

3.5.3. Focus Group Analysis

Focus group transcripts were analyzed using a structured thematic approach aligned with the guiding discussion questions. For each initial question, all three group transcripts were reviewed in parallel to extract relevant statements and themes. Identified elements were then categorized according to their recurrence across groups, their perceived importance within discussions, and their consistency or divergence relative to existing literature.

Attention was paid to statements that explained observed quantitative patterns or highlighted institutional, behavioral, or policy-related barriers not directly observable in survey or IRT data. Selected quotations were retained to support and nuance the interpretation of results in the Section 5.

All processed datasets, coding schemes, and analytical outputs are documented and shared in the Harvard Dataverse repository [79].

3.6. Mixed-Methods Integration and Triangulation

Mixed-methods integration constitutes the core analytical step of the study and is implemented following a convergent triangulation strategy. Quantitative and qualitative findings are first analyzed independently and subsequently brought together during interpretation to examine convergence, complementarity, and divergence across data sources [77].

Integration is carried out in two stages. In the first stage, survey data and IRT observations are jointly examined for all dwellings for which both sources of information are available. Survey responses related to dwelling characteristics, occupancy, heating practices, and perceived comfort are used to contextualize and interpret façade thermograms. This step addresses a key limitation of IRT, namely its dependence on unknown internal conditions and usage patterns, by linking observed heat-loss features to reported household practices and building attributes. Convergences between survey responses and thermographic observations are interpreted as reinforced findings, while discrepancies are examined as potential indicators of reporting bias, measurement constraints, or heterogeneous occupancy conditions.

In the second stage, results from the survey–IRT integration are compared with themes emerging from the focus group discussions. This step enables interpretation of household-level observations considering professional and institutional perspectives on energy renovation, energy poverty, and policy implementation. Focus group insights are used to explain observed patterns, identify structural barriers, and highlight mismatches between household experiences, technical diagnostics, and stakeholder expectations.

Across both stages, contradictions between methods are not treated as methodological failures but as analytically meaningful signals. Such divergences may reveal differences in perception between residents and professionals, limitations of diagnostic tools, or socio-technical tensions inherent to residential energy renovation. The integrated analysis, therefore, explicitly documents both reinforced findings and points of tension, which jointly inform the discussion and conclusions.

The integrated datasets supporting this triangulation process are documented and shared in the Harvard Dataverse repository [79].

3.7. Ethics, Data Protection, and Data Management

This study involves the collection and processing of personal data as defined by the General Data Protection Regulation (GDPR). Ethical and data protection measures were implemented throughout all stages of data collection, analysis, publication, and storage to ensure compliance with legal requirements and institutional guidelines.

All data handling follows the principle of "as open as possible, as closed as necessary", in line with FAIR data principles. Personally identifiable information, including names, exact addresses, and any elements that could enable direct identification of respondents or dwellings, was neither stored in the analytical datasets nor disclosed. For infrared thermographic images, distinctive façade elements that could allow location identification were blurred where necessary. No explicit linkage between façade images and household socio-economic data is disclosed.

Survey participants received written information explaining the study's objectives, the nature of the data collected, the data protection measures, and their rights as participants. Informed consent was obtained explicitly through a mandatory confirmation question at the end of the questionnaire. Focus group participants were informed verbally and in writing about recording procedures and data use, and their consent was obtained prior to audio recording.

Paper questionnaires were securely stored in a restricted-access room at the University of Liège and digitized for analysis. Digital data was stored on secure university servers. All research data will be retained for up to 5 years after publication, after which it will be permanently deleted. In accordance with the University of Liège's data protection procedures, the sensitivity of the data and the mitigation measures implemented did not require formal ethics committee approval.

Anonymized datasets, documentation, and metadata are shared via Harvard Dataverse to support transparency and reuse, while respecting all data protection constraints [79].

3.8. Quality Assurance, Robustness, and Limitations

Multiple complementary quality-assurance mechanisms ensure the study's robustness. The primary safeguard is methodological triangulation, whereby three independent methods addressing similar research questions are applied and integrated [77,100]. Consistent findings across survey responses, IRT observations, and focus group discussions are interpreted as robust results.

In addition to methodological triangulation, researcher triangulation was applied. Different research teams were responsible for the development and execution of the survey, IRT campaign, and focus group, thereby providing complementary perspectives and reducing the influence of individual researchers' bias. Survey instruments were pilot-tested, the IRT protocol was validated through a preliminary campaign, and focus group outputs were verified through member checking and cross-group comparison.

Several limitations must be acknowledged. The study is based on a single neighborhood case study and does not aim for statistical representativeness at the city or regional scale. Results should therefore be interpreted as context-specific and exploratory, rather than generalizable without caution. The survey's non-representative nature limits inferential claims, though this limitation is mitigated by triangulation with systematic IRT coverage and qualitative insights.

Some limitations are more specifically related to the self-reported survey method. Respondents may be influenced by the social desirability of their answers. The accuracy of responses on technical concepts, such as energy labels or wall insulation, may also vary depending on the occupants' knowledge in this area. To limit the effect of these limitations, this article (i) explains these limitations, (ii) describes their impact on the results, and (iii) outlines directions for future research [101]. From a technical perspective, the infrared camera's limited spatial resolution and calibration constraints necessitated qualitative interpretation of thermograms. While this approach is appropriate for neighborhood-scale diagnostics, higher-resolution equipment could improve consistency and reduce analytical uncertainty in future studies. The lack of access to all dwellings located in interior courtyards also constitutes a limitation in the representativeness of the study. Qualitative analysis of defects also involves subjective judgment, which should subsequently be formalized, for example, by quantifying temperature variability on a higher-quality IRT.

Finally, while the focus group provided rich contextual insights, qualitative findings are inherently shaped by participant composition and discussion dynamics.

Despite these limitations, the structured combination of multiple data sources, standardized protocols, pilot testing, and explicit validation procedures ensures that the methodology is reproducible, transparent, and robust within its intended exploratory scope.

4. Results

4.1. Survey

The results presented below enable us to characterize the respondent profile. The most interesting data relating to the research questions will be highlighted.

By socioeconomic status, 55% of single residents live in apartments, whereas 91% of couples live in houses. Homeowners occupy an average of 153 m^3 of living space, while renters occupy an average of 82 m^2. 52% of homeowners live in homes that have undergone ER work, compared to only 17% of tenants. Among owners of renovated homes, 23% of household members are over 55, 24% are between 40 and 54, 22% are between 25 and 39, and 31% are under 24. Among owners of non-renovated homes, 19% of household members are over 55, 17% are between 40 and 54, 37% are between 25 and 39, and 27% are under 24. However, if we focus on ER visits over the last five years, 43% of occupants of these buildings are aged 25–39.

By building type, 44% of respondents' homes were built before 1900, 38% between 1900 and 1945, and 14% between 1946 and 1970. Most respondents, therefore, live in homes built before energy standards were introduced. Most of these homes are terraced houses (57%). The remainder are apartments (24%), often formed by subdividing large terraced or semi-detached houses (14%). The building typology is therefore homogeneous, as desired when selecting the case study, with many buildings classified as traditional workers' and middle-class houses, some of which have been subdivided into apartments.

As shown in Figure 7a, 57% of respondents reported that part of their window frames was insulated (at least double-glazed). This will not be considered ER work in the rest of the study, but rather maintenance work. 54% of respondents report that part of their roof is insulated. Only 27% of respondents reported that part of their walls was insulated, and 16% reported that part of their floors was insulated, which can be explained by the greater technical complexity involved in working on these walls. Finally, it should be noted that 19% of respondents report producing renewable energy, and 16% have mechanical ventilation. Window frames and roofs are the most common types of work carried out but they are not representative of a deep ER. On the other hand, 91% of homes that have insulated their walls have also insulated their roofs, window frames, and made at least one other energy improvement. Gas boilers are installed in 78% of homes (Figure 7b), compared to 10% for oil boilers and 6% for gas or oil stoves. Wood stoves (20%), electric radiators (15%) and heat pumps (10%) are mainly used as secondary systems coupled with a gas boiler. This reflects both the impact of the area studied being supplied by town gas and the cost of electricity in Belgium. Considering that urban housing must in future be heated by a district heating network or a heat pump, this means that none of the homes visited meet future energy source requirements.

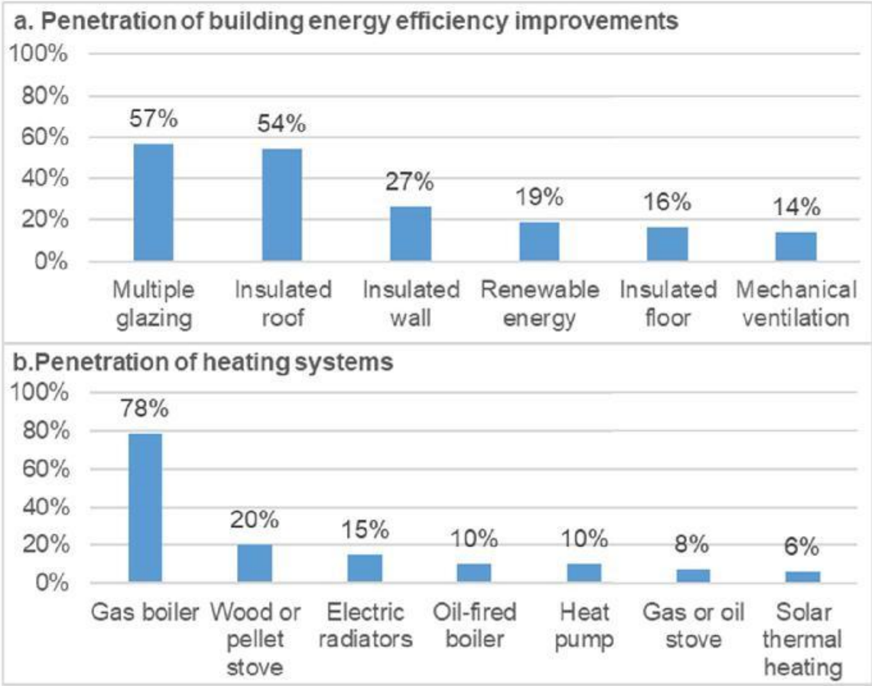

Figure 7. Penetration of (**a**) energy efficiency improvements in buildings and (**b**) heating systems.

