Head Office: Università degli Studi di Padova

Department of Tecnica e Gestione dei sistemi industriali (DTG)

Ph.D. Course in Management Engineering and Real Estate Economics

Series: XXXVIII Cycle

CAN THE REAL ESTATE MARKET DRIVE VIABLE RESIDENTIAL RETROFIT?

UNLOCKING THE POTENTIAL OF DEEP RETROFITS THROUGH BUSINESS MODELS AND OFF-SITE CONSTRUCTION

Coordinator: Ch.mo Prof. Luigi Salmaso

Supervisor: Ch.mo Prof. Ezio Micelli

Co-Supervisor: Ch.mo Prof. Ivan Blečić

Ph.D. student: Eleonora Righetto

ABSTRACT

The construction sector faces the critical challenge of reducing the costs of deep energy retrofits, essential to ensure the economic viability of the transition towards decarbonisation of the built environment. This doctoral research proposes an integrated analytical framework structured across three complementary dimensions.

The first dimension empirically investigates the **real estate green premium by applying hedonic regression models to four Italian urban markets**. Findings reveal significant differences between major cities (10–20%) and mid-sized cities (15–39%), showing that energy efficiency generates territorially differentiated value, **generally insufficient to cover investment costs without targeted public support.**

The second dimension examines the economic and financial viability of retrofit interventions through the comparative analysis of innovative business models. The **Managed Energy Service Agreement (MESA)** integrated with off-site technologies is evaluated using discounted cash flow analysis for three investor profiles. Profitability depends on investor type and the ability to capitalise on the price premium, with positive NPV mainly observed for developers in highly dynamic real estate markets.

The third dimension quantifies cost reduction dynamics through **empirical learning curves from 19 industrialised retrofit projects in France.** The analysis documents cumulative cost reductions exceeding 45% for single-family homes and 30% for apartments, with average learning rates of 6.4–6.6%, attributable to accumulated expertise and production serialisation.

The scientific originality of this study lies in the systemic integration of three dimensions: the real estate value proposition, the MESA business model, and off-site industrialised technologies. This approach overcomes the fragmentation typical of existing literature, providing evidence on the need for targeted public support and identifying minimum conditions to activate significant learning economies.

Overall, the research clarifies the dynamics of real estate markets related to energy efficiency, empirically validates the economic feasibility of industrialised retrofits, and quantifies the cost reduction mechanisms resulting from learning, contributing to both the theory and practice of real estate economics in the energy transition.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

DCF	Discounted Cash Flow Analysis
EPC	Energy Performance Certificate
EPBD	Energy Performance of Buildings Directive
ESCO	Energy Service Companies
GHG	Greenhouse Gases
HPM	Hedonic Pricing Models
MQO	Ordinary Least Squares (OLS)
MESA	Managed Energy Service Agreement
MOE	Maîtres d'Œuvre
OMI	Osservatorio del Mercato Immobiliare dell'Agenzia dell'Entrate
NPV	Net Present Value
VIF	Variance Inflation Factor

APPENDED PAPERS

This doctoral dissertation is based on the following papers:

Paper I	Micelli, E., & Righetto, E. (2023). How do metropolitan cities evolve after the 2008/2012 crisis and the Covid-19 pandemic? An analysis from real estate market values: Come evolvono le città metropolitane dopo crisi e pandemia Covid-19? Un'analisi a partire dai valori del mercato immobiliare. Valori e Valutazioni, 31, 49–67. DOI: 10.48264/VVSIEV-20223105
Paper II	Micelli, E., Giliberto, G., Righetto, E., Tafuri, G. (2024). The economic value of sustainability. Real estate market and energy performance of homes: Il valore economico della sostenibilità. Mercato immobiliare e prestazioni energetiche delle abitazioni. Valori E Valutazioni 2023, 34, 3–16. DOI: 10.48264/VVSIEV-20233402
Paper III	Micelli, E., & Righetto, E. (2024). The Great Concentration. Demography, Economy, Real Estate Values and the Development of Italian Metropolitan Cities. In S. Giuffrida, M. R. Trovato, P. Rosato, E. Fattinnanzi, A. Oppio, & S. Chiodo (A c. Di), Science of Valuations: Natural Structures, Technological Infrastructures, Cultural Superstructures (pp. 133–148). Springer Nature Switzerland. DOI: 10.1007/978-3-031-53709-7_10
Paper IV	Micelli, E., Giliberto, G., Righetto, E., Tafuri, G. (2023). Urban Disparities in Energy Performance Premium Prices: Towards an Unjust Transition? Land 2024, 13, 224. DOI: 10.3390/land13020224
Paper V	Micelli, E., Giliberto, G., & Righetto, E. (2024). Demographic Shift and Housing Market: Evidence from Italian Metropolitan Cities In F. Calabrò, L. Madureira, F. C. Morabito, & M. J. Piñeira Mantiñán (Eds.), Networks, Markets & People (pp. 88–96). Springer Nature Switzerland. DOI: 10.1007/978-3-031-74716-8_9
Paper VI	Micelli, E., Giliberto, G., & Righetto, E. (2025). Is the Energy Transition of Housing Financially Viable? Unlocking the Potential of Deep Retrofits with New Business Models. Buildings, 15(7), 1175. DOI: 10.3390/buildings15071175

Chapter 1

1. INTRODUCTION

1.1. The climate imperative and the global regulatory framework

Climate change and energy transition represent the most complex and pervasive challenges of the 21st century, with profound implications for ecological, economic and social systems globally (1,2). Anthropogenic **greenhouse gas** (GHG) emissions, mainly from the combustion of fossil fuels, are the main factor accelerating global warming, leading to empirically observable consequences such as an increase in the frequency and intensity of extreme weather events, loss of biodiversity, rising sea levels and the deterioration of established socio-economic structures (3).

In this context, reducing climate-changing emissions, limiting energy dependence, and adopting low-carbon development models are strategic priorities for public decision-makers and economic operators. The construction sector is of crucial importance, given that globally, buildings are responsible for 38% of CO2 emissions and **36% of total greenhouse gas emissions.** At the European level, buildings account for approximately 40% of total energy consumption and around **36% of energy-related greenhouse gas (GHG) emissions** (4).

The construction sector is of particular significance within the European Union's regulatory framework. The **European Green Deal** and the **2030 Climate Target Plan** establish binding targets to reduce net emissions by a minimum of 55% by 2030 and achieve climate neutrality by 2050. Despite these commitments, the most recent reports indicate that around 75% of European buildings have inadequate energy efficiency levels (5), highlighting a structural gap with respect to the targets set by the Paris Agreement (6).

Regulatory developments in the field of energy performance of buildings have gradually raised efficiency standards. The introduction of **Directive 2002/91/EC** (7) on energy performance in buildings resulted in the establishment of initial minimum performance standards and the requirement for energy certification, to enhance the efficiency of the existing building stock.

In 2010, **Directive 2010/31/EU** (**Energy Performance of Buildings Directive (EPBD)** recast) (8) replaced the previous legislation and addressed the European "20-20-20" targets: a 20% reduction in greenhouse gas emissions compared to 1990 levels, an increase in energy efficiency by 20%, and the achievement of 20% renewable energy in total consumption. The directive established the concept of **Nearly Zero-Energy Buildings (nZEBs)** and more rigorous monitoring tools, including minimum requirements for new and existing buildings, mandatory certification and periodic inspections of heating systems.

Directive 2018/844/EU (9) amended the EPBD 2010, thereby confirming the EU's commitment to modernising its building stock through the implementation of more energy-efficient and low-carbon buildings, in accordance with the European target of reducing CO2 emissions by 80-95% by 2050.

The most recent legislative development is the proposed revision of the **EPBD (COM/2021/802)** (10) as part of the Fit for 55 package, which aims to align European legislation with the commitments of the Green Deal and the Paris Agreement. The proposal, also known as the **Green Buildings Directive**, was approved by the European Parliament. It introduced a zero-emissions requirement for all new buildings from 2028, while existing buildings will have to achieve energy class E by 2030 and class D by 2033.

In this context, the process of deep retrofitting and energy upgrading of existing buildings assumes a pivotal role. This is not only because it ensures compliance with regulatory requirements, but also because it engenders direct environmental advantages through reduced energy consumption. **Concurrently, such measures generate substantial positive economic externalities, encompassing increased market value and demand for buildings with higher energy efficiency levels** (99).

1.2. Practical relevance of research

In recent years, environmental sustainability strategies and ESG (Environmental, Social, Governance) policies have assumed a pivotal role in the international real estate sector.

The analysis presented in the report "**Emerging Trends in Real Estate: The Eye on the Storm**" **(ULI, 2023)** (11) reveals that industry professionals identify environmental regulations and the implementation of ESG frameworks as key elements in ensuring the long-term competitiveness and economic viability of real estate assets (see Figure 1).

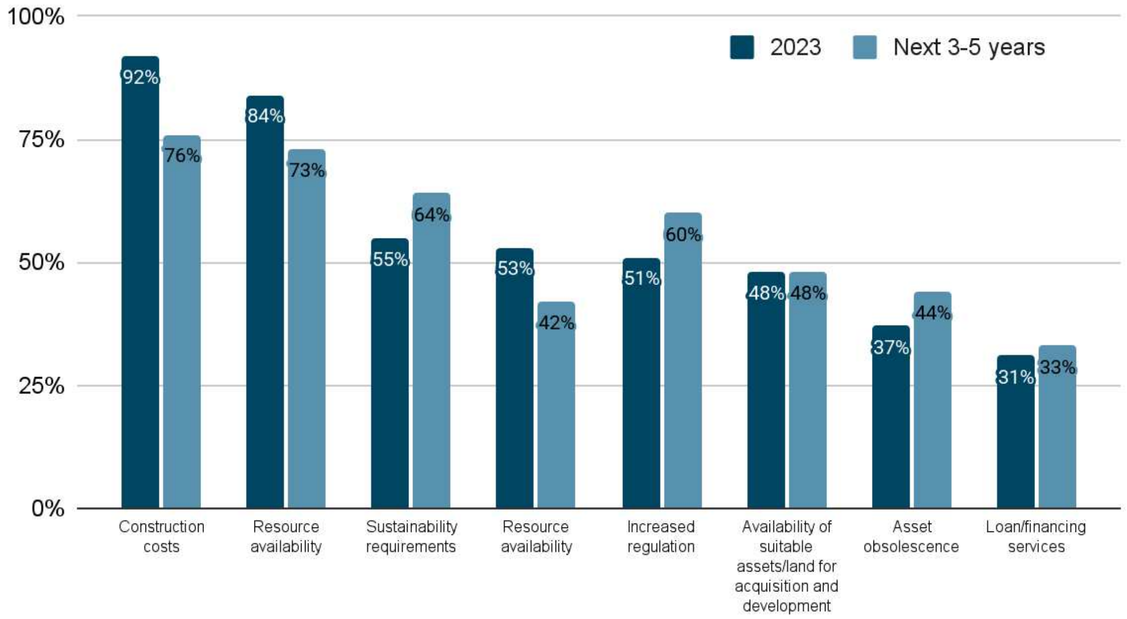


Figure 1: Challenges facing the real estate sector in 2023 and over the next five years.

Source: Emerging Trends Survey, ULI, 2023, p. 11 (11)

The survey results indicate that 64% of industry operators regard environmental sustainability as a key strategic priority for the next three to five years, with approximately 50% considering it relevant for the coming year. However, concomitantly, a substantial strategic contradiction has been identified: approximately 45% of respondents regard environmental issues as being less urgent than other short-term operational priorities, such as maintaining current profitability and adapting to market dynamics.

Concurrently, the real estate sector is confronted with substantial and pressing challenges, including escalating construction costs and challenges in sourcing materials and labour, compounded by inflationary pressures, supply chain disruptions, and geopolitical tensions. In this context, an integrated approach combining economic efficiency and environmental sustainability is imperative, with ESG strategies and decarbonisation being pivotal components for the resilience of the real estate sector.

The urgency of **climate change** further amplifies these dynamics. Climate risks manifest themselves in two distinct ways: firstly, directly, affecting individual buildings or entire property portfolios; and secondly, indirectly, through exposure to carbon-intensive ecosystems(12).

It is therefore essential to understand the **economic profitability of deep retrofitting** and how the advantages of increased value of energy-efficient properties can be effectively capitalised, including through innovative business models.

The following section delineates the context for the practical contribution of this research. The central question of the thesis, namely 'Can the real estate market drive viable residential retrofit?' is operationally relevant as it addresses one of the main critical issues of the energy transition, namely the economic viability of deep retrofit interventions in the residential sector. The results provide empirical evidence applicable to **different stakeholder groups**, thus helping to guide strategic and operational decisions in distinct but interconnected areas.

The research provides **public decision-makers** with empirical evidence on which contexts deep retrofits are financially viable without public support, where upfront contributions are necessary, and how advanced business models or off-site technologies can reduce the need for incentives. This evidence can inform the definition of enabling policies, the design of more efficient and equitable support schemes, and the implementation of tools to mitigate the risk of an unjust transition that penalises urban areas with a weak property market.

The present study offers **investors and property developers** a quantitative analysis of the price premium associated with energy-efficient properties. In addition, it measures the extent to which this value can contribute to covering the costs of the interventions. Furthermore, it provides methodological tools for the economic and financial evaluation of investments in deep retrofits. The findings of the study provide a framework for informed strategic portfolio decisions, facilitate risk and return expectations assessment in diverse urban markets, and identify market conditions conducive to property value-driven retrofit interventions that do not necessitate public support.

For **construction companies and operators specialising in retrofitting**, the study analyses how the off-site paradigm, supported by digitalisation and workforce specialisation, can reduce costs through learning economies and standardisation of production processes. This evidence supports operational assessments of the scalability of interventions, optimal production organisation and the skills required to carry out high-quality, low-cost deep retrofitting interventions.

The research provides a practical, decision-oriented contribution by clarifying how the combination of market dynamics, technological innovation and public policies can facilitate the spread of deep retrofitting interventions and accelerate the decarbonisation of existing residential buildings.

1.3. Main research themes

The research is structured around **three fundamental themes**. These themes are thus developed to address the main challenge that the construction sector is called upon to confront, in both response to European regulations and in relation to the needs expressed by the professional world. This challenge is to understand the current and future financial viability of deep retrofit interventions to promote their large-scale dissemination.

1.3.1. Value creation through energy retrofit

The transition to **high-energy performance buildings** is not just a cost, but also an opportunity to create economic value. Reduced **operating costs**, particularly for heating and cooling, have been shown to **increase the market value of properties**.

Concurrently, the tightening of European energy efficiency regulations is introducing increasingly **stringent regulatory** constraints on the sale and rental of properties with low energy efficiency levels. These regulatory dynamics are leading to a reallocation of value within the property stock: the most energy-efficient properties tend to advantage from a relative appreciation in market value, while those with lower energy performance are subject to progressive economic devaluation (13,14).

The literature indicates that energy-efficient buildings have the potential to command a price premium in the property market. This premium is not only attributable to lower energy costs and greater compliance with future regulatory requirements, but also to additional drivers highlighted in recent studies, such as reduced obsolescence risk, enhanced marketability, and the availability of financial incentives for green investments (15–19). However, the extent of this **value differential is unclear,** and some studies argue that the price premium may be significantly influenced by the urban context and market structure.

It is posited by other studies (20–22) that the differential between high- and low-energy-efficiency properties is diminished in mature property markets characterised by high demand. This is because the elasticity of market values with respect to energy performance is structurally limited by the presence of dominant **location factors and competitive dynamics** specific to the local market.

The imposition of a price premium that is differentiated on a territorial basis would have significant implications for the energy transition of the real estate sector. In less dynamic urban markets, the reduced attractiveness of low energy efficiency properties has the potential to amplify the depreciation of building stock. Conversely, in cities characterised by strong demand and high property values, the impact of poor energy efficiency on market prices would be more limited.

1.3.2. Innovative business models for energy-efficient building retrofit

The adoption of **innovative business models** is a strategic element in expanding the spread of **energy retrofitting** and fully exploiting its **value proposition.** These models are dynamic and adaptive systems capable of integrating technological innovations, organisational developments and changes in **market conditions** to simplify the implementation process (23–25).

Despite their potential, the **annual rate of renovation** of the European building stock is approximately 1%, of which only 0.2% relates to deep retrofits (26).

A review of the literature reveals two principal causes. The first of these is the prevalence of the **atomised business model**, which requires proprietors to independently manage energy audits, access incentives and technical coordination. This has a detrimental effect on the timing, cost and quality of the final intervention (27).

The second is linked to stagnant productivity and a lack of **specialist skills** in the construction sector. In contrast to other manufacturing sectors or supply chains that rely on prefabricated components, the construction sector has not experienced comparable productivity gains or cost reductions over time as a result of innovation and the integration of technologies (28).

In the realm of business models employed in the context of building interventions, the **Managed Energy Service Agreement (MESA)** emerges as a paradigm of efficacy, attributable to its integrated approach. In this scheme, a single operator is responsible for the entire process, from design to implementation, to ex-post verification of the energy savings achieved. In this manner, supplies are centralised, and a proportion of the economic advantages arising from energy efficiency are transferred directly to the customer (29).

An evolution of this model is represented by the Energiesprong model, which combines the goal of net-zero emissions buildings with advanced industrialisation, using off-site prefabricated modules for the construction of building envelopes and systems, reducing time and costs (30). The model provides a guarantee of performance for a period of 30 years, along with a high level of comfort and the possibility of customisation. It utilises standardised off-site construction to mitigate the sector's low productivity (31).

However, the literature highlights that, under current market conditions, the costs of deep retrofitting exceed the advantages derived from energy efficiency alone, making **public support** in the form of incentives and subsidies indispensable (32–36).

This underscores the pressing need to evaluate the viability of a MESA model integrated with Energiesprong-style off-site solutions and grounded in a robust value proposition. The central question guiding this inquiry is whether this model can attain an economic balance between costs and advantages without recourse to public funding. The investigation will also address the barriers that currently impede the dissemination of deep retrofits.

1.3.3. Cost reduction and learning economies in off-site construction

The **financial viability** of energy renovation projects necessitates an approach that extends beyond the mere capitalisation of the value proposition and advantages characteristic of the Energiesprong model. In instances where these elements prove inadequate in ensuring the economic and financial balance of the operation, intervention becomes imperative on the primary cost item: the **construction cost**.

Evidence from other sectors indicates the feasibility of achieving substantial cost reductions through the implementation of **integrated strategies**. These strategies encompass the combination of **financial viability**, industrialisation of off-site processes, and the exploitation of learning economies. Photovoltaics serve as a prime exemplar in this regard. Since 1976, the average cost per watt installed has experienced a precipitous decline of 99.6%, a feat attributable to the synergistic effects of learning, standardisation, and technological advancements (28,37).

These dynamics fall within the paradigms of the **technological learning economy**, consolidated in the industrial economy, which describes the inverse relationship between unit production costs and cumulative production volumes (38).

Endogenous learning is the primary catalyst for this evolution, engendering incremental enhancements in production efficiency through process optimisation, waste reduction and the accumulation of specialist skills (39).

Consequently, it is reasonable to hypothesise that analogous dynamics may also occur in the off-site industrialised construction sector. The increased prefabrication, improved component standardisation and enhanced worker skills that characterise this approach have the potential to result in substantial reductions in construction costs.

In this context, it becomes imperative to investigate the potential for reducing **off-site construction costs** and to trace the **learning curves** relating to such costs, resulting from the combined effects of technological learning and enhanced skills, in relation to the increase in the number of projects undertaken.

The identification of the **threshold**, beyond which a MESA model supported by optimised off-site prefabrication processes can achieve financial balance without recourse to public incentives, is facilitated by the tracing of this curve.

1.4. Research's gaps

A analysis of literature reveals **three significant research gaps** regarding the deep retrofitting of buildings. These gaps significantly limit both theoretical development and operational progress in the sector. Despite their conceptual distinction, these gaps are **closely interrelated**, thus identifying areas where studies conducted to date appear to be partial and incomplete.

Gap 1 – Value proposition

Scientific literature has identified the existence of a **price premium** associated with properties characterised by **high energy performance** (15,40–42). However, the precise quantification of this effect remains unresolved: empirical results do not show clear convergence and, indeed, often reach conflicting conclusions even regarding the **economic feasibility** of energy efficiency measures (43).

This divergence is reflected in a considerable **dispersion** in quantitative estimates of the price premium. While certain studies have documented marginal increases of a few percentage points, others have reported variations of close to 50% of **market value** (44).

The most significant gap lies in the absence of systematic research into the **influence of territorial factors** — such as the strength of the property market, the hierarchical position of the city in the urban network or local economic dynamics — in modulating the price premium.

This discrepancy hinders the capacity to interpret the observed variations and associate them with particular structural conditions in local markets.

The research gap is of particular relevance when viewed through the lens of **distributive justice** in the energy transition. If the economic advantages of energy efficiency are distributed very unevenly across territories, with preferential concentrations in areas that are already economically advantaged with strong property markets, the goal of a just transition risks being compromised. This scenario has the potential to engender regressive effects in terms of both wealth accumulation and **social cohesion,** thereby serving to amplify existing territorial inequalities rather than mitigating them (45,46).

Gap 2 – Financial viability

Research conducted on energy transitions and innovation systems in existing buildings has yielded considerable insight into the role of actors, institutions and infrastructure in innovation processes (47,48). However, the literature on deep retrofitting focuses almost exclusively on technical and regulatory aspects, neglecting the economic and financial dimensions of the interventions. This limitation is evident in the absence of in-depth assessments of the economic and financial feasibility of large-scale deep retrofitting interventions, even in hypothetically optimal market scenarios.

Most studies concentrate on the analysis of technical barriers, regulatory frameworks or consumer behaviour dynamics, omitting integrated assessments that simultaneously consider the optimisation of the value proposition, the efficiency of the business model and the exploitation of the most advanced technologies available.

Even business models recognised as the most efficient for deep retrofitting, such as **MESA** (49), have not yet been subjected to systematic empirical testing of their ability to generate **economic and financial balance**.

It has been argued by certain studies that deep retrofit interventions are not financially viable without significant **public support**. However, there is a paucity of detailed analyses of cases in which it is assessed whether such interventions can be economically self-sufficient by capitalising on the value proposition, adopting the most effective business model and exploiting the most advanced off-site technologies.

The operational implications of this knowledge gap are of particular relevance to **market development**. The prevailing uncertainty surrounding the economic viability of deep retrofitting has been shown to engender risk aversion among institutional investors, credit institutions and other financiers, thereby impeding the mobilisation of the requisite private capital to expand the scale of interventions (50,51).

Moreover, if the structural necessity for **public subsidies** is confirmed, the absence of reliable benchmarks hinders the quantification of the optimal amount of public contribution required to achieve economic balance.

Consequently, support policies risk being both inefficient from an allocative point of view, through the over-subsidisation of potentially self-sufficient interventions, and ineffective from a distributional point of view, through the concentration of resources in areas or types of intervention that do not have a priority need for them.

Gap 3 – Cost reduction and learning economies

Research on the costs of deep retrofitting is characterised by a methodologically static approach that implicitly assumes the invariance of unit costs, completely neglecting the transformative potential of **industrialisation processes** in generating technological learning dynamics.

This standpoint is particularly problematic as it fails to acknowledge the pivotal economic processes through which **industrialisation, prefabrication and standardisation** can facilitate systematic cost reductions, thereby leveraging the accumulation of production and organisational expertise. These processes have been instrumental in facilitating the economic parity of initially uncompetitive technologies with conventional alternatives, thereby enabling their subsequent establishment as dominant competitive options (52).

In the context of construction costs, analyses that evaluate cost reductions in **off-site industrialised construction**, considering learning economies resulting from supply chain efficiency, the adoption of new technologies or workforce specialisation, are rare (39).

This knowledge gap has significant implications for the assessment of the profitability of deep retrofit interventions and the estimation of their **market scalability**, a matter which remains fundamentally uncertain. The absence of compelling empirical evidence further restricts the capacity of investors and credit institutions to make informed decisions, for instance, regarding the incorporation of such assets into real estate portfolios or the provision of loans on favourable terms, thereby impeding their large-scale implementation.

In conclusion, these **three gaps** — (1) a still fragmented and non-contextualised understanding of the link between energy performance and property value; (2) the almost total absence of integrated assessments of the financial feasibility of deep retrofitting under optimal conditions; (3) the lack of in-depth investigations into the dynamic cost reduction mechanisms resulting from learning economies — constitute significant obstacles to both theoretical and practical developments in the sector.

It is imperative that these gaps are addressed in order to develop transition strategies that are simultaneously distributionally fair, operationally scalable and economically viable.

1.5. Research questions

The identification of the principal knowledge gaps that emerged in the literature allowed the formulation of the primary question that guides the scientific investigation of the thesis:

> ***Is it possible to achieve the financial viability of deep building retrofit interventions by capitalising on the value proposition, adopting innovative business models and implementing off-site prefabricated technologies capable of reducing construction costs?***

The complexity of this question necessitates a structured methodological approach that decomposes the primary problem into **three interconnected macro-areas**, each of which is further subdivided into **specific sub-questions** (cfr. Table 1):

1. **Value proposition** - Determine whether the market recognises a price premium for energy-efficient buildings and how this increase in value varies according to the urban context and real estate market dynamics (RQ1a, RQ1b).
2. **Financial viability** - Assess the economic and financial viability of deep retrofit interventions, considering the adoption of innovative business models, the use of off-site prefabricated solutions and the possible need for public incentives (RQ2a, RQ2b).
3. **Cost reduction through learning economy** - Analyse the potential for cost reduction through technological learning economies, verifying their actual existence by studying real case studies (RQ3a, RQ3b)

Gap	Sub-question	Gols	Chapter
Value proposition	**RQ1a**: Does the Italian property market recognise a price premium for energy-efficient residential properties? If so, to what extent?	Determine the presence and extent of price premium differentials associated with energy performance in the residential market	2
	RQ1b: Does the price premium vary according to the city range and the vitality of the urban property market?	Analyse the influence of the urban context and market conditions on the extent of the price premium	2

Financial viability	**RQ2a**: Is the financial viability of deep retrofit interventions achievable, under current conditions, through business models integrated with off-site construction solutions?	Assess the economic and financial viability of deep retrofits in Italy, estimating costs and advantages	3
	Rq2b: Do deep retrofit interventions require upfront public funding to be financially viable?	Determine the level of upfront public support required and analyse territorial variability	3
Cost reduction through learning economies	**RQ3a:** Is it possible to empirically document a reduction in construction costs linked to learning-by-doing mechanisms in deep retrofit projects carried out with off-site construction solutions?	Develop cost reduction curves in the construction sector resulting from the technological learning effect	4
	RQ3b: Is it possible to determine the threshold construction cost value at which deep retrofit interventions are financially balanced?	Determine the threshold construction cost value for financial self-sufficiency in different local markets	5

Table 1: Sub-questions and objectives that answer the main research question

The analysis of the three macro-areas enables the identification of gaps in the literature and the subsequent offer of original contributions on both a theoretical and operational level. The research also aims to provide **empirical evidence** useful for guiding the decisions of institutional investors, property owners, construction industry operators and public decision-makers.