65% of tenants are unaware of the energy rating of their homes. However, the energy certificate must be provided at lease signing, and half of the households have lived in the home for two years or less. Only 32% of homeowners are unaware of their home's energy rating, while 22% know that their building has not yet been certified.

Residents report heating their living rooms to an average of 19.1 °C and their bedrooms to 17.2 °C. However, tenants heat their living rooms to an average of 0.8 °C higher than homeowners do, and their bedrooms to 2 °C higher. Part of the explanation offered by some tenants lies in the method of paying for energy as a fixed charge, which does not incentivize energy conservation. There seems to be little correlation between heating temperature and ER work, except that the most energy-efficient buildings (A, B, C) do not drop below 19 °C in the living room.

Several observations can be made on the energy expenditure reported by respondents (Figure 8). The self-reported nature of the data collected may contribute to underestimating or overestimating energy expenditure, even though a large proportion of respondents consulted their energy bills when completing the questionnaire. It is therefore important to focus on general trends rather than outliers. First, an improvement in the energy rating does not necessarily result in a significant reduction in energy use; conversely, the absence of an energy rating can lead to high energy costs. Lack of knowledge about this energy rating has a more moderate effect. Tenants tend to have higher average use than owners. In any case, only 25% of residents are aware of their home's energy performance, which is clearly insufficient to accelerate ER. Residents with a budget meter or a social tariff pay an average of €21.54 per m^2. Owners consume an average of €17.87/m^2, while tenants spend an average of €22.36/m^2. Residents of renovated homes spend an average of €17.90 per m^2, whereas residents of non-renovated homes spend an average of €20.41 per m^2.

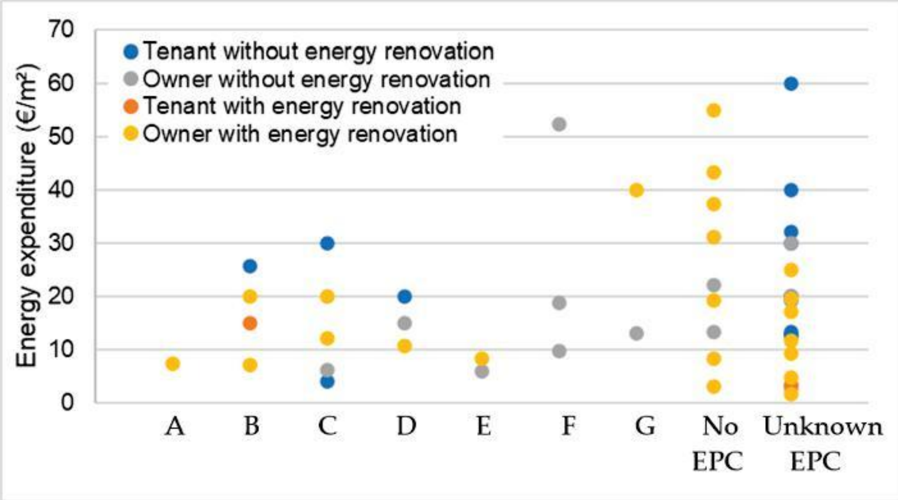

Figure 8. Breakdown of energy expenditure according to EPC label, indicating occupant status and ER work.

Table 1 summarizes the main technical and socioeconomic criteria previously studied [9,12]. All apartments are grouped into a single category. Incomes are classified into two categories: low and medium income (below €39,999 per year) and high income (above €40,000 per year), allowing us to divide our sample into two groups of similar sizes. Three specific categories of resident/building pairs are particularly well represented in our sample: high-income owners of renovated terraced houses (23% of the sample), low-income owners of non-renovated terraced houses (15%), and low-income tenants of apartments (18%). The underrepresentation of detached and semi-detached houses in the case study precludes further conclusions regarding their distribution. Calculating Cramer's V for this contingency table gives: 0.56. The literature suggests that this result indicates a strong association between the technical and socioeconomic criteria examined, which reinforces our previous observations.

Table 1. Contingency table cross-tabulation of technical criteria (housing geometry and ER) with socio-economic criteria (occupancy status and income category) among survey respondents.

Tech. Criteria	Socio-Eco. Criteria	Owner		Tenant	
		Low/Med. Income	High Income	Low/Med. Income	High Income
Energy renovated	Detached house	0	1	0	0
	Semi-detached house	1	2	2	0
	Attached house	5	15	1	0
	Apartment	0	0	1	1
Energy non-renovated	Detached house	0	1	0	0
	Semi-detached house	0	2	2	0
	Attached house	10	2	2	3
	Apartment	1	0	12	1

Background color: Well represented categories of resident/building pairs.

When creating the questionnaire, four sections were designed to elicit a more detailed understanding of the motivations and obstacles faced by four profiles: owners of renovated homes, owners of non-renovated homes, tenants of renovated homes, and tenants of non-renovated homes. As there were only a few tenants of renovated homes, we will focus mainly on the other profiles. Figure 9a shows that owners who have not renovated their homes may be motivated by multiple factors. However, the main motivations are financial gain (60% high or very high impact), energy prices (56% high or very high impact), and environmental awareness (52% high or very high impact). When compared to what actually motivated renovating homeowners to renovate (Figure 9b), we see that the primary trigger for ER is often a change related to the home, such as purchasing it (59% high or very high impact), ahead of environmental awareness (52% high or very high impact), and energy prices (44% high or very high impact). Although many levers could, in principle, be mobilized, the purchase of a home is the ideal time to renovate. Conversely, financial criteria remain a primary factor distinguishing those who have renovated from those who have not. Environmental awareness is particularly stable, with or without renovation. While this may reflect the penetration of these issues among the population, this high rate could also be representative of the social desirability of the response.

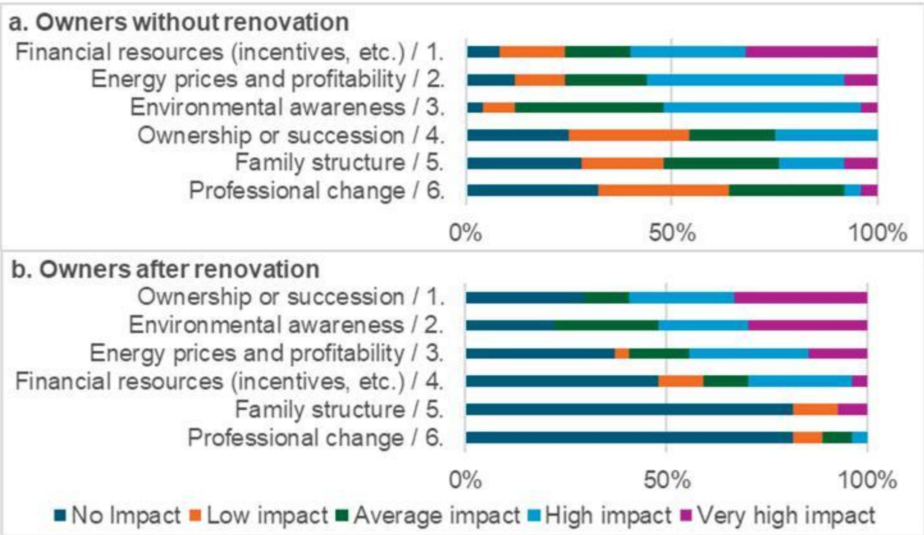

Figure 9. Assessment of the importance of various changes that could (**a**) encourage homeowners to renovate or that have (**b**) encouraged homeowners to renovate from the most important to the least important.

Tenants do not have the same opportunities to undertake ER work. However, it should be noted that although only 17% of tenants took energy performance into account when choosing their current home, 79% consider it a deciding factor when looking for a future rental property. Respondents who will not consider this criterion report that they do not have the option to select housing based on it.

Finally, regarding comfort, owners who have renovated their homes report being satisfied or very satisfied. Conversely, owners who have not renovated report being dissatisfied or very dissatisfied with their winter (48%) and summer (33%) comfort. 43% of tenants living in non-renovated housing report being somewhat dissatisfied or very dissatisfied with their comfort in both winter and summer. ER therefore results in improved comfort in both winter and summer for the time being, although these results will need to be recontextualized in light of the effects of climate change.

4.2. Infrared Measurements

The study of IRT images allows us to make several observations about the technical characteristics of buildings visible from the street and their use. On the one hand, we can compare the number of buildings with presumed poor facade insulation, poor window insulation, thermal zoning, or high vacancy rates with the total number of buildings visible from the street. In addition, we can compare the number of open windows with the presumed number of dwellings that need ventilation. These observations are summarized in Table 2.

Table 2. Main observations from IRT.

Housing (Estimate)	Open Windows	Buildings	Poor Insulation	Poor Windows	Temperature Zoning	Empty
522	73 14%	288	169 59%	81 28%	103 36%	34 12%

Poor insulation in buildings was an expected finding. It is clearly visible in more than half of them, not counting apparently unoccupied buildings whose performance cannot be determined. The rate of 59% of heat loss indicates an underestimation of the problem, given that these are largely terraced buildings facing the street, which can easily improve their compactness by insulating the roof and rear facade, but which are difficult to insulate at the front (esthetics, facade alignment, technical problems with interior insulation). However, this is also why this measure alone is insufficient to assess a building's performance.

Poor window insulation is a better indicator. Replacing windows is among the first energy-efficiency measures to enhance comfort. Observing poorly performing window frames is a strong indication of the likely absence of energy-efficiency improvements in the rest of the building. This is especially true if it coincides with poor wall insulation.

It is also noticeable that a significant number of buildings are visibly thermally zoned. This apparent thermal zoning can be explained by a difference in wall insulation or a difference in indoor setpoint temperature. For thermal zoning to be visible on the IRT, given the camera's low resolution, these differences in composition and/or temperature must be significant.