1.6. Research approach and design

The research design is characterised by a unified methodological architecture, divided into **four consecutive and logically interconnected thematic phases.** This sequential structure was deemed necessary due to the exploratory nature of the topic. Although the general object of the study was defined from the outset, the specific development and interconnections between the different dimensions could not be predetermined.

The study adopted an **adaptive, multi-phase approach**, in which each phase informed and shaped the subsequent ones. The methodological process was initiated with the identification of real estate valuation mechanisms, followed by the assessment of financial viability, and concluded with the analysis of long-term cost optimisation dynamics. This sequential and modular approach enabled the adaptation of methodologies according to emerging empirical evidence, thereby enhancing the reliability of the results.

Despite the heterogeneity of the methodologies employed, all analyses are commensurate with the **real estate economics paradigm, encompassing industrial economics** for the analysis of business models and economies of learning. In this sense, the research represents a significant methodological advance in the study of energy transition in the built environment, proposing a framework that integrates real estate and industrial economics.

The first phase pertained to the research question concerning the **price premium** associated with the energy performance of buildings. The literature review concentrated on price premiums in property markets, drawing on established scientific literature, particularly for European and Italian markets, which provided a solid theoretical basis for empirical analysis. Then, the study employed established real estate economics procedures to determine this, including hedonic pricing models and regression analysis to estimate value differentials.

It was only after the identification of the existence and extent of the value proposition that the subsequent research question could be formulated, relating to the **optimal business models for capitalising on this value**. This question emerged organically from the results of the first phase and required a new literature review focused on business models applicable to deep building retrofitting.

The paucity of scientific contributions in this area necessitated the development of innovative methodologies to assess the economic and financial feasibility of the interventions. These methodologies took into consideration different demand profiles, time horizons and cost-advantages scenarios, to determine profitability and the possible need for public funding.

In light of the findings from the second phase, the research concentrated on the **feasibility of decreasing construction expenses with a view to ensuring the financial viability of deep retrofitting**. This phase utilised a multidisciplinary approach, incorporating insights from industrial economics and learning curves in other technological domains. The objective of this phase was to ascertain the extent to which economies of technological learning processes can influence the costs of interventions.

In order to achieve this objective, a cost **reduction curve** was developed in relation to the increase in units built and the improvement in the efficiency of **off-site industrial processes**. The analysis was based on empirical data collected through case studies of deep retrofit interventions carried out with industrialised construction in social housing in France, the country with the highest number of completed projects.

The learning curve thus traced was utilised as a foundation for the subsequent evaluation of the variation in the profitability of the interventions as construction costs decreased. The research also identified the **threshold cost value**, differentiated for major and mid-sized urban contexts, necessary to ensure the financial balance of the interventions.

The four phases of the research are illustrated in Figure 2:

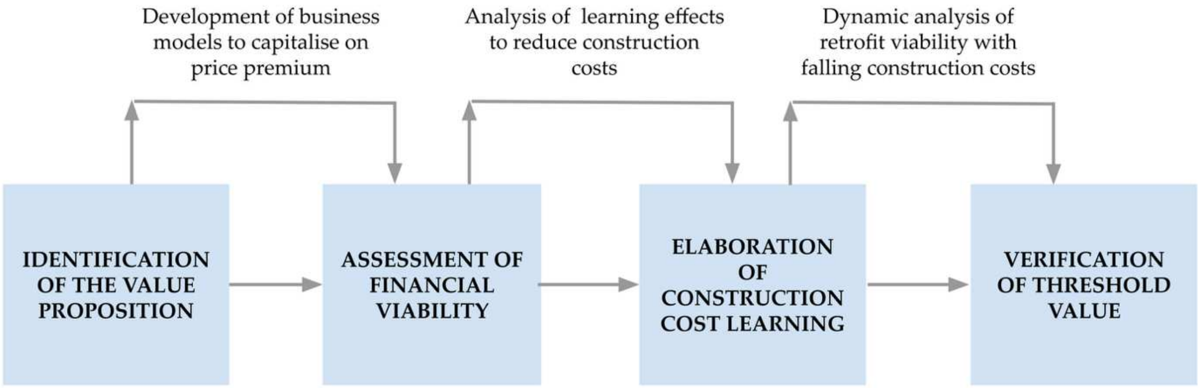


Figure 2: Research design: four thematic phases

As previously stated, the three macro areas of research are structured according to a standardised methodological framework consisting of five sequential components. The overarching objective of this systematic structure is to address the identified knowledge gaps and provide rigorous answers to the research questions (cfr. Figure 3).

Figure 3: Research design and methodological structure for each chapter of the thesis

1. Literature Review

In this phase, the theoretical basis is constructed through a review of the literature focused on each area of investigation: energy price premium for the first phase, business models for deep retrofitting in the second, and cost reduction processes through economies of learning in the third. The primary objective of this study is to provide a comprehensive overview of the current state of the art, identify existing contributions, and address knowledge gaps. The study will also seek to determine the most appropriate methodological practices, to define the most suitable analytical approach to address the research questions.

2. Problem definition

Following a thorough review of the literature, a series of specific research questions have been formulated in order to address the gaps identified in the existing knowledge in this field. This phase involves the clarification of the research problem, the definition of specific objectives, and the establishment of working hypotheses. The model functions as a conceptual conduit between theoretical frameworks and methodological designs, ensuring congruence between the identified gaps and the analytical approaches to be employed.

3. Materials and Methods

For each phase, the methodology adopted to address the research question is described, including data sources, sample selection criteria, analytical techniques used, and the theoretical and empirical reasons justifying these choices.

4. Data and descriptive analysis

The data collected is presented using descriptive statistics and frequency analysis, broken down by property type, geographical context and relevant demand profiles. This phase enables the dataset to be characterised, thereby highlighting the primary variables and their distribution, thus paving the way for subsequent quantitative assessments.

5. Assessment

Quantitative analyses are conducted in accordance with the methods defined in the methodological phase. The approach adopted is contingent upon the specific nature of the research question; for instance, hedonic price models may be utilised to estimate price premiums, financial feasibility analyses may be employed to assess the viability of business models, and learning curve modelling may be employed to facilitate cost reduction.

6. Discussion

For each phase, a critical discussion of the results is conducted, interpreting them in light of the theoretical framework and assessing their implications for the specific research question. The discussion considers the robustness of the results and evaluates their theoretical and practical relevance, both for the field of real estate economics and for the territorial context.

1.7. Relevance of the research

The construction sector is currently facing a crucial challenge: that of reducing the costs of deep retrofitting, in order to ensure the economic viability of the transformations necessary for the energy transition. The present research addresses this issue through an innovative and multidimensional approach divided into three complementary phases.

The initial strand of the study undertakes an analysis of the concept of **price premium** within the framework of **social unjust transition**. This approach facilitates the quantification of the value generated by **energy efficiency measures**, thereby highlighting both the opportunities and risks associated with a potentially inequitable energy transition.

The analysis demonstrates how, in different **territorial contexts**, deep retrofitting measures can represent both an opportunity and a threat to property value. The significant differences in value determined by energy efficiency constitute a phenomenon of unjust transition, which requires rigorous empirical investigation.

The second strand of research examines the economic and social costs and revenues of deep retrofit interventions. These are evaluated from the perspective of their transformation into entrepreneurial actions capable of **capturing value**. The research goes beyond traditional atomised models by proposing and analysing the **MESA business model** as the most efficient solution for the sector.

Utilising established assessment tools, the study provides a novel verification of the economic and financial viability of the interventions. The findings indicate that in the absence of integrated strategies and targeted public investment, numerous interventions are deemed to be economically unviable.

The third strand of the research introduces the analysis of **construction costs** in the field of **off-site industrialised construction**. The integration of **digital technology** and the specialisation of the workforce are transforming the traditional logic of the construction site, increasing the efficiency, quality and scalability of retrofit interventions. This transformation suggests a **paradigm shift:** the transition from traditional craftsmen to specialised fitters, capable of carrying out high-quality deep retrofits while reducing the number of hours of work required.

The research employs **learning curves** to evaluate the actual reduction in unit costs resulting from this transformation and to identify the conditions under which interventions can become financially viable even without direct public support.

The originality of the study lies in the integration, for the first time, of three fundamental dimensions in assessing the economic feasibility of deep retrofit interventions:

1. The value proposition that can be derived from energy efficiency;
2. The most efficient business model (MESA) applicable to the interventions;
3. The optimisation of industrialised production chains is facilitated by the concept of learning economies.

This integrated perspective overcomes the historical fragmentation of the sector, transforming the energy transition into a concrete environmental and economic opportunity and promoting the large-scale diffusion of deep retrofits, with measurable advantages in terms of energy consumption, living comfort, building performance and market value.

From a **scientific point of view**, the research clarifies the dynamics of real estate markets related to energy efficiency, empirically validates the economic viability of industrialised retrofitting and quantifies the cost reduction mechanisms resulting from learning. These results represent a significant contribution to the theoretical evolution of real estate economics in the context of the energy transition.

From an **operational perspective,** the study provides concrete analytical tools for the evaluation of investments, the planning of interventions and the definition of optimal public policies. The capacity to estimate the requisite investment levels and economic viability in diverse scenarios constitutes a pivotal element in expediting the energy transition of constructed buildings.

1.8. Thesis outline

The thesis undertakes an economic and financial evaluation of deep retrofitting interventions in residential buildings, with a particular focus on business models and construction cost reduction curves. The research combines theoretical insights and empirical analysis.

The research focuses on retrofitting measures applied to **existing residential buildings**, which are the main target of European energy efficiency regulations. In Italy, the majority of residential buildings demonstrate substandard energy performance: approximately **4 million units**, constituting 68.6% of the total, are classified within the **lowest energy performance** classes designated E, F and G of the EPC scale (51,52).

The majority of these structures were constructed in the post-war period, extending to the close of the 20th century, and predate the implementation of contemporary energy efficiency regulations. Consequently, the adoption of targeted and effective redevelopment strategies assumes significant importance.

The following section provides a synopsis of the thesis's six chapters.

1. Introduction

The present chapter delineates the central problem of the research, highlights the main gaps and illustrates the methodological design, which is divided into several phases. The study's primary focus is delineated as follows: the value proposition of deep retrofit interventions, the viability of business models, and the profitability of investments in efficient residential buildings.

2. Green price premium for residential buildings

The present chapter conducts an analysis of the existence and extent of the price premium associated with the energy class jump in Italian residential properties. This analysis is conducted based on market data. The objective of this study is to conduct a comparative analysis between major cities and mid-sized cities to ascertain whether real estate market dynamics contribute to defining the gap in the value proposition of energy retrofits.

3. Deep retrofit and financial unviability

The present chapter analyses the financial viability of deep retrofit interventions for a variety of demand profiles and major and mid-sized cities. The objective of this study is to estimate the requisite amount of public funding and to analyse its correlation with the ranking and characteristics of the property markets in the cities under consideration.

4. Reducing construction costs in off-site building applied to building renovation: empirical evidence from Energiesprong projects in France

This chapter employs a case study approach, examining social housing projects in France that were executed between 2018 and 2025. The analysis focuses on the cost reduction achieved through the implementation of off-site industrialised construction technology in deep retrofit projects, and its correlation with the augmentation in the number of units retrofitted. The learning curve associated with this reduction is traced, and the main determinants of the savings achieved are analysed.

5. Determination of the financial break-even point in deep retrofit projects

The chapter commences with an examination of indicative cost values, subsequently undertaking a dynamic evaluation of the profitability of interventions in diverse urban contexts. This evaluation incorporates the cost reduction associated with technological learning processes. The objective of this study is to ascertain the critical cost level at which off-site industrialised interventions become financially viable, even in the absence of public incentives.

6. Conclusions

The final chapter provides a synopsis of the primary outcomes observed across the three macro-areas, addressing their ramifications for urban planning, real estate investment management, and public policies aimed at facilitating deep retrofitting. Operational recommendations and ideas for future research developments are proposed, highlighting the scientific contribution and practical relevance of the work.

Chapter 2

2. GREEN PRICE PREMIUM FOR RESIDENTIAL BUILDINGS

2.1. Introduction

The construction sector exerts a pivotal influence on urbanisation processes, contributing to the creation of residential and productive spaces and generating significant effects on national economic growth. Concurrently, construction activities and the utilisation of buildings impose considerable pressure on ecosystems and natural resources, resulting in substantial levels of pollution and heightened environmental stress.

The European Union has set ambitious targets for reducing energy consumption and greenhouse gas emissions, translating them into a binding regulatory framework, precisely because of the dual impact on both the economy and the environment. The primary reference framework is **Directive 2010/31/EU on the Energy Performance of Buildings (EPBD**), which represents the culmination of several decades of legislative developments in the field of energy efficiency in the building sector (53).

The obligation to provide buildings with an Energy Performance Certificate (EPC) was first introduced by the initial EPBD, **Directive 2002/91/EC (EPBD I)**, and subsequently reinforced by this 2010 directive.

This directive introduces a structured set of tools, criteria, and assessment procedures designed to encourage improvements in energy performance in both new and existing buildings. A fundamental component of the legislative framework pertains to the stipulation of the obligation to furnish each property, during the process of construction, sale or rental, with an **Energy Performance Certificate (EPC).** This certificate must be made visibly accessible to prospective buyers or tenants and must be explicitly indicated in all forms of advertising and promotional materials (Article 12, paragraphs 1, 2, and 4).

From a theoretical standpoint, the energy certification of buildings has the potential to mitigate information asymmetries in the property market. This is because it enables operators to reflect the expected value of reduced energy consumption and operating costs in market values. However, a consensus among the scientific community on this relationship has yet to be reached.

The impact of EPCs on market values has been the subject of numerous studies, which sometimes report conflicting results. Several studies have documented a positive and statistically significant effect, thus indicating the presence of a green price premium. This effect is characterised by an **increase in the market price** recognised for properties that are more energy-efficient in comparison to less efficient properties. However, other studies have reported limited or insignificant effects (13,54).

The underlying causes of these variations remain to be fully elucidated. The heterogeneity of the results can be attributed to several factors, including the different estimation methodologies adopted, local macroeconomic conditions and the degree of application and compliance with energy regulations in various urban contexts.

The literature also posits the hypothesis that the price premium associated with energy efficiency may vary **depending on the characteristics of the property market**. According to the theoretical approach of Eichholtz et al. (2013) (20), in markets characterised by high liquidity and strong demand — as is typical of metropolitan areas — the influence of energy performance on the final value tends to diminish.

This outcome aligns with economic theory, which posits that real estate is heterogeneous and not perfectly substitutable, in contrast to standardised products. Consequently, the real estate market can be conceptualised as a model of monopolistic competition, wherein each property possesses distinct characteristics and there aren't perfect substitutes for it (54).

In this context, location is a crucial factor. In major cities, which are characterised by liquid markets and high demand, market value tends to be less sensitive to energy performance. In smaller or less dynamic urban markets, however, energy characteristics become distinctive elements that can determine more marked differences in value.

Empirical confirmation of these differences is not only academically relevant but also economically and socially significant. In less attractive contexts, the presence of low-energy-efficiency buildings has the potential to lead to a significant depreciation of real estate assets, thereby increasing the economic vulnerability of local communities. Conversely, in more dynamic urban areas, greater market resilience could reduce the value gap between efficient and inefficient buildings, thereby limiting the distributional impact of the green transition.

As Rodríguez-Pose (55) observes, the financial burden of the **ecological transition may be disproportionately shouldered by regions** already facing socio-economic disadvantage, thereby exacerbating existing territorial inequalities. In this context, energy efficiency policies and their impact on property values influence the composition of urban assets. They also determine the ability of cities to preserve social cohesion and economic attractiveness.

In view of the aforementioned considerations, the present chapter endeavours to explore the initial gap identified in the literature, structuring the analysis around two fundamental questions. The first of these concerns the identification of the existence and extent of a market value differential recognised by the market for properties with superior energy performance, measured through the EPC classification. The second aspect pertains to the evaluation of the variability of this green price premium in relation to diverse urban contexts (cfr. Table 2).

Gap	**Research question**
The existence and extent of the green price premium have not yet been clearly quantified, nor has there been adequate analysis of how the territorial characteristics of urban markets influence its variability.	RQ1a: Does the property market recognise a market value differential in favour of properties with higher energy performance on the EPC scale?
	Rq1b: To what extent do the size and vitality of the urban market influence the value of the green price premium between different territorial contexts?

Table 2: Gap 1 and sub-questions of the first research question (RQ1a and RQ1b)

The objective of this study is therefore twofold:

1. To determine the market value differential between high and low energy efficiency properties, verifying its statistical significance;
2. To analyse the role of the size and vitality of the urban market as possible determinants of the variability of the green premium between different areas.

The analysis focuses on the Italian residential market, comparing two groups of cities differentiated by territorial size and the dynamism of their respective property markets. The first group, called "**Major Cities**", includes four large urban centres in Northern Italy: Milan, Florence, Turin and Trieste. The second group, called “**Mid-Sized Cities**”, includes four mid-sized cities: Padua, Bergamo, Mestre and Udine.

The research design is divided into the following subchapters:

- **2.2 – Literature review and theoretical framework**
  Critical analysis of existing studies on the green price premium, estimated values and determining factors, with a specific focus on Europe and Italy;
- **2.3 – Choice of cities and real estate market dynamics**
  Reasons behind the selection of four major cities and four mid-sized cities, with an in-depth analysis of urban, socio-demographic and real estate characteristics;
- **2.4 – Materials and methodology**
  Description of the data collection methodology, the aggregation schemes of the 12 energy classes and the hedonic model adopted for the evaluation of the price premium;
- **2.5 – Descriptive analysis**
  Presentation of the sample and analysis of the intrinsic and technological characteristics of the properties, using descriptive statistics and frequency tables;
- **2.6 – Hedonic pricing model**
  Illustration of the procedure followed for hedonic regressions, accompanied by robustness analyses aimed at verifying the soundness and reliability of the estimates;
- **2.7 – Results**
  Presentation of the quantitative results obtained from the regression analyses, considering the two different aggregations of energy classes and all the cities examined;
- **2.8 – Discussion**
  Interpretation of the results in relation to the theoretical hypotheses, with reflection on the implications for urban policies and real estate market operators.

2.2. Literature review and theoretical framework

2.2.1. EPC and the aim of the literature review

The introduction of the **EPBD**, as established by the European Commission, provided the technical and regulatory framework for the standardisation of energy performance metrics, thereby rendering energy certification a mandatory requirement in all real estate transactions (8). The energy labelling system, as defined here, rendered price differentials observable and measurable in a manner that was previously unobjectively quantifiable.

The price premium is the **quantitative measure** by which the real estate market attributes an economic premium to assets characterised by higher energy efficiency standards. Operatively, the price premium is characterised by a percentage discrepancy between the transaction price of high energy performance properties and that of comparable properties exhibiting lower efficiency levels.

The economic theory of market segmentation finds direct application in the real estate sector, where demand distinguishes and values assets according to characteristics related to energy efficiency and environmental sustainability (56).

As demonstrated in the relevant economic literature, this dynamic has been formalised through two complementary concepts. Firstly, the '**green premium**', which is defined as the increase in value recognised for energy-efficient properties. Secondly, the '**brown discount**', which is defined as the reduction in value affecting energy-inefficient assets.

The energy efficiency of buildings is a determining factor in the increase in market value of properties, as it integrates several elements: the economic savings deriving from expected and discounted energy flows, the **reduction in consumption** and environmental protection (57), the improvement in **perceived comfort** and the long-term health of occupants (58), as well as the effect of **regulatory expectations** generated by European and national regulations.

Two economic theories underpin the price premium. The primary concern pertains to the **potential for capitalising on energy savings**. Prospective purchasers of energy-efficient properties may reap future financial advantages in the form of reduced operating costs. These cost savings can be capitalised, resulting in a premium price that reflects the anticipated savings. As Aydin et al. and Eichholtz et al. (13,14) demonstrate, demand accurately values the initial investment and future savings associated with higher energy performance. However, it is important to note that certain factors may serve to moderate this effect.

Geographical variability in demand has been demonstrated to reduce the value differential (20,59). In markets characterised by strong demand pressure, the differences between properties with different energy performance are smaller. This is in confirmation of previous observations made by Eichholtz et al. (20). Moreover, the existence of a discrepancy between the performance levels indicated by energy certifications and actual consumption can exert an influence on demand appreciation. Coyne and Danny (60) identified significantly higher consumption levels in the Irish residential market than indicated in EPC certifications, while Rajithan et al. (61) emphasise that such discrepancies can impact market valuations.

Finally, the specific utilisation of properties, such as second homes utilised solely during certain seasons, can render energy efficiency factors less pertinent, thereby impacting demand sensitivity. Despite these exceptions, there is no evidence to suggest that they have a significant impact on aggregate market preferences, which generally consider energy efficiency to be a distinctive feature capable of generating a recognisable premium price.

The second theoretical reference pertains to **regulatory expectations**. As is the case in other sectors, such as the automotive sector (62), the introduction of increasing constraints in terms of energy and environmental performance may render certain properties **difficult to sell or rent, resulting in a loss of value**. In this context, it can be expected that the market will assign a premium price to properties that already comply with regulations, as opposed to those that risk future restrictions.

The extant empirical evidence demonstrates equivocal results. The literature on the subject is inconclusive, with some studies confirming the existence of a statistically significant premium, while others find no or marginal effects. Despite the existence of studies that have documented a positive impact, there is considerable variation in the estimates of the green premium. This variation extends from a few percentage points to increases of more than 10%, indicating the influence of methodological, institutional and contextual factors.

A substantial body of research (63–66) has contributed to the consolidation of the scientific discourse, substantiating the existence of a price premium and offering consistent empirical evidence. However, a systematic and comparative analysis of the extent of the green premium in the residential sector is still lacking, both between different European markets and in the Italian context (44).

2.2.2. Methodological design and material selection protocol

The systematic literature review is based on the **PRISMA** (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol (67) to summarise the empirical evidence relating to property value differentials associated with EPCs in the European residential sector.

The study has three scientific objectives:

1. **Literature mapping:** identifying the European scientific community active on the subject, through bibliometric analysis of authors, affiliations and years of publication;
2. **Empirical verification of the price premium differential:** ascertaining the existence of a positive price premium associated with energy-efficient properties;
3. **Quantification of the green premium:** determining the extent of the property price premium in European markets, with a specific focus on the Italian context.

The methodological design of the research follows a five-stage sequence (cfr Figure 4):

- **Phase I:** delimitation of the research domain, with definition of thematic boundaries;
- **Phase II:** systematic search of academic databases using structured queries;
- **Phase III:** descriptive analysis and categorisation of the selected corpus according to temporal, geographical and institutional variables;
- **Phase IV:** extraction and codification of quantitative evidence on price premiums;
- **Phase V:** discussion and critical evaluation of the results.

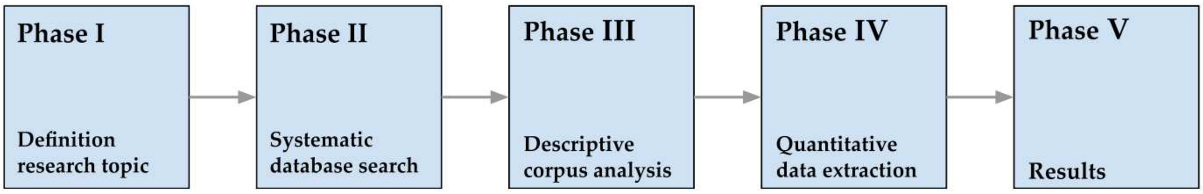


Figure 4: Research methodology design of the literature review in five steps

In the initial phase, the research is oriented towards the European residential market, with the investigative domain being delineated according to the principles of bounded rationality. The

European context is particularly well-suited for analysis due to the presence of a harmonised regulatory framework at the EU level, derived from the EPBD directives, consolidated energy certification systems, extensive historical series, and structural comparability between national real estate markets.

The decision to focus exclusively on the **residential sector** is based on methodological consistency, as the commercial and office market has different evaluation criteria, decision-making processes involving institutional actors other than households, energy regulations that vary according to intended use, and contractual complexities that can introduce confounding factors into price analysis (68). Restricting the analysis to the residential sector guarantees greater data homogeneity and enhanced precision in identifying the price premium associated with energy-efficient properties.

The second phase involves systematic research on academic databases using structured queries, constructed through a semantic analysis of existing literature that combines terms related to energy performance and residential real estate. The selection of Scopus as the primary database is substantiated by its extensive coverage of peer-reviewed journals, standardisation of metadata, reliability of ranking algorithms and transparency of inclusion criteria. The preliminary search yielded **4,255 documents**.

The filtration process was divided into multiple stages, with increasingly restrictive criteria being applied. The **temporal filter** imposed a limitation on the reference period to 2010-2025, as 2010 marks the beginning of a phase of greater seriousness and ambition in building energy policy, making studies conducted before this year potentially less representative of market dynamics and the "green premiums" generated by a more mature and stringent regulatory framework, thereby reducing the sample to 3,860 documents. The **typological filter** excluded non-peer-reviewed publications, such as working papers and grey literature, reducing the corpus to 2,426 documents.

Consequently, the **geographical filter** was utilised to restrict the analysis to European contexts only, thereby further reducing the number of documents to 1,477. The selection by **subject area** retained only studies of an economic and financial nature, thereby limiting the search to the areas of Economics, Business, Management and Accounting, Environmental Science, Engineering and Energy. Concurrently, the **selection of keywords** was constrained to terms that were directly pertinent to the investigation of the energy-efficient residential market, encompassing exclusively "housing" and "energy performance".

The employment of a dual disciplinary and thematic filter facilitated the isolation of the most pertinent contributions for price premium analysis, with studies focusing on other aspects of building sustainability or indoor comfort, such as air quality, noise pollution, HVAC systems, heat pumps or architectural design, being excluded.

The final selection phase entailed a meticulous examination of abstracts, titles and full texts, to identify only pertinent contributions. This process culminated in a total of **55 articles** being incorporated into the analysis (cfr Figure 5).