The number of empty buildings is consistent with findings from other indicators. Although this is not directly relevant to our study, it is an essential element in the public authorities' assessment of the housing policies to be implemented in each neighborhood.

Finally, the most unexpected observation was the number of open windows. While it is recommended to open windows to ventilate homes without mechanical ventilation, this should be limited to a few minutes per day. Thermographic readings were taken at different times of day, thereby reducing the likelihood that windows were opened at a fixed time. Finally, some of these homes have CMV, while it is likely that other residents do not open their windows enough to ventilate. It is therefore likely that this opening rate reflects excessive ventilation in some homes, resulting in energy loss.

4.3. Focus Group

Following a study by three Focus Groups (FG01, 02, 03) on issues relating to EP in the city of Liège and the Walloon region, several lessons were summarized. First, the three groups (FG01, 02, 03) highlighted four factors that exacerbate EP in Liège. (i) The stock of buildings in Liège has some distinctive technical characteristics. It is old, aligned along property lines, with significant heritage issues and a general lack of maintenance. (ii) The population of Liège also has a high concentration of socio-economic disadvantages: households in precarious economic situations, people with disabilities, single-parent families, young people and students, people from immigrant backgrounds, and tenants. (iii) The energy crisis of 2022 has caused hardship for households that are less protected by existing assistance and safeguards, and which, until then, had been able to pay their energy bills.

(iiii) According to participants, energy issues in housing require a great deal of knowledge: energy billing, how a home works, and administrative management of renovations and subsidies. The fragmentation of ownership makes it more difficult to pool this knowledge.

Liège is not a homogeneous entity; significant disparities exist among neighborhoods. In general, neighborhoods in valleys are denser and have a higher concentration of households in precarious economic situations, whereas neighborhoods on hillsides are less dense and have a lower concentration of households in precarious economic situations (FG01, 02, 03). However, some participants (FG02) note the success of certain urban renewal projects that have altered the dynamics in certain neighborhoods, thereby triggering a virtuous cycle.

From the perspective of households facing EP, two contrasting behaviors have been highlighted. (i) FG02 and 03 thus tended to focus on households that were cutting back on energy use, either directly on energy use or on other types of use, at the risk of putting themselves in danger. (ii) In addition, other participants in FG01 also highlighted the particularly energy-intensive behavior of certain households in precarious situations, who apparently had no idea how much energy they were consuming. However, all groups agree on the risks of social isolation and health depletion associated with EP.

The three focus groups unanimously agreed that there has been no structural response to these difficulties. After the significant expenditure in 2022, most residents and institutional actors have returned to their pre-crisis behavior. On the contrary, the rules governing ER subsidies have been revised, which has reduced confidence in public authorities (FG03). However, uncertainty remains very high regarding energy prices. Although winters are becoming less cold (FG01), the increase in heat waves is raising concerns among many stakeholders that households in precarious situations are overexposed to heat waves (FG02, 03). As mentioned in the state of the art section, this exposure to overheating affects both certain unrenovated buildings and other buildings that have been renovated without specific attention to summer comfort.

Following this observation, participants expressed their opinions on the various strategies to reduce the number of households in EP. We have grouped these strategies into three areas:

1. The energy crisis of 2022 demonstrated that short-term financial assistance is essential to prevent many households from falling into poverty, but it is unsustainable in the long term for the state's finances. Depending on how this aid is distributed, it can also be used for other purposes (FG01, 02). On the contrary, investing funds in energy-saving measures should prove more profitable or less risky in the long term. The first proposal is to reallocate ER assistance to prioritize comprehensive support for households most in need. This seems preferable to all participants compared with the current scattergun approach, which ultimately benefits households that are better able to invest (FG01, 02, 03). However, other actions were also mentioned, such as implementing ER programs (FG01, 02), working on heating networks to decarbonize and reduce energy prices (FG01, 03) and targeting social housing (FG01). To finance the additional investments, FG02 noted the possibility of redirecting funds and leveraging the future European carbon tax, while emphasizing the long-term profitability of energy-saving measures. FG01 also mentioned two additional difficulties: the lack of skilled labor in the building trades and rising land prices.
2. Some participants noted that awareness campaigns on energy and housing always reach the same audience already invested in these issues (FG01, 03). While it is necessary to continue training, it is also necessary to develop tools to reach new people by drawing on local associations and cultural organizations that enjoy greater trust (FG01, 03) or by refining our understanding of the region (FG01). However, these awareness

campaigns must take care not to stigmatize certain population groups (FG01), but rather to listen to them. We need to develop new housing standards that people want (FG01). This awareness-raising goes hand in hand with simplifying administrative procedures to reduce non-take-up (FG01, 02, 03). Support must continue after the work is completed to provide training on the proper use of the premises and limit the rebound effect (FG02).

3. At the same time, regulations should continue to be developed to identify and encourage certain groups to renovate, such as landlords and co-owners, who are particularly prevalent in large cities such as Liège (FG01, 02, 03), as well as new buyers who find themselves at a turning point in the life of the building (FG02).

5. Discussion

5.1. Triangulation of Survey Data, Infrared Survey Data, and Focus Group Data

The first part of triangulation involves studying buildings for which we have both a survey response questionnaire and infrared imagery of the facade. By organizing these infrared images using the same logic as in Figure 6, we obtain a distribution of images based on the PEB and the respondent's reported energy expenditure (Figure 10). The image heterogeneity is relatively significant. However, we still observe a trend among buildings for which PEB is known, with increasingly homogeneous and cold IRT. However, the energy production criterion appears to be more informative for assessing low energy expenditure, even in a very warm IRT. This observation appears to confirm that renewable energy production is more effective than envelope insulation at reducing energy costs. And that is without even mentioning the installation costs and technical difficulties involved in insulation. Unfortunately, this production of local renewable energy never translates into the priority installation of a carbon-free heating system. This highlights a partial failure of the certification system, which is unable to logically coordinate the various works undertaken.

Furthermore, we note that respondents who benefit from the regulated social tariff on the purchase price of energy seem to have warmer IRT, probably because they live in lower-quality housing. As a result, the social tariff does not translate into financial savings, but rather as essential assistance in avoiding skyrocketing bills. Conversely, households using a budget meter have lower energy costs, which may indicate better budget control, although the sample size is too small to draw definitive conclusions.

Overall, the three methods converge on several common findings. Starting with the chronic inefficiency of Liège's building stock and the total absence of energy transition in these dense, old neighborhoods, which still rely heavily on gas. The observation of thermal zoning is particularly interesting for single-family homes. Whether it is a deliberate reduction in temperature by the occupant or an unoccupied room that does not need to be heated, it illustrates the widespread practice of energy-saving behavior in poorly performing buildings. However, it is important to be aware that this thermal zoning will reduce the cost-effectiveness of the ER work recommended by an energy audit. This is especially true if the occupant pays less attention to their behavior after the work is completed (rebound effect).

However, there has been a slow but steady improvement in ER work. Rather than for financial gain, which remains limited due to relatively low energy prices, the work is being carried out as part of a broader renovation and redevelopment of the property, particularly at the time of purchase. Notably, people with the financial means to do so are increasingly taking this information into account, a pattern that was not necessarily the case before. However, they say they do not need a subsidy to do so. From this perspective, we can see that energy issues are indeed permeating the population, with more than half reporting that

https://doi.org/10.3390/su18031370

they are willing to consider energy-saving measures out of environmental awareness. The current financial incentives are ineffective. They are not the reason for the work that has been done, and they are insufficient to convince new households to undertake renovation, particularly those in precarious situations.