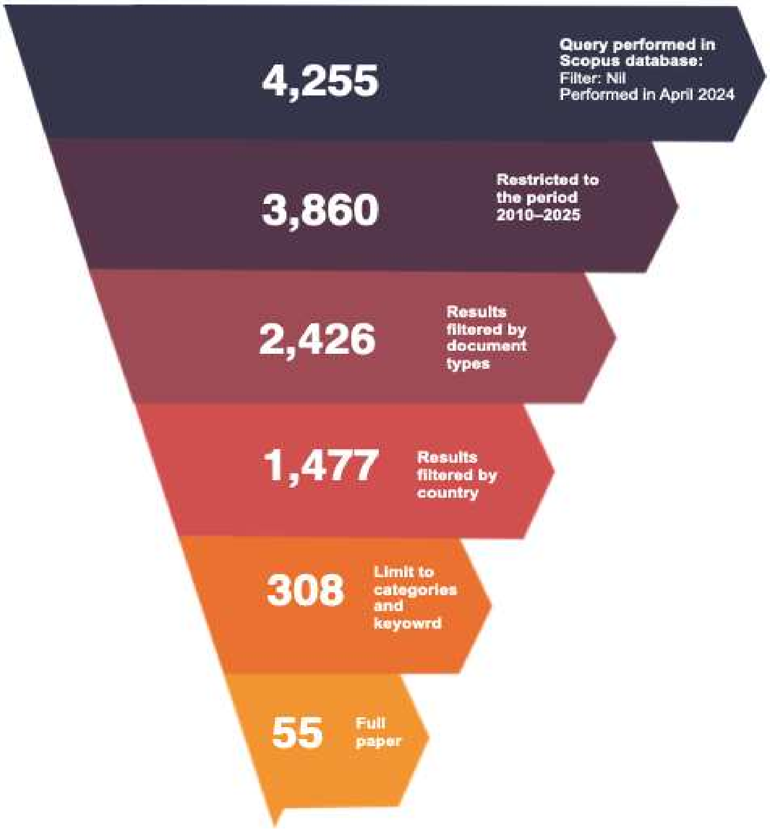


Figure 5: PRISMA diagram of the literature selection process

A detailed dataset was constructed for the 55 selected articles, containing information on sequential number, authors, affiliations, title, year of publication, journal, volume, issue, pages, DOI, abstract, keywords and bibliographic references.

All contributions were included in the preliminary literature mapping phase, during which the temporal evolution of the studies was analysed, as well as the frequency and type of keywords, the research centres involved, the main authors and recurring theoretical references. The descriptive analyses of Phase III were performed using Excel data, while VOSviewer software was used to identify common theoretical references and keywords.

In the context of the price premium analysis (Phase IV), the selection of contributions was constrained to those reporting original empirical data on the added value of energy-efficient properties, excluding literature review articles or theoretical discussions of value. This process resulted in the restriction of the corpus to 31 papers.

A secondary dataset was then constructed on this subset to reconstruct the price premium values for each author, country and field of investigation. In addition, the specifications relating to the EPC scale adopted were also included where available. The descriptive analysis and the analysis of the price premium were conducted by distinguishing between the European and Italian contexts, offering a comparative view of the European real estate market as a whole and, concomitantly, exploring the peculiarities of the Italian market within the EU regulatory framework.

2.2.3. Descriptive analysis

The finalised dataset encompasses 55 scientific contributions from the European academic ecosystem, providing a comprehensive mapping of intellectual output on property value differentials associated with energy efficiency. The descriptive analysis aims to illustrate the geographical distribution of institutions, temporal trends and the main researchers involved in scientific output.

The analysis of geographical distribution, based on the first affiliation of the corresponding author to avoid duplication in multinational projects, highlights a concentration of research in certain key countries (cfr. Figure 6).

Italy emerges as the dominant corpus, with 11 contributions (20% of the sample). This predominance is indicative of the dynamism of the national academic discourse surrounding these issues. The United Kingdom is a close second with five studies, while Germany contributes four publications.

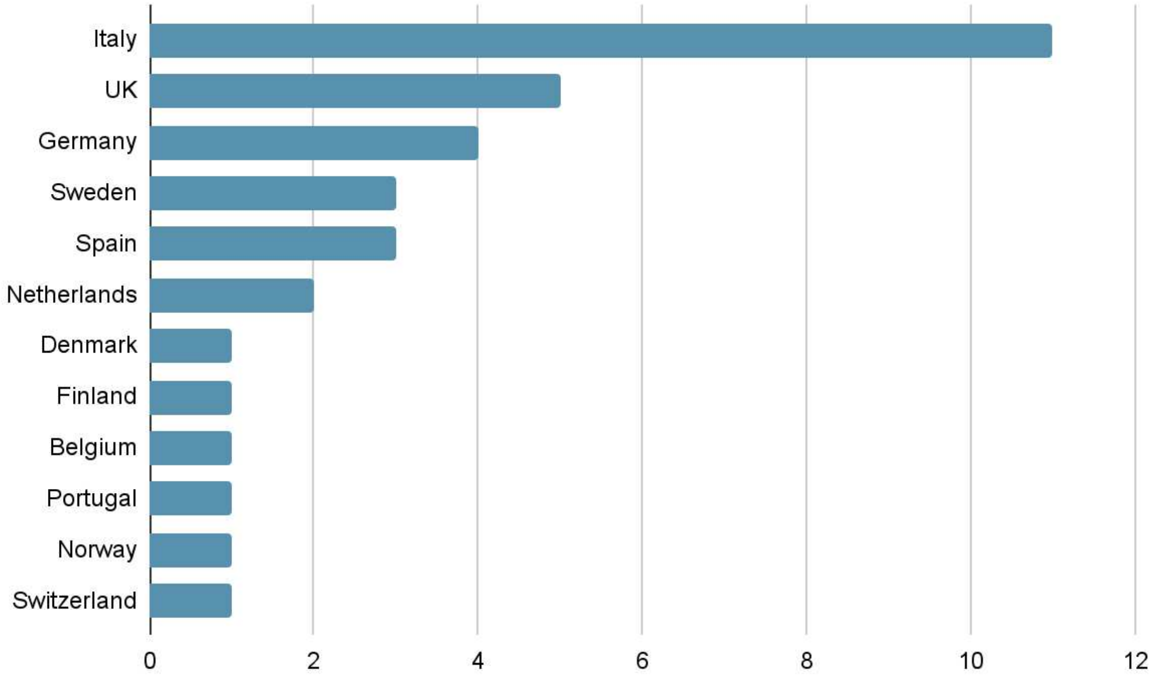


Figure 6: Geographical distribution of the sample of European scientific contributions by first author

A second tier comprises Sweden and Spain, with three contributions each. This finding indicates the presence of research groups specialising in Nordic and Mediterranean contexts. The Netherlands (two studies) and Denmark, Finland, Belgium, Portugal, Norway and Switzerland (one contribution each) make significant but limited contributions in terms of numbers.

It is noteworthy that France is absent from the research, given the size of the national property market and its established tradition of economic research. This suggests the possibility of an alternative thematic focus not captured by the adopted research strategy.

The analysis of **institutional affiliations** highlights a polycentric structure with well-defined centres of excellence. Italy is distinguished not only by the quantity of its contributions but also by the greater density of its institutional connections, which are indicative of well-established collaborative networks and coordinated research programmes. The most prominent Italian universities are Sapienza University of Rome, the Polytechnic University of Turin and IUAV University of Venice, with four contributions each. These are followed by the University of Padua and the Polytechnic University of Bari (three each) and southern universities such as Naples Federico II and Reggio Calabria (two each).

At the European level, the University of Cambridge (United Kingdom) and the Royal Institute of Technology – KTH (Sweden) are noteworthy for having published five papers each, while the NTNU Business School (Norway) has published three. With two repetitions, the University of Duisburg-Essen and the University of Regensburg (Germany), the Polytechnic University of Catalonia (Spain), and the University of Reading and the University of Aberdeen Business School (United Kingdom) are also worthy of mention.

The temporal analysis demonstrates a consistent increase in scientific output between 2010 and 2024, suggesting both the maturation of the sector and an escalating interest in energy efficiency in real estate.

The early years (2010–2011) saw a limited number of publications (1 each), with an increase in 2013–2014 (3 publications per year) and more marked growth in 2015–2016 (up to 5 contributions). The 2017–2019 period was characterised by stability, with a consistent annual output of 3–5 publications. The 2020–2022 period, however, signified a notable escalation in productivity, with 6 publications in 2020 and 7 in 2022. The most recent years (2023–2024) demonstrate a slight decline (2 publications each) (cfr. Figure 7).

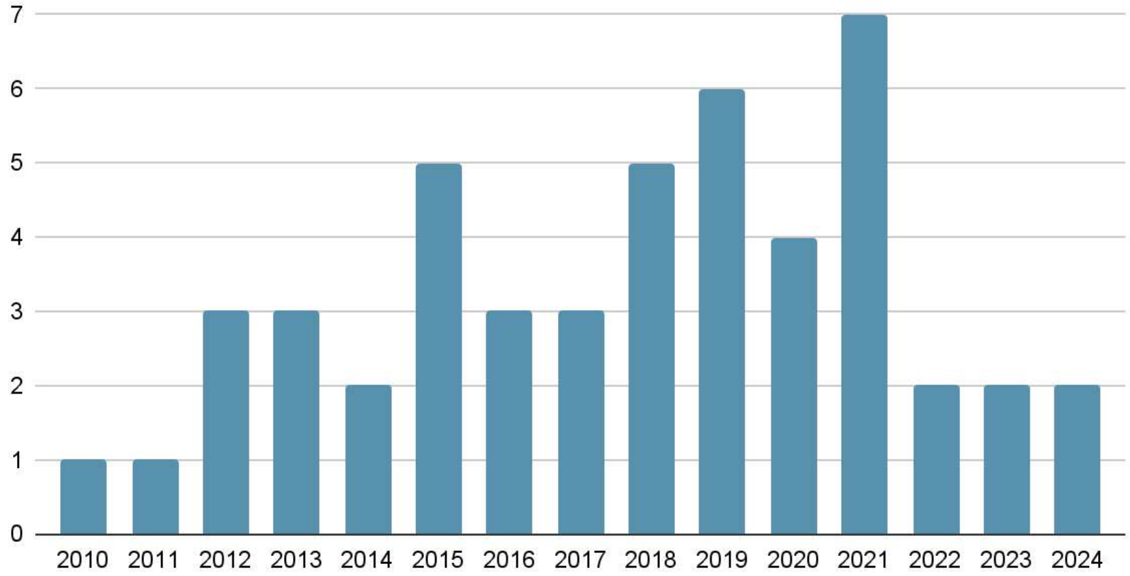


Figure 7: Annual number of scientific publications (2010–2024)

An analysis of the **authors' composition** reveals the presence of researchers who appear in multiple documents, indicating the formation of stable nodes in the European research network.

Among the most prolific researchers in Europe, with a minimum of three contributions, are Nils Kok (Maastricht University) with four contributions (13,14,20,69) and Piet M.A. Eichholtz (Maastricht University) with three (13,69). In the United Kingdom, Franz Fuerst (University of Cambridge) is cited in six publications (15,70–74), while Patrick McAllister is cited in three (15,70,75).

In Italy, recurring authors include Sergio Copiello (IUAV Venice) with four works (42,76–78), Elena Fregonara and Diana Rolando (Turin Polytechnic) with three each (79–81), and Pierluigi Morano and Francesco Tajani (Bari Polytechnic and Sapienza University of Rome) with three contributions (82–84).

The **analysis of co-citations** has made it possible to identify the most cited articles in the literature. Six studies appear at least five times among the references and represent key points of reference for the scientific community (cfr. Figures 8):

- Brounen and Dirk, *On the economics of energy labels in the housing market* – 22 citations, 28 links (69);
- Amecke, *The impact of energy performance certificates: a survey of German homeowners* – 13 citations, 21 links; analyses the impact of energy performance certificates on homeowners (85);
- Cajias and Marcelo, *Green performs better: energy efficiency and financial return on buildings* – 8 citations, 12 links; links energy efficiency and financial return on buildings (40);
- Cerin and Pontus, *Energy performance and housing prices* – 6 citations, 13 links; investigates the relationship between energy performance and property values (41);
- Eichholtz, Piet M.A. (2010), *Doing well by doing good? Green office buildings, American Economic Review* – 5 citations, 13 links; demonstrates the economic relevance of sustainability in offices (20);
- Fuerst, Franz (2015), *Does energy efficiency matter to home-buyers? An investigation of EPC ratings and transaction prices in England, Energy Economics* – 5 citations, 17 links; assesses the impact of EPC certifications on residential transactions in England (70).