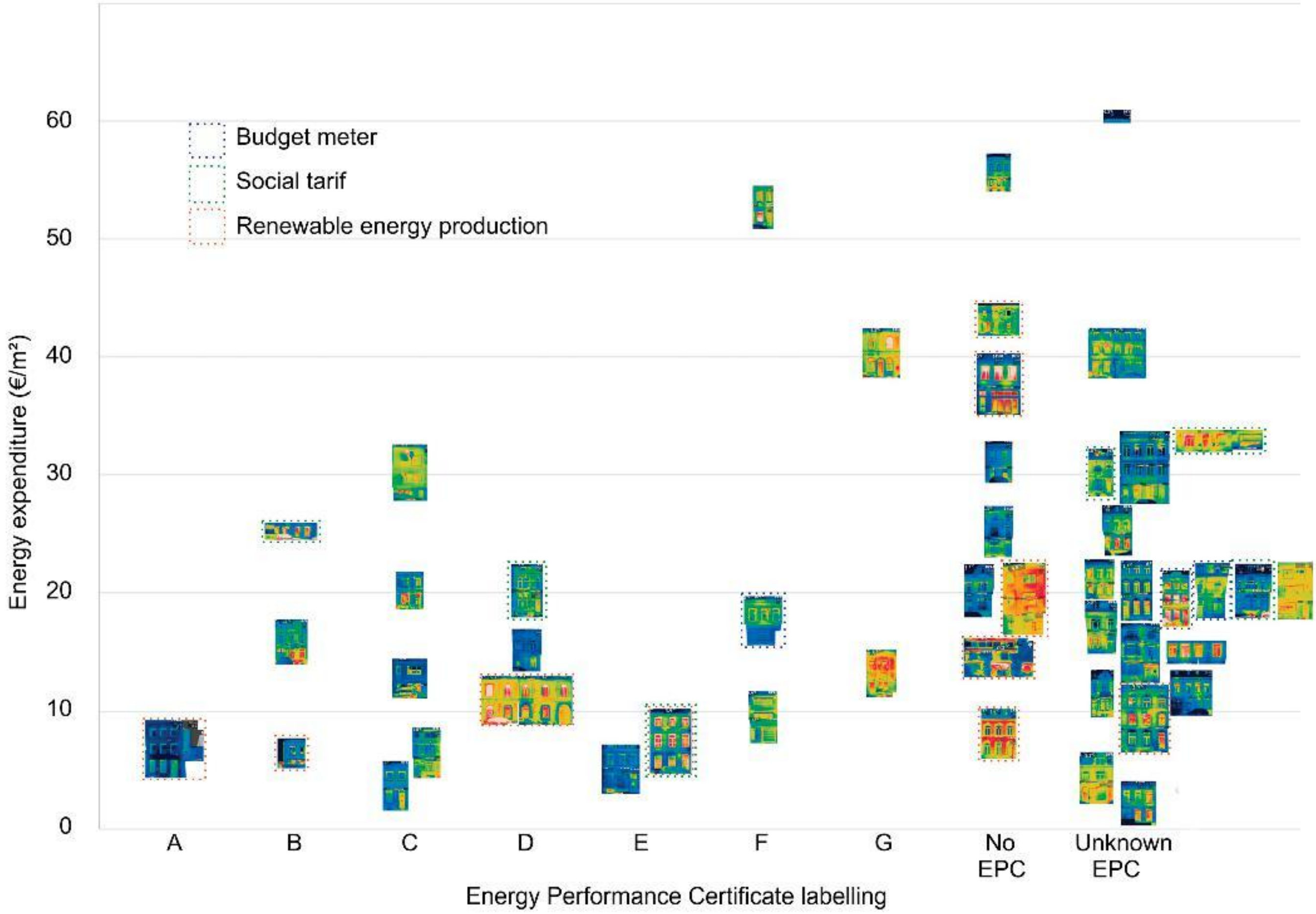

Figure 10. Classification of facades IRT according to their energy expenditure and EPC label, with indication of buildings that produce renewable energy and buildings with special energy prices.

One of the most interesting findings of the study is the marked dichotomy between households that report being sensitive to these issues and attempting to implement energy-saving measures and those that are less concerned. This dichotomy is evident across household income and education levels, as observed in both the survey and the focus group conclusions. IRT also highlights these significant differences. Awareness of energy issues is likely to become a real social marker, but also a factor of exclusion, in the same way as income, level of education, language proficiency, etc.

At the same time, tenants emerge unanimously as big losers, even though they occupy more apartments that are theoretically more compact. They experience poorer-quality buildings, less power to influence them, energy charges that do not encourage energy-saving behavior, and a concentration of risk profiles that can be cumulative (e.g., lower incomes, isolated individuals, single-parent families, people with disabilities, people under guardianship).

From a ventilation perspective, the IRT survey findings were corroborated by the questionnaire and focus group. Indeed, 76% of respondents reported regularly opening their windows to ventilate, thereby ensuring a minimum degree of indoor air renewal. However, this habit often leaves windows open for too long. As shown in the IRT, this opening time results in significant heat loss, which presents an opportunity for energy savings, particularly if the home is equipped with a single-flow mechanical ventilation system.

The limitations of facade IRT do not diminish its value. In a large-scale mapping approach, it could be used to estimate heat loss from the building envelope with greater accuracy than aerial IRT. The facade IRT highlights differences between window frames and walls, as well as between apartments in the same building. This precision also enables raising awareness among all building residents while avoiding the "disappearance" of houses with unheated attics.

5.2. Key Findings and Recommendations

This study identifies three interacting mechanisms, listed in Table 3, that explain why residential energy renovation systematically stalls in energy-inefficient urban neighborhoods, even when technical need is evident.

Table 3. Socio-technical mechanisms stabilizing residential renovation inertia at the neighborhood scale.

Mechanisms	Why Does Residential Energy Renovation Systematically Stall in Energy-Inefficient Urban Neighborhoods?
1. Adaptive Masking Mechanism	Households respond to poor building performance through behavioral adaptation, including under-heating, spatial thermal zoning, intermittent occupancy, and acceptance of discomfort. These practices reduce immediate energy expenditure and partially conceal technical inefficiency, weakening the perceived urgency of renovation. As a result, technical degradation persists while remaining socially normalized.
2. Constrained Renovation Agency Mechanism	Renovation capacity is unevenly distributed across households and structured by tenure, income, and decision-making authority. Households most exposed to inefficiency often lack the authority or resources to undertake renovation, whereas those with sufficient agency face weaker incentives. Renovation inertia thus reflects a misalignment between responsibility, benefit, and control rather than a lack of motivation.
3. Energy Awareness Stratification Mechanism	Energy awareness and access to renovation information function as selective enablers rather than universal drivers. Higher-income and higher-education households are more able to interpret and act on energy-related information, while vulnerable households remain structurally excluded. Awareness-based policies, therefore, risk reinforcing inequalities instead of overcoming renovation barriers.

Together, these mechanisms produce a socio-technical lock-in in which technical degradation, behavioral adaptation, tenure asymmetry, and institutional fragmentation reinforce non-renovation as the least risky and most stable outcome. These lock-ins can be locally reinforced by the conflicting interests that guide local governments, architects, and historical heritage managers in their own vision of territorial development. These interests can hinder or even negate social and ecological priorities. Breaking this lock-in requires interventions that redistribute agency and coordinate action at the neighborhood scale, rather than relying solely on individual awareness or voluntary uptake.

5.3. Strengths and Limitations

The primary strength of this study lies in its integrated neighborhood-scale triangulation, which enables identification of mechanisms that remain invisible in single-method approaches. Survey data alone would underestimate technical inefficiency due to adaptive masking, while IRT alone would ignore the social constraints shaping renovation behavior. Focus group insights further reveal how institutional logic interacts with household-level realities. The convergence of these perspectives strengthens the credibility of the findings, while divergences are analytically productive rather than problematic.

A second strength is the deliberate focus on a homogeneous building stock with heterogeneous households, which allows socio-economic mechanisms to emerge clearly. This design choice allows attributing differences in renovation to agency, tenure, and institutional context rather than to building typology.

Several limitations must nonetheless be acknowledged. The study is exploratory and non-representative, and its findings cannot be statistically generalized. Surveys rely on residents' statements and may suffer from potential biases, such as social desirability and lack of knowledge. IRT suffers from low resolution and imperfect representativeness. It is interpreted qualitatively and does not provide calibrated performance metrics. However, these limitations are consistent with the study's diagnostic objective. The methodology is not intended to predict energy savings, but to explain why renovation does or does not occur under real-world conditions.

Importantly, these limitations do not weaken the core contribution: the identification of structural mechanisms that stabilize renovation inertia at the neighborhood scale. Nevertheless, improvements in these various areas would individually contribute to strengthening the overall quality of the results.

5.4. Implications on Practice and Research

The findings explain why many energy renovation policies systematically underperform. Policies centered on information provision, voluntary uptake, or individual financial incentives implicitly assume that households possess the agency to act once informed. The evidence contradicts this assumption. When renovation capacity is constrained by tenure, income, or institutional complexity, such instruments primarily benefit already advantaged households, leaving structurally vulnerable households behind.

Effective practice, therefore, requires shifting from individualized renovation logic to collective and tenure-sensitive strategies. Neighborhood-scale interventions, landlord-targeted obligations, coordinated renovation programs, and trusted local intermediaries are more likely to disrupt the identified lock-in mechanisms than are additional awareness campaigns or marginal increases in subsidies. Renovation techniques could be adapted to the specific characteristics of each building rather than being constrained by performance requirements for each element, which can prove counterproductive. An integrated approach is essential to transform opportunistic interventions into real environmental gains, such as local PV panels powering heat pumps.

For research, this study demonstrates the value of framing residential energy renovation as a socio-technical transition problem rather than a purely technical optimization challenge. Future work should replicate this approach across contrasting neighborhoods, explore longitudinal dynamics of adaptation and lock-in, and examine which institutional arrangements successfully reallocate agency. Comparing the results obtained with other methods, such as physical measurement campaigns and administrative records, would also help to strengthen the conclusions. Methodologically, the study supports further development of mixed-method diagnostic frameworks that prioritize explanation over prediction and equity over average performance gains.

In sum, residential energy renovation stalls not because solutions are unknown, but because existing systems reproduce non-renovation as a stable outcome. Understanding and dismantling this stability is the central challenge for both research and policy.

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6. Conclusions

This study demonstrates that the persistent low uptake of residential energy renovation in older urban neighborhoods cannot be explained solely by technical deficiencies. Instead, renovation inertia emerges from a set of interacting socio-technical mechanisms that stabilize non-renovation as the most feasible outcome for many households.

At the building level, infrared thermography confirms widespread envelope inefficiencies across the neighborhood. Yet these deficiencies do not systematically trigger renovation. Survey and qualitative evidence show that households frequently rely on adaptive strategies, such as under-heating, spatial thermal zoning, or acceptance of reduced comfort, to cope with poor performance. These practices temporarily reduce energy expenditure while simultaneously masking technical inefficiencies, thereby reducing the perceived urgency of renovation.

Crucially, renovation capacity is unevenly distributed. Households most exposed to energy inefficiency and energy poverty are often tenants or low-income occupants who lack decision-making power, financial leverage, or long-term security. In contrast, households with sufficient agency to renovate are less exposed to energy stress. This misalignment between need, control, and benefit explains why policies centered on voluntary uptake, information provision, or generic financial incentives systematically underperform.

Methodologically, the study shows the added value of neighborhood-scale mixed-methods triangulation. Combining façade infrared thermography, household surveys, and stakeholder focus groups enables the identification of mechanisms that remain invisible in single-method approaches. Importantly, discrepancies between methods are not treated as noise but as signals revealing gaps between measured conditions, lived experience, and policy assumptions.

Beyond the Liège case, the findings highlight a broader challenge for residential energy transitions in post-industrial urban contexts. Effective renovation strategies must move beyond individual choice models and address structural constraints related to tenure, agency, and institutional fragmentation. Neighborhood-based, tenure-sensitive, and coordinated interventions are more likely to break renovation lock-in than incremental adjustments to existing incentive schemes.

Aligning building conditions with household realities is therefore not an implementation detail but a central requirement for equitable and effective residential energy renovation.