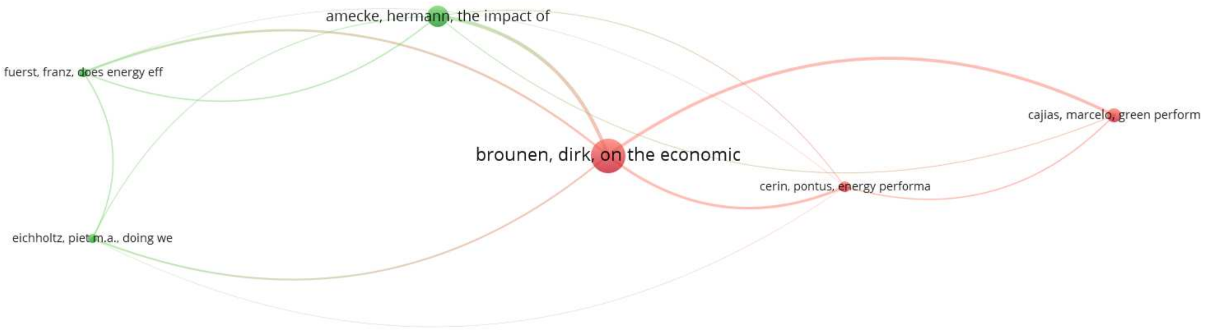


Figure 8: Key publications in energy efficiency research: co-citation analysis

Keyword analysis is a valuable tool that can be used to identify the central themes that structure the literature under consideration. As demonstrated, the term "energy efficiency" is identified on more than 40 occasions among the total number of terms identified. The search string is accompanied by other relevant keywords, including 'energy performance' (20), 'housing' (19), 'cost' and 'commerce' (18 each), and 'housing market' (17), which collectively reflect the two central focuses of the search string set in the query (cfr. Figure 9).

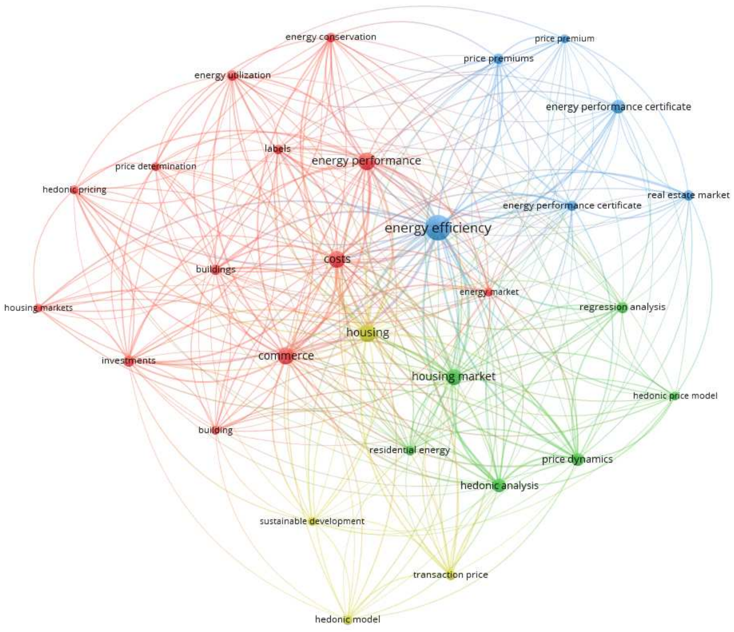


Figure 9: Most frequent keywords in the sample of selected publications

Other significant terms include "economic analysis" and "energy performance certificate" (both 12 occurrences), as well as "price dynamics" (11), suggesting a mounting interest in economic evaluation and energy certification instruments. It is evident that other concepts, albeit less frequent, such as "investment", "energy price premium" and various valuation methodologies, including "hedonic price" and "hedonic model", underline the link between energy efficiency, economic incentives and investment choices.

The analysis confirms that the literature is predominantly focused on the energy performance of buildings and its economic and market implications, while methodological and conceptual contributions play a subsidiary role, enriching and consolidating the principal research trajectories.

2.2.4. Empirical analysis of the price premium in Europe and Italy

The present study is an updated review of the literature on the subject, and its **findings confirm the theoretical hypothesis that** the property market is segmented according to the energy performance of buildings. The study provides solid empirical evidence of price differentials linked to energy efficiency in the European residential sector.

The analysis yielded two primary outcomes. Firstly, the majority of studies documented statistically **significant price premiums** associated with enhanced energy performance. Secondly, the market exhibited greater sensitivity to environmental sustainability issues in northern European countries compared to those in southern regions.

As illustrated in Table 3, the quantitative results about the price premium documented in European studies have been arranged according to the year of publication. The values displayed herein represent percentage changes in comparison to the reference energy classes, thereby highlighting both the minimum and maximum premiums ascertained in the various studies. The table facilitates a comparison of the value differential associated with the energy performance of residential buildings in different European countries and highlights the methodological and territorial variations between the studies.

Reference	**Year**	**Country**	**Premium Price Minimum**	**Premium Price Maximum**
Brounen & Kok (69)	2011	Netherlands	G → D : 5%	D → A : 10.20%
Cajias & Piazolo (40)	2013	Germany	G → B/C: 32.80%	G → B : 114.30%
Hyland et al. (86)	2013	Ireland	D → A : 9.3%	E/G → D : 10.60%

Feige et al. (75)	2013	Switzerland	n.s. → n.s. : -29.00%	n.s. → n.s. : 12.00%
Kholodilin, et al. (87)	2014	Germany	—	n.s. → n.s. : 23.70%
Cerin et al. (41)	2014	Sweden	reduction in energy consumption ↓1% → market value ↑0.37%	
Fuerst et al. (73) 30/11/25 21:08:00	2014	Finland	E → D : 1.20%	D → A/B : 6.50%
Fuerst et al. (15)	2015	England	D → A : 5%	G → D : 7%
Davis et al. (88)	2015	Belfast (Northern Ireland)	D → C : 4.90%	D → B : 28.00%
De Ayala et al. (89)	2016	Spain	E/F/G → A/B/C/D : 5.40%	—
Fuerst et al. (15)	2016	Wales	F → D : 6.5%	D → A : 12.8%
Chegut et al. (90)	2016	Netherlands	B → A : 1.10%	C → A : 5.80%
Fuerst et al. (71)	2016	Finland (HMA)	D → A/B/C : 3.5%	—
Jensen et al. (91)	2016	Denmark	D → A : 6.6%	G → D : -9.3%
Wahlström (92)	2016	Sweden	reduction in energy consumption ↑1% → market value -9.0%	
Taltavull et al. (93)	2017	Bucharest (Romania)	n.s. → n.s. : 2.20%	n.s. → n.s. : 6.70%
de La Paz et al. (94)	2019	Spain (Alicante)	reduction in energy consumption ↓1% → market value ↑3.10%	
Marmolejo-Duarte & Chen (95)	2019	Barcelona (Spain)	G → A : 7.8%	G → D : 3.3%
Dell'Anna (96)	2019	Barcelona (Spain)	—	+1,8%
Aydin et al. (13)	2020	Netherlands	EPC ↓1% → market value ↑0.20%	
McCord et al. (97)	2020	Northern Ireland (Belfast)	D → C : 3.30%	G → D : 23.50%
Fuerst et al. (74)	2020	England	D → B/C : 6.30%	E/G → D : 11.90%
Evangelista et al. (98)	2020	Portugal	D → C : 1.40%	C → A : 26.60%

Table 3: Price premium of European residential properties by energy class

Focusing on the residential market, the reviews by Fuerst et al. (2016), Copiello et al. (2021) and Zhang et al. (2018) summarise the main findings of studies on the premium price linked to the energy efficiency of buildings. Notwithstanding the existence of certain exceptions, such as Wahlström's (2016) study on the Swedish market, which reports negative effects associated with increased consumption, the majority of studies highlight positive price increases attributable to energy savings in the home.

In Northern European countries, there is a particularly marked sensitivity to energy efficiency. In the Netherlands, Brounen and Kok (2011) identified a 5% differential between class G and class D homes, with peaks of up to 10.2% for class D properties compared to class A. In subsequent studies, Chegut et al. (2016) quantified a smaller premium, between 1.1% (B → A) and 5.8% (C → A), while Aydin, Brounen and Kok (2020) estimated marginal increases of 0.2% for each percentage point of improvement in the EPC.

In Germany, Cajias and Piazolo (2013) found high differentials, ranging from 32.8% (G → B/C) to 114.3% (G → B), which were confirmed by Kholodilin et al. (2014) with premiums of up to 23.7%, though without specifying the reference classes.

In Denmark, Jensen et al. (2016) demonstrated an increase of 6.6% for properties in class D compared to class A, while properties in class G exhibited a depreciation of -9.3%.

Within the United Kingdom, analogous trends are evident. In England, Fuerst et al. (2015) identify differentials between 5% (D → A) and 7% (G → D), while in Wales, Fuerst et al. (2016) report premiums of up to 12.8% (D → A) and devaluations of 6.5% (F → D).

In Northern Ireland, Davis et al. (2015) document increases of up to 28% (D → B), while McCord et al. (2020) report increases of between 3.3% (D → C) and 23.5% (G → D). In Ireland, Hyland et al. (2013) report premiums of 9.3% (D → A) and 10.6% (F/G → A). The positive effects of energy efficiency have also been confirmed in the Nordic countries. In Finland, Fürst et al. (2014) report premiums ranging from 1.2% (E → D) to 6.5% (D → A/B), and Fürst et al. (2016) estimate a 3.5% increase in the Helsinki metropolitan area.

In Sweden, however, the results are more mixed: Cerin, Hassel and Semenova (2014) report a marginal positive effect of up to 0.37% for each 1% reduction in consumption, whereas Wahlström (2016) reports a devaluation of around 9% for each 1% increase in consumption.

In Switzerland, Feige, McAllister and Wallbaum (2013) report a wide range of results, from a negative impact of -29% to a maximum premium of 12%, though they do not specify the energy classes involved.

In a Mediterranean context, de Ayala et al. (2016) estimate an average premium of 5.4% for efficient homes (classes D → A) compared to less efficient ones (classes G → E) in Spain. In the Barcelona metropolitan area, Marmolejo-Duarte and Chen (2019) report increases of 7.8% (G → A) and 3.3% (D → A), while de la Paz et al. (2019), in Alicante, estimate an increase of 3.1% for each percentage point reduction in consumption.

In Portugal, Evangelista et al. (2020) quantify premiums ranging from 1.4% (D → C) to 26.6% (C → A). In Romania, Taltavull et al. (2017) highlight premiums ranging from 2.2% to 6.7% in Bucharest without specifying the energy classes (cfr. Figure 10).

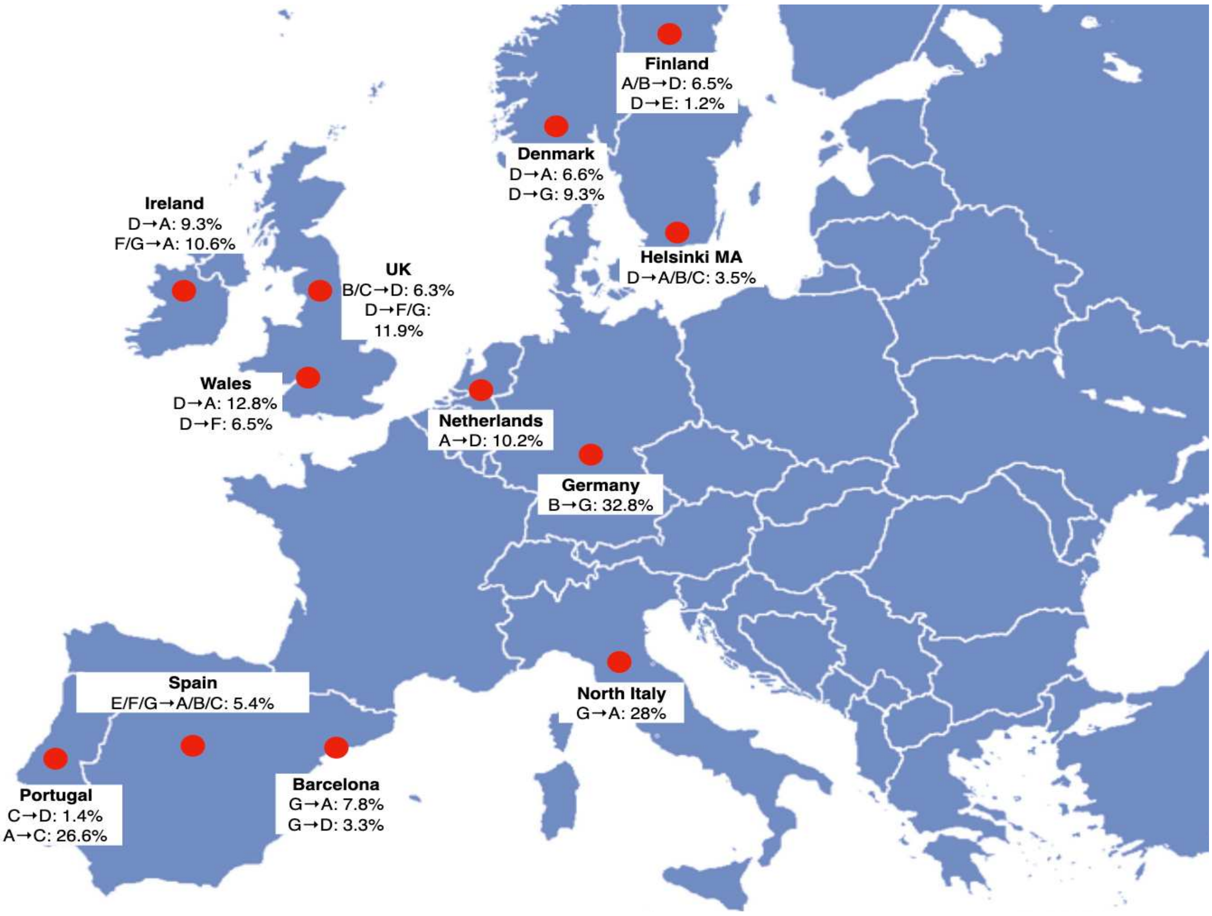


Figure 10: Green price premium across European residential markets

Research on the **Italian residential market** shows an increase in demand for energy-efficient properties, with price differentials varying between cities and climatic contexts. While the sign of the differentials is always positive as energy efficiency increases, the extent varies from a few percentage points to as much as 30%. Markets in northern Italy demonstrate consistent but moderate price premiums. The case of Bolzano shows an interesting evolution over time. While Morano and Tajani (2018) document premiums of up to 45%, Bisello et al. (2020) estimate more modest increases of around 6.4% using more refined methodologies. This suggests possible market corrections or methodological differences. The cities of Turin and Veneto confirm the existence of significant premiums, with the latter's market showing dynamism, with increases for the G - A class of up to 34.18%.