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Abbreviations

The following abbreviations are used in this manuscript:

CWaPE	Commission Wallonne Pour l'Énergie
EPC	Energy Performance Certificate
ER	Energy Renovation
EU	European Union
GDPR	General Data Protection Regulation
IRT	InfraRed Thermography
LLM	Large Language Models
LVM	Large Visual Models
PV	PhotoVoltaic
SCEPA	Scaling-Up Energy Poverty-Actions

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4. Discussion

This thesis demonstrates that energy renovation dynamics in the Walloon residential building stock cannot be explained by technical factors alone. The results show that renovation outcomes emerge from the interaction between building characteristics, socio-economic conditions, and behavioral mechanisms. By combining statistical analysis, clustering, and field observations, this work provides an integrated understanding of renovation inertia and identifies leverage points for accelerating deep renovation.

4.1. Revisiting research sub-questions

RQ1. *What statistically significant relationships exist between the technical characteristics of dwellings and the socio-economic characteristics of their occupants in the Walloon Region?* **(Chapters 3.1 and 3.4)**

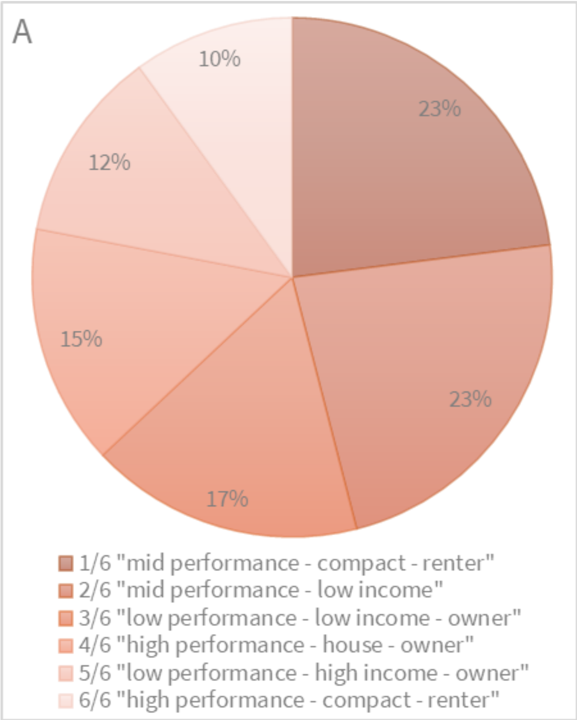
The Spearman correlations calculated between technical data on housing (energy performance certificate and geometry) and socio-economic data on residents (income and ownership) provide a better understanding of the dynamics underlying the improvement in the energy efficiency of housing.

- In line with the literature review, apartments are more efficient, while three-sided houses are less efficient. This can be explained by the compactness of the distinct types of housing and the specific difficulties of three-sided houses.
- Contrary to what the literature review on the tenant/landlord dilemma suggests, a 1% increase in the ownership rate is accompanied by a 2.35 kWh/m^2.year decrease in energy efficiency. This could be explained by the greater compactness of rented properties (more apartments) and by the more recent construction of these properties, implying compliance with minimum energy efficiency standards.
- Less affluent households also occupy less efficient housing. However, this correlation is not linear and is not significant for middle and high incomes.

Cramer's V calculation for a contingency table combining technical characteristics of the dwelling (geometry and energy renovation) and socio-economic characteristics of the occupant (income level and ownership) gives a result of 0.56. Considering literature, such a result confirms a strong association between the technical and socio-economic criteria studied in this sample.

RQ2. *Which representative dwelling–occupant clusters can be identified in the Walloon residential building stock based on integrated technical and socio-economic data?* **(Chapter 3.2 and 3.4)**

The set of six clusters is primarily characterized by the thermal performance of the dwellings, income, and title to property. These characteristics are therefore the most relevant factors for analyzing the housing stock. The ten-cluster analysis further integrates housing geometry in addition to the characteristics mentioned above.



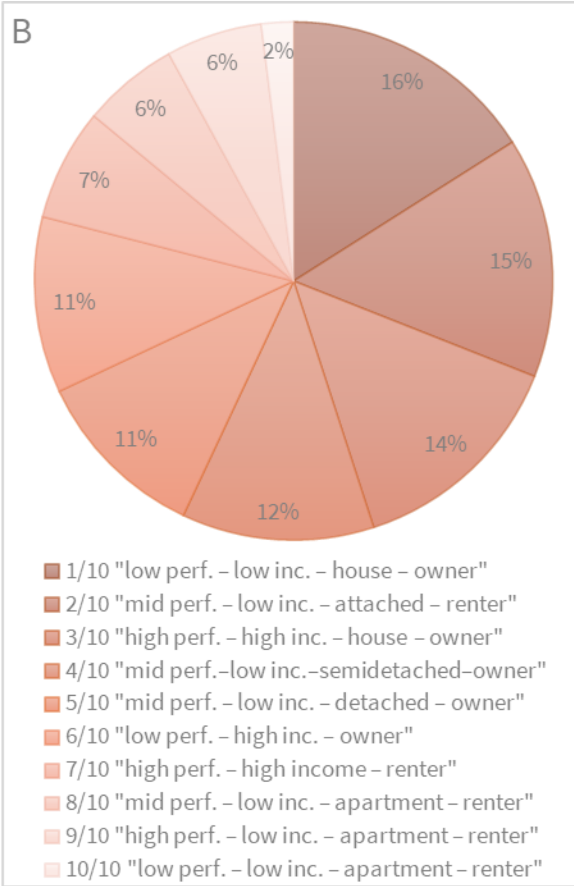


Figure 4-1 Distribution and specific characteristics of the (A) six and (B) ten housing/occupant clusters identified in the Walloon Region

Whether clustering into six or ten clusters, there are always two clusters that are particularly interesting to target to improve the energy efficiency of the building stock (Figure 4-1):

1. **"Low performance – Low income – owner"** (3/6 and 1/10). This cluster accounts for 17% and 16% of all clusters, respectively. This cluster could also correspond to households in fuel poverty.
2. **"Low performance – high income – owner"** (5/6 and 6/10). This cluster accounts for 12% and 11% of all clusters, respectively. The obstacles to energy renovation in this cluster may be multiple, going beyond the strict financial framework.

Apart from cluster 10/10, which accounts for 2% of clusters, the two clusters mentioned above clearly include a large majority of low energy performance homes. These clusters require the implementation of diametrically opposed strategies. The heterogeneous distribution of these two clusters across Wallonia is discussed in more detail in the response to RQ3. It should also be noted that the least efficient clusters are also predominantly owner-occupied.

The case study in Chapter 3.4 is not representative of the entire Walloon building stock, particularly because this case study consists almost exclusively of terraced houses and apartments. Therefore, some clusters in Chapter 02 are logically almost absent from Chapter 3.4. However, the survey results reveal three main clusters that overlap with the observations in Chapter 3.2:

"High performance – High income – house – owner" These individuals could be included in clusters 4/6 and 3/10.

“Low performance – Low income – house – owner” These individuals could be included in clusters 3/6 and 1/10.
“Low performance – Low income – apartment – renter” These individuals could be included in clusters 1/6 and 8/10 or 10/10.

Chapter 3.4 thus confirms the relevance of analyzing energy renovation dynamics through the lens of housing technical data and resident socioeconomic data, as proposed by the clustering in Chapter 3.2.

RQ3. *What are the patterns of geographical distribution of these characteristics across Wallonia?* **(Chapters 3.1 and 3.2)**

The results highlight the heterogeneity of the distribution of the technical characteristics of the housing stock and the socio-economic characteristics of the inhabitants across Wallonia. This heterogeneity can be interpreted through (1) the industrialization of the region, (2) its suburbanization, and then its gradual deindustrialization in favor of (3) new centers of activity. The results identify four types of housing that are widely represented in the WR:

1. Formerly urbanized cities had many low-energy-efficiency terraced houses occupied by low-income households. These dwellings seem to correspond to the old workers' houses that are widely represented in the Sambre and Meuse valley.
2. Small towns and villages have many detached houses occupied by high-income owners. This type seems to correspond to the development of numerous housing estates on the outskirts, increasingly distant from the major urban centers.
3. Large cities have a higher concentration of apartments, which are more compact and/or newer, and therefore more efficient. This concentration reflects both the higher density of large cities and the densification dynamics still at work today around the region's economic centers.
4. Dynamic towns on the outskirts of Brussels and Luxembourg. These towns are characterized by a recent and more efficient building stock, including a significant proportion of apartments, occupied by a population with higher incomes.

However, this analysis can be supplemented by additional observations.

- The city of Liège has an extremely specific composition. This is probably due to its historical and industrial heritage, but also to its size and economy, as well as the presence of the university. This is reflected in the high number of apartments and tenants.
- The city of Ottignies-Louvain-la-Neuve is another unique agglomeration in the WR, due to the relocation of the University of Louvain, which contributed to the creation of a new city from scratch in the 1960s. As a result, the proportion of apartments is remarkably high, and the considerable number of students has a significant impact on household taxable income.
- Several towns are characterized by a remarkably high density of the two priority clusters identified in RQ2: the low energy performance cluster occupied by low-income owner-occupied households and the low energy performance cluster occupied by high-income owner-occupied households. These municipalities, scattered across the WR, seem to be

isolated from both past industrial dynamics and current peri-urbanization. However, the chronic inefficiency of their building stock should be put into perspective in view of their low density.

All these observations highlight the need for an ER strategy that considers the heterogeneity of this distribution to better target the actions to be implemented. These observations specific to the WR could be transposed to other territories, for which renovation strategies must be adapted to their specific characteristics.

While we know that recent buildings—and apartments in particular—are overrepresented in EPC certificates, we can correct for this overrepresentation to derive a weighted average efficiency for the building stock (409 kWh/m².y), which is logically lower than the average efficiency of the certificates (386 kWh/m².y). Nevertheless, this correction remains minor given the well-documented inaccuracies in the EPC.

RQ4. *To what extent can façade-based infrared thermography (IRT) complement statistical datasets to improve the characterization of building performance and energy use at the neighborhood scale?* **(Chapter 3.3 et 3.4)**

IRT applied to the building's exterior envelope allows for the analysis of temperature variations in the various visible elements. At a constant outside temperature, IRT depends on the relative thermal performance of the distinct parts of the building and its use by its occupants. This combined importance of technical and usage characteristics led us to question the use of this technique to better understand the previously identified occupant/building pairs. An analysis of the state of the art highlights the advantages of this technique in assessing the technical characteristics and energy performance of the building stock. IRT can thus provide relevant information on housing performance in the context of an energy audit, especially since the results depend on actual rather than assumed usage. Furthermore, the speed and relatively low cost of taking images make it possible to take multiple images to reduce the uncertainties inherent in the measurement method.

The implementation of an IRT survey of street facades thus makes it possible to better characterize the energy performance of the building stock studied in comparison with the aerial thermography previously used in the sector. Facade thermography has the advantage of allowing the energy losses of distinct levels of a building to be distinguished, which is an undeniable asset for distinguishing between several dwellings, or thermal zoning within a dwelling. Generic occupant behaviors have also been identified (unoccupied spaces, thermal zoning, overventilation). Although it can be difficult to tell the difference between an unheated building and a very well-insulated one, there are clues that help us distinguish between them, such as the presence of slight thermal bridges along the window frames. Although this could not be tested during the case study, IRT could also complement the arsenal of awareness-raising tools by allowing residents to better identify with the more familiar image observed.

However the results reveal the current limitations of IRT. The quality of the results obtained depends largely on the quality of the equipment used and the rigor of the protocol implemented. While IRT succeeds in revealing the most striking behaviors, it fails to reveal more subtle differences. Finally, thermography of street-facing facades is undeniably more interesting than thermography of roofs, but it still only represents a single heat-loss wall of the building envelope and is not representative of the performance of the whole building.

Large-scale IRT readings of facades appear to be promising tools for giving public authorities a better understanding of energy losses in their territories, within reasonable timeframes and at reasonable costs, while providing customized awareness-raising material. Drone thermography could be the synthesis of the best that is technically available, but it raises inevitable safety and legal considerations. Finally, large-scale analysis of the building stock by IRT would greatly benefit from the development of automated analysis tools by Large Visual Models.

RQ5. *How do dwelling–occupant clusters contribute to explaining observed renovation behaviors and renovation inertia?* **(Chapter 3.4)**

"Low performance – Low income – owner" The first obstacle to energy renovation in this cluster is financial, as households have no funds to invest in renovation work. Furthermore, there is a marked dichotomy in this cluster between households that have developed knowledge about energy in buildings and other households that seem much less informed. Only comprehensive support (financial, administrative, technical, educational) seems capable of really encouraging renovation.
"Low performance – High income – homeowner" The primary motivation for renovation is the purchase of the home. If owners have lived in their homes for a long time and are satisfied with the level of comfort, they see little point in putting up with the inconvenience of renovation work.
"Low performance – Low income – apartment – renter" While the issue of rentals tended to be downplayed during clustering, the case study in the city of Liège highlighted the extent to which this population was exposed to energy-related poor housing conditions.
Although the clusters identified above are the first line of renovation, clusters with average performance are also a target for energy renovation. There is even a double challenge for these clusters, which should be renovated by 2030: (i) how to prevent the least efficient homes from falling into this category and switching directly to highly efficient homes, and (ii) how to encourage the renovation of moderately efficient homes, which have probably already carried out the most cost-effective work (roof insulation, boiler replacement, window replacement), at the risk of falling into the lock-in effect?

The results highlight three mechanisms to explain the shift in behavior towards energy efficiency in buildings: adaptive masking mechanisms, constrained renovation agency, and energy awareness stratification.

1. **Adaptive Masking Mechanism.** The parallel use of infrared thermography and surveys highlights that building envelopes remain largely inefficient. However, this inefficiency is partially offset by a set of adaptive behaviors: reducing heating levels and spatial thermal zoning. These behaviors tend to mask and normalize the need for renovation, both for residents and authorities. The key distinction lies in the difference between changes that occupants choose to make and those they are forced to endure. Some of the households in question voluntarily lower the temperature without this affecting their comfort, which remains adequate. It is therefore important to note that, for these households, energy-

efficient renovations must be tailored to their actual needs rather than assumed ones, lest they increase the carbon footprint or even contribute to the rebound effect.

2. **Constrained Renovation Agency.** The possibilities for energy renovation actions depend largely on socio-economic criteria and are therefore distributed very unevenly. While the most vulnerable households do not have the capacity to renovate, households with the means have little incentive to do so.
3. **Energy Awareness Stratification Mechanism**. Although public environmental awareness seems to be improving significantly, there are still marked disparities, partly linked to education and income levels, in understanding how energy works in buildings and in access to information on energy renovation. Awareness-raising policies must take this dichotomy into account, otherwise they risk reinforcing inequalities.

RQ6. *What differentiated renovation strategies and policy instruments can be derived from dwelling–occupant cluster analysis to effectively increase deep renovation rates?* **(Chapiter 3.1, 3.2 and 3.4)**

Here are the main strategic recommendations for increasing the rate of deep energy renovation that emerge from the cross-analysis of technical housing data and socio-economic data on residents:

Governance Relocation (Chapters 3.1, 3.2, and 3.4). The governance of energy renovation must continue to be relocated, giving local authorities regulatory and financial tools to define priorities and act in their areas.

Neighborhood programs (Chapters 3.1, 3.2, and 3.4). Conversely, the diversity of individual situations can be leveraged by pooling resources and sharing the results of energy-retrofit initiatives at the street, block, or neighborhood level. Retrofit programs, district heating networks, and local energy cooperatives are all tools that should be promoted to improve the system's overall performance.

Energy Billing (Chapter 3.4). The way energy is billed can be both a hindrance and an incentive. Currently, households see insignificant effects of their efforts on their bills, and energy costs remain unpersuasive outside of times of crisis. For some tenants, co-owners, and district heating networks, flat-rate charges can be completely counterproductive and should be phased out. Conversely, progressive energy billing, like water billing, would provide relief to the most modest households. The gradual introduction of smart meters could help raise awareness.

Energy Poverty Actions (Chapters 3.1, 3.2, and 3.4). Households that own poorly performing homes and are in a situation of energy poverty do not have the means to renovate. As a result, they need comprehensive support (administrative, financial, technical, literacy, etc.). Part of the funding could come from a reduction in energy consumption subsidies, such as the social rate, particularly by targeting households with the highest energy consumption ("measured" energy poverty). For households in a situation of "hidden" energy poverty, who spend little, it is important to recognize that the energy savings generated by ER will be minimal. These households require additional investment.

High-income Targeting (Chapters 3.2 and 3.4). High-income households that own poorly performing homes should face increasing obligations, while simplifying the entire administrative process currently required to carry out major energy renovation work.
Split-Incentive Regulation (Chapter 3.4). Split-incentive regulation requires the implementation of regulations that oblige owners of the least energy-efficient homes to undertake renovation work, while providing the necessary support to avoid a shortage of rental properties and a subsequent increase in prices.
From EPC (Chapter 3.4). The EPC must be better adapted to renovation. Based on the principles of the Trias Energetica, the performance of the whole must take precedence over the performance of the individual elements.
To Buying Building Renovation Passport (Chapter 3.4). The moment of purchase must become a mandatory trigger. Mandatory performance improvements are a first step. However, the introduction of mandatory audits would be a logical next step.
Targeted Awareness (Chapter 3.4). While awareness-raising efforts are progressing, more needs to be done to reach populations that have not yet been reached, particularly those in precarious situations.
Condominium Calendar (Chapter 3.4). It seems necessary to put in place specific obligations for condominiums, in addition to split-incentive regulation. The mandatory implementation of a calendar of energy performance interventions is the minimum requirement.

Other recommendations can be made based on observations made throughout the thesis but have not been specifically developed:

Local Energy Priority: The choice of heating type (heat pump vs. biomass vs. district heating) should typically be decided based on the urban characteristics of the neighborhood, with heat pumps becoming the default choice in city centers.
Social Housing: Housing companies have the tools and skills to act both on households in precarious situations and on the rental market.
Demolition/Reconstruction: Mapping: A map of the housing that would be preferable to demolish and rebuild should be drawn up to ensure the sustainability of investments.
Sufficient Needs: Before delving into the topics of EPC and Renovation Passports, the literature highlights the importance of first assessing residents' needs before focusing on improving housing performance, as this could risk exacerbating the rebound effect.
Extensions: Facade and roof extensions have the potential to combine energy efficiency, adaptation to new uses, and an increase in property value through expanded floor space.

4.2. Core synthesis

MRQ. *To what extent can the joint analysis of technical characteristics of dwellings and socio-economic characteristics of residents explain renovation dynamics and support strategies to accelerate deep energy renovation in the Walloon residential building stock?*

4.2.1. Determinants and integrated approaches

As discussed in 1.1 Background, energy renovation of buildings addresses many issues: energy savings, GHG emissions, resource management, local air pollution, health and well-being, poverty alleviation, disposable income, employment, public budget, energy security, and asset value. Despite the various public instruments that have been used to encourage energy renovation, the rate of energy renovation—and the rate of DER that radically improves energy performance—has not really changed and remains below regional and European targets. Various political, technical, economic, and social barriers may explain this lack of enthusiasm, starting with the mismatch between policy targets and the real motivations for renovation. It also appeared that scientific literature tended to model the functioning of the building stock according to purely technical and economic logic, without taking residents into account. A joint analysis of the technical characteristics of housing and the socio-economic characteristics of residents therefore appears promising in explaining the dynamics of renovation and supporting strategies to accelerate deep energy renovation.

Table 4-1 Summary of recommendations tailored to the ten-representative housing/resident clusters in the Walloon Region.