The market in Southern Italy has peculiar characteristics. Studies on Bari document high but highly variable premiums, ranging from +0.7% for marginal G → F transitions to +84% for the G → A comparison. This indicates possible problems with the robustness of the estimates.

The most recent national-scale evidence (54–56) shows average premiums of between 28% and 36% for the G → A comparison, with peaks of up to 41.5% for classes B and A. This suggests a maturation of the Italian market in terms of energy efficiency (cfr. Table 4).

Reference	**Year**	**Cities**	**Premium Price Minimum**	**Premium Price Maximum**
Bonifaci & Copiello (78)	2015	Padua	G → E : +9,5%	G → A : +21,9%
Morano et al. (82)	2018	Bari	G → baseline: −26,44%	A → baseline: +27,94%
Manganelli et al. (84)	2019	Bari, Acri	G → F : +0,7%	G→ A : +84%
Dell'Anna (96)	2019	Turin	—	+6,5% (Turin)
Bisello et al. (99)	2020	Bolzano	G → C : +2,6%	G → A : +6,4%
Morano et al. (83)	2020	Bari	G → baseline: −26,44%	A → baseline: +27,94%
Del Giudice et al. (53)	2021	Italia	—	A/B → baseline: +29,07%
Del Giudice et al. (100)	2022	Italia	—	A/B → baseline: +41,52%
Ruggeri et al. (101)	2023	13 cities north Italy	G → A : +28%	G → A4 : +36%

Table 4: Price premium of Italian residential properties by energy class

2.2.5. Discussion on the Energy Efficiency Price Premium

A systematic review of the literature identified 55 studies published over 14 years, highlighting an **acceleration in scientific output in recent years**. However, this quantitative growth is accompanied by geographical variation in the distribution of empirical evidence.

The existing literature shows a significant lack of studies focused on Central and Eastern European markets. This limits the generalisability of the results and our understanding of market dynamics in different institutional and economic contexts.

The systematic review confirms the **robustness of the theoretical framework** proposed for capitalising on energy efficiency in residential property values. A comparative analysis of the selected studies supports the existence of two distinct mechanisms for transmitting the energy premium, which were previously theorised, but not systematically verified, in the international literature. The first of these is a direct channel that incorporates expected energy savings into the price, and it is particularly relevant in markets with high information transparency. The second, an indirect channel linked to regulatory expectations, can generate premiums that exceed the simple capitalisation of energy costs.

A quantitative analysis of the selected studies reveals an empirical landscape characterised by significant variability in the amount of the premium prices documented. Estimates range from zero, or even negative, values — as seen in the extreme cases documented in Switzerland and Sweden, with reductions of up to 29% — to substantial increases of over 20%, as observed in specific urban contexts in southern Europe.

As reported in the literature, the average price premium for properties belonging to inefficient energy classes compared to efficient properties generally ranges between 3% and 10%. In Northern European markets, however, premiums are more stable, typically ranging between 5% and 8%. In contrast, premiums in southern markets are more variable, sometimes reaching very high levels, but are characterised by less stability over time and less methodological robustness.

A comparative analysis reveals that **geography and climatic conditions are the main factors** in explaining the differences observed between markets. In Nordic countries, which are characterised by harsher climates and a long-standing tradition of environmental awareness, the recognition of the value of energy efficiency appears to be more firmly established.

A particularly significant finding that emerged from the review is the **inverse relationship between housing demand pressure and price differentials based on energy efficiency**. In markets characterised by strong housing demand, the price differential between efficient and inefficient properties tends to narrow significantly as scarcity of supply prevails over segmentation by energy characteristics. This suggests that the market's ability to 'reward' energy efficiency critically depends on overall supply and demand conditions.

This result has important theoretical implications for understanding the mechanisms of property value formation. In conditions of excess demand, 'secondary' attributes such as energy efficiency lose their discriminatory power in determining property values, whereas in more balanced markets, these attributes can fully express their economic value.

The extent of the energy price premium is largely determined by **urban size**. Mid-sized cities consistently exhibit higher premiums than large cities, where demand pressure and supply scarcity offset price variations based on energy characteristics. This pattern suggests the existence of a 'critical threshold' of urban size beyond which traditional market mechanisms are influenced by scarcity factors.

For instance, in northern Italy, price premiums tend to be consistent but moderate (e.g. Bolzano: 6–45%; Veneto: up to 34%), whereas in the south, wider but less stable differentials emerge (e.g. Bari: +0.7–84%).

This territorial variability in the impact of the energy transition could lead to **“green discontent”,** i.e. social resistance resulting from the concentration of costs in vulnerable areas. This is a critical factor to consider, as it could undermine political consensus and lead to a loss of property value, as highlighted by several European studies. In addition to undermining political consensus, this phenomenon can affect social cohesion and lead to a loss of property value, as highlighted by several European studies (102–104).

The concept of a '**just transition**', introduced in the 1970s by the North American trade union movement, is now central to environmental policies as it calls for a balance between labour, technology, society and geography (45,46). European and national governments are seeking to integrate this perspective, recognising that an unfair transition is not viable from an environmental point of view either (105).

With the introduction of new European regulations, the sale and rental of low-efficiency properties will gradually become more restricted. Given that Italian households' wealth is heavily concentrated in real estate (106), it is crucial to understand how losses in value will affect large cities and smaller towns differently. This will enable the design of policies capable of ensuring a fair transition in energy, social and economic terms (107).

2.3. Selected cities and real estate market dynamics

The reference sample comprises eight cities in Northern Italy, categorised by size and regional significance. **Major cities** serve as key drivers of regional and national development, typically functioning as regional capitals, highly urbanised, and characterised by elevated property values. In the sample: **Milan, Turin, Florence, and Trieste**.

Mid-sized cities are smaller but economically and socially relevant, playing an important role in local real estate dynamics. In the sample: **Mestre (Venice), Padua, Bergamo, and Udine**.

The territorial distribution of the sample is as follows:

- Lombardy: Milan (Major City) and Bergamo (Mid-Sized City)
- Piedmont: Turin (Major City)
- Veneto: Mestre and Padua (Mid-Sized Cities)
- Friuli Venezia Giulia: Trieste (Major City) and Udine (Mid-Sized City)
- Tuscany: Florence (Major City)

The selection of cities was guided by two main criteria:

1. **Belonging to a cold climate zone**
2. **Intra-group homogeneity**

Most of the cities included in the sample are in the continental climate zone, the second coldest in Italy, except Florence, which is in the Mediterranean climate zone. Continental areas are characterised by cold winters and hot summers, with average temperatures ranging from -6 °C to 25 °C and uniform precipitation throughout the year (108) (cfr. Figure 11).

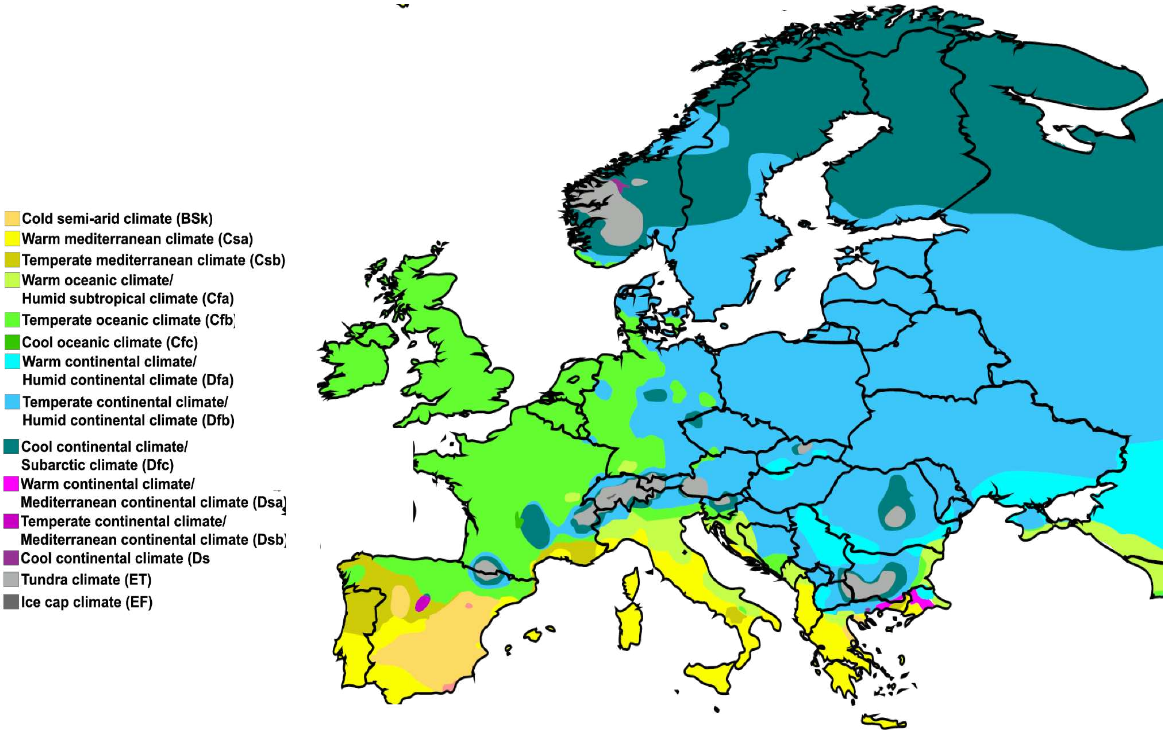


Figure 11: Distribution of climate zones in Europe according to the Köppen-Geiger classification

Analysing cities in cold climates is particularly insightful for evaluating building energy performance, as heating constitutes the most significant energy demand. This configuration allows a rigorous assessment of energy efficiency, highlighting both strengths and weaknesses in a context where energy savings have the greatest impact.

Furthermore, as the continental climate zone covers many areas in Europe, the results could, with the necessary precautions, be applied to other comparable European urban contexts. Metrics such as Heating Degree Days (HDD) provide a robust framework to quantify heating demand and refine energy performance certification (EPC) methodologies, supporting the promotion of sustainable building practices in regions with high heating requirements.

According to Presidential Decree No. 412/1993 (109), the national territory is divided into six climate zones (A–F) based on **degree days (DD),** which are calculated independently of latitude. Almost all the cities in the sample belong to Zone E (2,100 ≤ DD ≤ 3,000); only Florence falls within Zone D (1,400 ≤ DD ≤ 2,100) (cfr. Table 5).

Heating Degree Days							
Major cities				**Mid sized cities**			
Milan	Turin	Florence	Trieste	Padua	Bergamo	Venice	Udine
2404	2617	1821	2102	2383	2533	2345	2323

Table 5: Climate zones and Heating Degree Days of the cities in the sample

The second selection criterion favoured cities that showed a high degree of homogeneity in terms of economic structure, production diversification, real estate market dynamism and administrative importance within each size group.

When selecting the Major Cities, preference was given to metropolitan areas. An exception is Trieste, which, despite not formally belonging to the group of metropolitan cities defined by Law No. 56 of 7 April 2014, is the capital of the Friuli Venezia Giulia region, and its harsh Alpine climate is similar to that of the other cities.

To verify the similarities and differences between the Major and Mid-Sized Cities, a **comparative analysis** was conducted on the cities' demographic, social, economic and real estate indicators. All values refer to the year **2022**.

The data were collected from multiple official sources: ISTAT for demographic figures and the number of active enterprises; the OMI database of the Italian Revenue Agency for real-estate market values; the Italian Ministry of Economy and Finance (MEF) for indicators of economic performance (average income and GDP per capita); and the Chambers of Commerce for the number of formally registered start-ups (see Table 6).

Major cities are characterised by a significantly **large population**, with Milan and Turin having 1,374,582 and 858,205 inhabitants respectively. Among mid-sized cities, the population ranges from a minimum of 98,430 in Udine to almost 300,000 in Venice.

City	Inhabitant	Manufacturing Units	Financial units	Average income (€)	Start-ups	GDP per capita (€)	Real estate values (€/m²)
			Major cities				
Milan	1,374,582	9,275	64,043	31,778	2,150	33,936	4,552
Turin	858,205	5,045	20,056	23,626	411	24,604	1,969
Florence	368,419	2,806	11,968	23,666	145	25,224	3,394
Trieste	199,015	571	3,150	23,168	12	28,002	1,957
			Mid-sized cities				
Padua	206,651	1,104	7,399	26,550	120	32,793	1,776
Bergamo	119,476	893	5,381	29,090	114	36,275	2,099
Venice	256,083	1,482	4,982	21,227	78	22,459	2,677
Udine	98,430	393	3,177	25,782	51	31,200	1,395

Table 6: Socio-economic and real estate market indicators of the selected cities

In economic terms, major cities have a high number of **manufacturing and financial units**. Milan is the leader in this respect, with 9,275 manufacturing units and 64,043 financial units, followed by Turin with 5,045 manufacturing units and 20,056 financial units. To a lesser extent, mid-sized cities also have significant productive and active financial networks capable of supporting growth and innovation. Padua has 1,104 manufacturing units and 7,399 financial units; Bergamo has 893 manufacturing units and 5,381 financial units; and Venice has 1,482 manufacturing units and 4,982 financial units.