Cluster	**%**	**Actions**
1/10 "low performance – low income – house – owner"	16 %	**Energy Poverty Actions + Targeted Awareness** + *Extensions*
2/10 "mid performance – low income – attached – renter"	15%	**Split-Incentive Regulation + Targeted Awareness** + *Extensions*
3/10 "High performance – high income – house – owner"	14 %	N/A
4/10 "mid performance – low income – semidetached – owner"	12%	**Energy Poverty Actions + Targeted Awareness** + *Extensions*
5/10 "mid performance – low income – detached – owner"	11%	
6/10 "low performance – high income – owner"	11%	**High-income Targeting** + *Extensions*
7/10 "high performance – high income – renter"	7 %	N/A
8/10 "mid performance – low income – apartment – renter"	6%	**Split-Incentive Regulation + Targeted Awareness + Condominium Calendar** + *Extensions*
9/10 "high performance – low income – apartment – renter"	6%	N/A
10/10 "low performance – low income – apartment – renter"	2%	**Split-Incentive Regulation + Targeted Awareness + Condominium Calendar** + *Extensions*
Municipal / Intermunicipal		**Governance Relocalisation +Neighbourhood programms + Multi-level behavioral actions** + *Local Energy Priority* + *Social Housing* + *Demolition/Reconstruction Mapping*
Regional		**Energy Billing + From EPC + To Buying Building Renovation Passport** + *Sufficient Needs*

The thesis confirmed and clarified the links between the technical characteristics of housing and the socio-economic characteristics of its occupants. Among these correlations, it quickly and explicitly became apparent that less affluent households were more likely to live in poorly performing housing. However, other dynamics also emerged, such as the significant presence of high-income households that did not renovate either, or the secondary aspect of rentals in the Walloon building stock. Indeed, another important lesson from this part is the need to adapt renovation policies to local contexts that vary greatly from one city to another. This partial relocation of renovation policies also implies providing these entities with the regulatory and financial means to act. The correlations highlighted in this way have made it possible to produce different sets of clusters, the most important of which are: "Low performance – Low income – owner" and "Low performance – high income – owner".

The case study of a former suburb of the city of Liège enabled regional and local results to be compared. The general dynamics were thus confirmed, supplemented, or, on the contrary, put into perspective. For example, the renovation cluster, which appears secondary at the regional level, is, on the contrary, essential for the city of Liège. This comparison made it possible to identify several recommendations (Table 4-1), which were explained in greater detail in the answers to the research questions. This table thus summarizes the strategic recommendations for increasing the renovation rate, which are based on a joint analysis of the technical characteristics of the housing and the socio-economic characteristics of the inhabitants.

4.2.2. Needs-Capabilities-Willingness

Despite the importance of these two characteristics in the decision to renovate, a third factor emerges clearly from chapter 3.2, a factor that represents behavioral change (awareness, education, action). The survey results show that this behavior is indeed linked to socioeconomic characteristics, in line with the initial hypothesis. Nevertheless, the variability of this third factor raises questions about the model.

The model developed in the thesis considers that the technical condition represents the **Need to renovate**. Substandard and energy-inefficient housing must be renovated to meet adequate performance standards. This need varies depending on the standards and requirements set by the policy makers, as well as on energy prices, The socioeconomic level represents the **Capabilities to renovate**. Depending on their income, knowledge and housing situation, residents have varying degrees of ability to undertake a renovation project. This factor is also influenced by subsidy and loan policies, as well as by the renovation market, which determines the cost of the improvements. One of the underlying assumptions of this thesis is that the willingness and ability to undertake renovation work depended largely on these broader socioeconomic factors.

The change in behavior is the third variable in this model, the **Willingness to renovate** (Figure 4-2). The selected socioeconomic characteristics are not sufficient to explain residents' behavior regarding energy-efficient renovations. While this discrepancy can easily be explained by the significant simplification inherent in the proposed model compared to individual cases, this should not prevent us from asking whether it would be feasible to incorporate a third dimension representing behavioral change, independent of the previous two. Chapter 3.2 thus highlights a group of homeowners with substantial incomes who lived in energy-inefficient homes. Chapter

3.4, on the other hand, examined low-income homeowners who also lived in energy-inefficient homes but expressed a strong desire to renovate.

This question warrants further research into residents' profiles and the extent to which there is a decoupling between socioeconomic characteristics and changes in behavior. However, a brief review of the literature on behavioral theories of change reveals similarities between this discussion and the Transtheoretical Model of Change (Prochaska & Velicer, 1997). This model theorizes an individual's readiness to adopt healthier behaviors. This model is based on six stages of change (Precontemplation, contemplation, preparation, action, maintenance, relapse) that pave the way for energy-efficient behaviors. To make progress, individuals need the "pros" (Needs to renovate) to outweigh the "cons" (Capabilities to renovate). But they must also want to make the changes and believe they can implement and maintain them (Willingness to renovate). Ten "processes of change," which are later supplemented by 21 additional processes, can help make and sustain change.

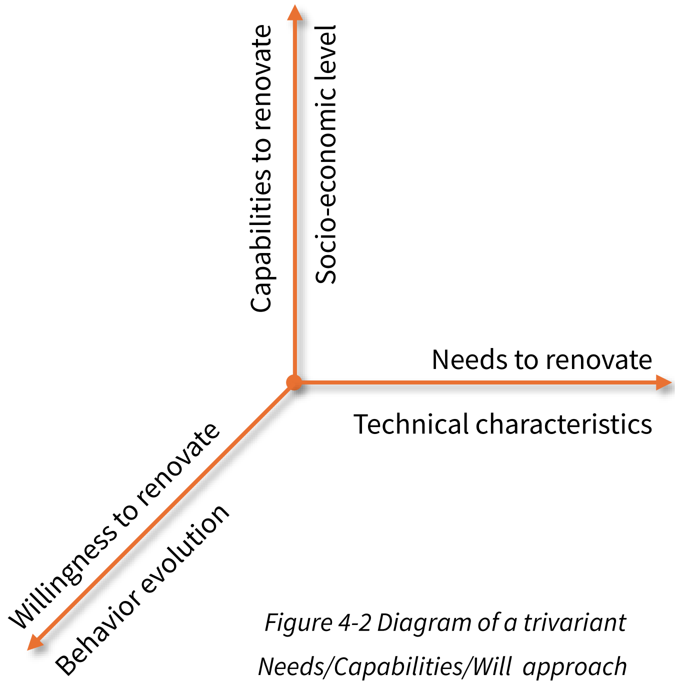


Figure 4-2 Diagram of a trivariant Needs/Capabilities/Will approach

Many respondents were already aware of general environmental issues but still lacked specific knowledge about energy use and renovation. However, the purpose of recontextualizing the results considering theoretical contributions from behavioral sociology is only to confirm the main findings while paving the way for future developments. Beyond the specific application of this model—which would obviously need to be confirmed through in-depth research and consultation with specialists—the discussion leads us to believe that, at this stage, it is essential to explore behavioral theories to further develop the idea underlying the thesis.

4.2.3. Integrated interpretation

Taken together, the results reveal three key mechanisms structuring renovation dynamics: (i) structural constraints linked to building characteristics, (ii) socio-economic capacity and inequality, and (iii) behavioral adaptation mechanisms that can delay or suppress renovation decisions. This explains why purely technical or financial policies have limited impact when implemented in isolation.

4.3. Thesis contribution

4.3.1. Scientific contribution

The results confirm the relevance of a model based on technical and socioeconomic data for explaining renovation dynamics, beyond purely engineering-based models. This analysis, which seeks to understand the energy performance of existing buildings in relation to the financial capacity of residents to finance the investment, ultimately addresses the three pillars of sustainable development—environmental, social, and economic. A new housing model for the Walloon region has been developed by cross-referencing technical and socio-economic data. This model identifies housing/resident clusters with specific needs and capacities. Recommendations for appropriate renovation strategies can thus be developed to simultaneously address environmental, economic, and social issues. The logic of integrating technical and socio-economic data underlying the entire project could be replicated in other areas facing similar issues. The model produced could also be adapted to analyze different issues related to housing governance.

However, the various observations suggest that technical and socioeconomic models would benefit from being supplemented with behavioral data. To gain a more detailed understanding of occupants' actions, it is also necessary to consider their level of awareness, education, and motivation, which varies from one occupant to another. This triptych of Technical/Socio-economic/Behavioral factors seems promising to understand housing dynamics and developing appropriate and effective governance.

The thesis also provides new insights and discussion points on the consideration of energy poverty and split incentives in housing energy renovation policies.

4.3.2. Methodological contribution

The research proposed in this doctoral thesis is distinguished by four methodological contributions: its integration of independent data sets and its mixed, multi-scale, and long-term approach.

Cross-referencing existing databases successfully produced a mixed model while minimizing the costly data collection phase. The methodology used can contribute to literature and be adapted to address other issues.

The multi-method approach adopted in this thesis highlights both the complementarity and the limitations of statistical, survey-based, and case study methods when used in isolation. The various tools used throughout the four chapters address issues of quality and effectiveness. On the one hand, the different tools were chosen so that their strengths and weaknesses would complement one another. The use of quantitative and qualitative methods is the best example of this synergy, which allows each tool to analyze a specific aspect of a complex problem. However, the selection of these tools was also guided by considerations of efficiency to make the best use of the available data. The qualitative interviews at the beginning of the thesis paved the way for a purely quantitative approach in the statistical studies, before confronting the mixed results of the case study. This regular alternation reinforces the scientific quality of the results ultimately obtained. Nevertheless, the multi-method approach should be used with caution, avoiding the extrapolation of results without highlighting their specific limitations.

The multiscale approach demonstrates its value for studying the built environment, even though it also highlights different insights. The shift from a national and European scale to a neighborhood scale illustrates this desire to gather multiple perspectives on similar issues to reveal different results. These results were complementary but also contradictory, as the findings on the energy efficiency of rental properties demonstrated.

Finally, the thesis highlights the value of conducting this type of research over the long term, so that it can be informed by ongoing feedback. This feature has made it possible to evolve both the objectives and methods of various studies, in line with developments in the state of the art and technical possibilities.

These four specific features constitute a reproducible contribution to other studies and are adaptable to other contexts and issues.

4.3.3. Policy implications

The findings suggest that Wallonia's building stock will not meet these energy targets by 2030 and 2050. The current uniform renovation policies are structurally misaligned with the heterogeneity of the building stock and its occupants. Cluster-based analysis provides a concrete operational framework to design differentiated and targeted policy instruments. The results highlighted a set of recommendations specific to these particular cases.

The results indicate that energy renovation policies would benefit from being fairer rather than equally distributed. Renovation strategies should be tailored so that the needs of all residents align with decarbonization goals. These strategies would benefit from incorporating issues related to energy poverty and social justice. Public performance indicators, such as the EPC, should be adapted to better reflect the housing stock's ability to meet these needs and goals.

Energy and housing policies require a partial relocation of competences to align with the specific characteristics of the local context. This relocation can take the form of renovation programs based on the local dominance of a particular building type and the appetite of an identified audience. Renovation strategies can also involve group purchases, encouraging the installation of technical solutions particularly suited to the local context, such as heating networks, and the establishment of energy communities. Shifting decision-making and action to local levels could lead to greater public engagement.

The inclusion of a behavioral component in the thesis's final findings demonstrates its importance in the dynamics of energy consumption and renovation. This behavioral component can be directly reflected in awareness-raising and local education work. The thesis highlights the importance of this awareness in the decision to renovate. This awareness-raising effort also helps limit the rebound effect while encouraging energy-efficient behaviors.

4.4. Limitations

The limitations specific to each chapter have been highlighted in the corresponding articles. The main limitations of this doctoral thesis can be summarized as follows.

Use of existing datasets: Chapters 01 and 02 are based on existing databases collected at different periods, from 2011 to 2020. These times lags between databases imply a risk of error in the correlations that have been observed. The EPC database used in these chapters is itself made up of certificates collected in different years since 2008. These certificates tend to underestimate the energy performance of the building stock, particularly in the lowest performing categories. Furthermore, the unit of measurement used in the energy performance certificate—kWh/m²·year—reflects a significant bias that was already mentioned in the introduction. Certificates say nothing about how well a home is suited to its intended use; on the contrary, they favor larger homes at the expense of sufficient renovations.

Dynamic behavior: The study is based on a static and uniform approach to energy consumption, without considering dynamic behaviors that are known to significantly affect energy consumption in residential buildings.

Statistical analysis: Statistical analysis relies on geographical correlations between independent databases. This approach results in a reduction in the accuracy of the final model. Furthermore, the results of this model are valid only on a large scale and should not be used as-is to analyze a specific building.

Multiple-methods and multiple-scale: The use of multiple methods introduces uncertainties related to changes in scale and variables.

Age of the occupants and buildings: The age of the occupants is not considered in the data analyzed in chapters 3.1 and 3.2. This age could be an interesting variable not only for estimating the resources a household has available to undertake renovations, but also for understanding the household's willingness to undertake such projects. The age of buildings is also not considered, even though it can provide a wealth of information about the construction techniques used and, therefore, the insulation techniques to be implemented.

Geographical scope of the study: The thesis focuses specifically on the Walloon region in chapters 01 and 02, and on the city of Liège in chapter 03.2.

These limitations serve as a reminder that the results—whose quality and reproducibility have been structurally ensured—depend largely on the context and initial assumptions. Integrating data on behavioral dynamics remains a significant challenge for fully understanding the dynamics of renovation.

4.5. Suggestions for future work

Several proposals for future work have already been developed in the various chapters. The principal areas of research are summarized below:

If this thesis produces strategic recommendations in favor of increased strategic renovation, it would be interesting to focus on accurately assessing both the costs and the expected effects of these recommendations.

The thesis chooses to focus on occupants rather than owners. This does not change anything in the case of owner-occupiers, but it inevitably introduces a bias in the case of rentals, especially if the property is rented by a small owner. In this case, this choice is primarily based on the available data. An analysis of the socio-economic characteristics of landlords is necessary to improve energy policies for this part of the building stock. However, this area of research needs to be developed further.

The thesis focuses mainly on direct energy consumption to assess the need for renovation. However, it is necessary to consider not only white energy, but also gray energy and all environmental impacts throughout the building's life cycle. As noted in the introduction, energy-efficient renovations can yield numerous benefits related to the sustainability of housing. However, energy-efficient renovation focused solely on efficiency can prove ineffective—or even counterproductive—by requiring significant resources and causing substantial environmental impacts, only to result in increased energy consumption due to the rebound effect.

Energy certification of housing is central to the development of a renovation strategy. While the Walloon EPC has the merit of existing and being increasingly understood by the public, there is still room for improvement and questions remain. (i) Simulated adaptation of results based on simplified behaviors. (ii) Automatic integration of suggestions for improvements. (iii) Adaptation of PEB requirements to the specificities of renovation. Performance requirements per wall are completely out of step with the reality of energy renovation in urban areas. (iv) Performance assessment per unit area automatically favors large homes. (v) Overestimation of photovoltaic production. The installation of solar panels has become the most cost-effective method of improving the EPC, favoring wealthy households and detached houses, regardless of the Trias Energetica logic. This improvement to the certification system must be accompanied by a more in-depth and comprehensive examination of the objectives of this certification and how it effectively contributes to a low-carbon society. A recent review of the literature highlights the risks of focusing on an unrealistic vision of energy efficiency rather than implementing sufficient energy retrofits.

The thesis confirms the value of an integrated model of technical and socio-economic factors. However, it also opens the door to the development of a three-pronged Technical/Socio-Economic/Behavioral approach inspired by models from behavioral psychology, such as the Transtheoretical Model, which could fuel discussions on the effectiveness of behavioral change tools and open new avenues of research.

5. Conclusion

The fight against global warming and for an energy transition capable of reducing European countries' dependence on external pressures necessarily requires improving the energy performance of the existing building stock. The reasons for acting do not end there as numerous benefits could be gained from a sustainable approach to the renovation of the building stock. However, the various policies implemented in the WR, in Belgium, and in Europe have so far failed to improve the performance of older buildings. On the one hand, renovation work is costly and complex, and the return on investment is uncertain. On the other hand, these renovation projects like the policies that encourage them are still largely guided by the principles of energy efficiency, to the detriment of the actual needs and capabilities of the occupants.

To address this issue, this thesis aims to reassess energy-efficient housing renovation policies through the lens of residents' characteristics and to provide appropriate recommendations. The underlying objective is to help increase the rate of comprehensive energy-efficient renovations in Belgium, improve residents' comfort and well-being, while reducing the environmental impact of the building sector and contributing to the Belgian state's resilience and energy independence.

This thesis focused on examining the interrelationships between housing technical data and residents' socioeconomic data. The study highlights the importance of an innovative methodological approach aimed at strengthening the validity of the results obtained by employing a variety of analytical tools and scales. The initial qualitative state-of-the-art at the European and national levels was thus followed by a quantitative statistical analysis combining correlation, regression, and clustering algorithms applied to the WR. The subsequent triangulation of three qualitative tools—IRT, survey, and focus group—applied to a local case study concludes the process. This approach constitutes one of the main lessons of this work, which can be reused in future research.

Both the statistical analysis and the case studies reinforce existing knowledge regarding the correlations between housing characteristics and residents' socioeconomic characteristics. Following the clustering analysis, a "low performance – low income – owner" cluster, representing 16% of Wallonia's housing stock, emerges as a priority target for any comprehensive energy renovation policy, requiring the implementation of financing solutions with uncertain returns.

At the same time, the significant number of high-income homeowners living in energy-inefficient homes illustrates the lack of interest in energy-efficient renovations among a large segment of the population. This "low-performance–high-income–owner" cluster, which accounts for 11% of Belgium's housing stock, represents one of the thesis's key findings. While regulatory constraints may play a role in improving the energy efficiency of this cluster, it seems particularly essential to take advantage of changes in ownership to encourage such renovations.

The statistical analysis tended to downplay the significance of the tenant/landlord dilemma in the Walloon context. However, the case study in Liège served as a reminder that this was a very real problem in certain cities, requiring proactive policy responses for populations particularly vulnerable to energy poverty. These complementary results fully illustrate the value of changing scales and tools to detect weak signals.

To address the specific needs of the various target groups identified, this thesis highlights the need to devolve some housing energy policy decisions to the municipal or supra-municipal level. Indeed, the diversity of urban landscapes requires context-specific solutions. Such local decisions would greatly benefit from a better understanding of the actual technical characteristics of the local housing stock and how these relate to the socioeconomic data of residents.

Among the other recommendations mentioned in the discussion, it seems essential to emphasize here the importance of scrutinizing how energy certification for energy-efficient renovations operates. This assessment tool has the merit of providing insights into a building's gross performance, which can be useful for property owners, policymakers, and researchers alike, as we have demonstrated in this thesis—despite the limitations of the approach that have been highlighted. Indeed, the current version of the EPC seems ill-suited to energy-efficient renovations, and even less suited to sustainable renovations. More generally, the very objectives of the EPC perpetuate a kind of techno solutionist myth in which only performance matters, without regard for actual needs.

In summary, this thesis contributes to providing targeted recommendations based on an innovative model of Wallonia's building stock, supported by a multi-methodological approach. At the conclusion of this thesis, we believe it would be advisable to direct future research toward a more thorough integration of sustainability criteria into our study and toward an examination of the effectiveness of the EPC.

A cross-analysis of housing technical data and residents' socioeconomic data has proven valuable in providing a fresh perspective on the dynamics of energy-efficient renovation in Wallonia's building stock. However, the discussion ultimately suggests the possibility of a potential distinction between what strictly falls under these socioeconomic characteristics and what would be more closely related to the specific knowledge and preferences of each household. This triad of Need for Renovation/Capabilities for Renovation/Willingness to Renovate, which emerges from our analysis, strikes us as an interesting avenue for improving our understanding of these dynamics.

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