Conversely, **entrepreneurial innovation** is heavily concentrated in major cities. Milan has 2,150 start-ups, compared to 411 in Turin and significantly lower figures in mid-sized cities such as Padua 120 and Bergamo 114.

Economic indicators show broadly comparable patterns between Major cities and Mid-Sized cities. **Average income**, which captures the typical earnings of residents, is almost identical across the two groups, amounting to €25,560 in Major cities and €25,662 in the Mid-Sized cities.

By contrast, clearer differences emerge when considering **GDP per capita**, which reflects the total economic output generated per resident. This indicator reaches €27,942 in Major cities, compared with €30,682 in the Mid-Sized cities, indicating a comparatively stronger economic performance in the latter.

Within the mid-sized group, some cities stand out: For example, Bergamo has an average income of €29,090 and a GDP per capita of €36,275, which is higher than in some major cities. In contrast, Venice has lower figures (€21,227 and €22,459, respectively).

These data confirm that some mid-sized cities can compete with major cities in terms of economic well-being, indicating that this group is more heterogeneous than its population size would suggest.

Property values consistently reflect the size and dynamism of different urban centres. Overall, the residential markets of the two samples are comparable, with differences primarily relating to housing demand and the characteristics of the local economy.

Among the major cities, the average market value is €4,552/m^2 in Milan, €3,394/m^2 in Florence, and €1,957/m^2 in Trieste. Among mid-sized cities, Venice stands out with an average market value of €2,677/m^2, followed by Bergamo with €2,099/m^2 and Udine with €1,395/m^2.

To strengthen the consistency of the sample and ensure the necessary homogeneity for subsequent analyses, a **second analysis focusing on the evolution of the residential property market** and the main socio-economic indicators in cities in northern Italy between 2012 and 2022 was also carried out.

This time frame includes two critical phases: the 2012 recession, a consequence of the second global economic crisis, and the 2020–21 health crisis linked to the SARS-COVID-19 pandemic. These events had a profound impact on demographic, economic, and real estate dynamics, necessitating a longitudinal comparison between major and mid-sized cities.

Table 7 shows the percentage changes in **socio-economic and real estate indicators** recorded in the eight cities analysed between 2012 and 2022.

City	Δ Inhabitant (%)	Δ Manufacturing Units (%)	Δ Financial units (%)	Δ Average income (%)	Δ Start-ups (ABS)	Δ GDP per capita (%)	Δ Real estate values (%)
				Major cities			
Milan	10.76	-0.049	15.49	6.30	2,149	10.83	37.76
Turin	-1.30	-0.088	2.92	7.44	410	9.15	-27.08
Florence	0.64	-0.080	2.32	1.40	144	5.07	4.63
Trieste	-1.38	-16.06	8.65	9.51	-	9.41	1.02
				Mid-sized cities			
Padua	0.49	-11.58	7.28	8.16	-	8.01	-8.38
Bergamo	3.60	-4.30	9.01	10.70	-	11.00	3.30
Venice	-1.85	-12.78	-0.78	-0.30	77	1.98	-18.96
Udine	-0.35	-18.11	2.54	13.25	-	11.93	-7.08

Table 7: Percentage changes in Socio-economic and real estate market indicators of the selected cities from 2012 to 2022

The percentage changes in the main socio-economic and real estate indicators between 2012 and 2022 confirm the different dynamics between major cities and mid-sized cities identified in the previous analysis.

In major cities, population growth is uneven: while Milan has experienced a substantial population increase of 10.76%, rising from approximately 1.24 to 1.37 million inhabitants, Turin and Trieste have witnessed slight population declines of 1.30% and 1.38%, respectively. Florence has grown modestly (+0.64%). In mid-sized cities, demographic changes are more moderate and uniform. Bergamo grew by 3.6%, Padua by 0.5%, Udine decreased by 0.4%, and Venice by 1.9%.

Regarding manufacturing activities, major cities have experienced modest declines, whereas mid-sized cities have seen more pronounced declines, with Trieste (-16.06%) and Udine (-18.11%) showing the most significant decreases.

Financial institutions remain heavily concentrated in major cities: Milan recorded significant growth (15.49%), while Turin and Trieste saw more moderate increases, and Venice showed a slight contraction (-0.78%).

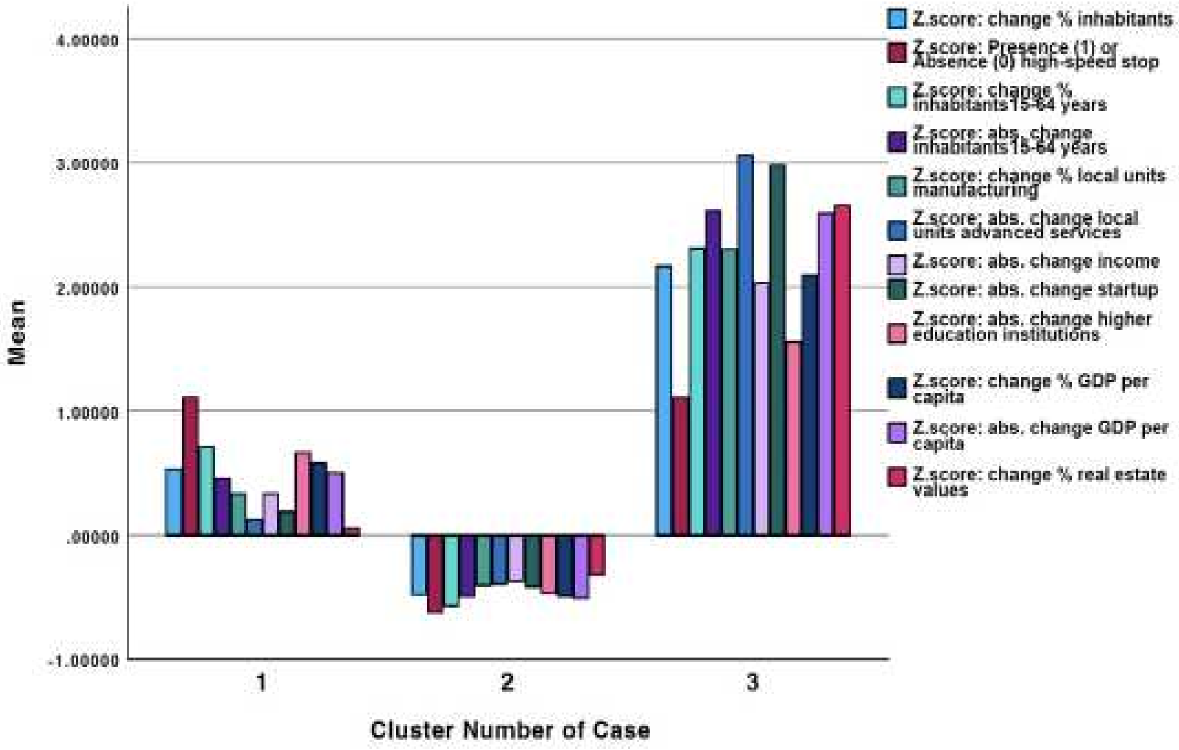
Innovative entrepreneurial activities are also heavily concentrated in major cities: Milan had 2,149 new start-ups and Turin had 410. Mid-sized cities have limited capacity to attract, suggesting that innovation is mainly concentrated in large centres, gradually transferring to smaller ones.

The increases in average income and GDP per capita are relatively consistent across the major cities: Milan: +6.3% and +10.83%; Turin: +7.44% and +9.15%; Trieste: +9.51% and +9.41%; and Florence, which experienced more modest growth, but consistent with the group. In mid-sized cities, performance is more variable. Bergamo recorded an average income increase of 10.7% and a per capita GDP increase of 11%, while Venice showed more modest increases of 0.30% and 1.98% respectively.

Real estate trends confirm significant differences between the groups. In the major cities, Milan shows a marked increase in property values (+37.76%), confirming its attractiveness as a location for residential investment. Meanwhile, Florence and Trieste show stability or slight increases. In mid-sized cities, the variations are more moderate: Bergamo (+3.30%), Padua (-8.38%) and Venice (-18.96%).

The first and second analyses confirm the distinction between the two groups of cities. This is also evident in previous studies on metropolitan cities (110,111), which analysed the evolution of Italian metropolitan cities through socio-economic and real estate indicators between 2012 and 2022. Market values were considered in the research as an indicator of a city's ability to attract new residents, as well as real estate, financial capital and new economic activities.

The study Micelli & Righetto (2022) classified the 14 metropolitan cities into three distinct clusters (cfr. Figure 12).



Cluster number: (1) Turin, Bologna, Florence, Rome; (2) Genoa, Venice, Naples, Reggio Di Calabria, Palermo, Cagliari, Bari, Catania, Messina; (3) Milan. Source: Micelli & Righetto, 2022.

Figure 12: Final clusters of standardised changes in metropolitan cities (2012–2022). (Micelli & Righetto, 2022)

The analysis revealed that urban concentration depends on structural factors, such as demographic dynamics, the density of economic activity and the presence of strategic infrastructure. These factors enable urban centres to compete (112–115).

Contrary to some hypotheses, the pandemic did not favour mid-sized cities; instead, it reinforced the trend of concentration in attractive hubs.

Milan remains the leading city for urban growth in Italy, with superior performance in almost all economic, demographic, and production indicators. This is reflected in an increase in property values of around 40%.

Although far from Milan's levels, Turin and Florence, like Naples and Rome, maintain significant appeal and stable property markets with slight growth. Florence has stable property values and moderate expansion in the advanced tertiary sector.

Conversely, Venice, along with Genoa and other southern cities, has experienced significant reductions in property values and sales volumes. These phenomena are linked to declining demographic trends and loss of residents, further exacerbated by poor infrastructure, which limits their competitiveness compared to more dynamic urban centres (116).

In conclusion, the fact that they are located in the same climate zone, combined with an updated socio-economic and property analysis (updated to 2022) and the changes recorded over the last ten years, provides a solid basis for assessing the impact of urban size on the green price premium and property values.

2.4. Materials and methodology

The methodology comprised a series of systematic phases designed to develop an integrated analytical model that could be reproduced and applied in different territorial contexts. The analytical process was divided into seven phases:

1. Selection of the urban contexts to be analysed;
2. Collection of property asking prices via digital portals for each city;
3. Cleaning of the collected data;
4. Processing descriptive statistics and frequency distributions of the collected data;
5. Regression analysis;
6. Statistical validation of the model;
7. Quantification of the impact of energy classes on property market value.

As described above, selecting the urban contexts to be investigated was the first stage of the study. **Eight cities in northern Italy** were included in the study. These cities are characterised by particularly harsh winters, where energy efficiency is a key factor in reducing energy consumption for domestic heating. The cities were divided into two main groups: **Major cities** (Milan, Turin, Florence and Trieste) and **Mid-sized cities** (Padua, Venice/Mestre, Bergamo and Udine).

Data collection was limited to the municipal boundaries of each city, excluding the larger metropolitan areas. Venice is a special case: for the analysis, only Mestre's urban area was considered, with the historic centre excluded. This was because the historic centre of Venice is subject to strict architectural and urban heritage protection restrictions and offers very few opportunities for energy efficiency measures.

The second phase of the study focused exclusively on the residential sector, involving **data collection**. There were three main reasons for this decision. Firstly, the residential sector is particularly sensitive to the energy performance of buildings, which has a direct effect on demand and market values.

Secondly, it is subject to stringent European regulation in the form of the EPBD Directive, which has been transposed into national law. Thirdly, the residential sector accounts for around 70% of the national building stock in terms of energy consumption and constitutes a significant proportion of Italian households' total assets (117).

Furthermore, a large proportion of Italian housing does not meet recommended energy performance levels: around 4 million residential units (68.6% of the total) belong to the lowest energy classes (E, F and G) (118).

The data comes from **asking prices** published on Immobiliare.it (119), the main Italian property portal. This source indicates the energy class of properties alongside other essential information, such as technological features, type, size, location, and urban context.

There are several reasons for relying on asking prices rather than on actual sales values. First, asking prices offer greater data availability and provide broader access to information contained in Energy Performance Certificates (EPCs). In Italy, the collection of transaction data is often constrained by strict privacy regulations and substantial limitations on access to such records (307).

It is therefore unsurprising that the scientific literature frequently relies on asking prices due to their accessibility, as demonstrated by numerous studies that have confirmed their usefulness for analysing real-estate market dynamics (308) and for conducting investigations that closely resemble the one developed in this research (101; 309).

Regarding the major cities, the dataset comprises a total of 2,484 units, distributed as follows: 858 in Milan, 744 in Turin, 394 in Florence and 488 in Trieste, with data acquired in July 2023. For mid-sized cities, the dataset includes 1,283 units: 348 in Padua, 246 in Mestre, 285 in Bergamo, and 404 in Udine (cfr. Figure 13).This data was collected in January 2023.

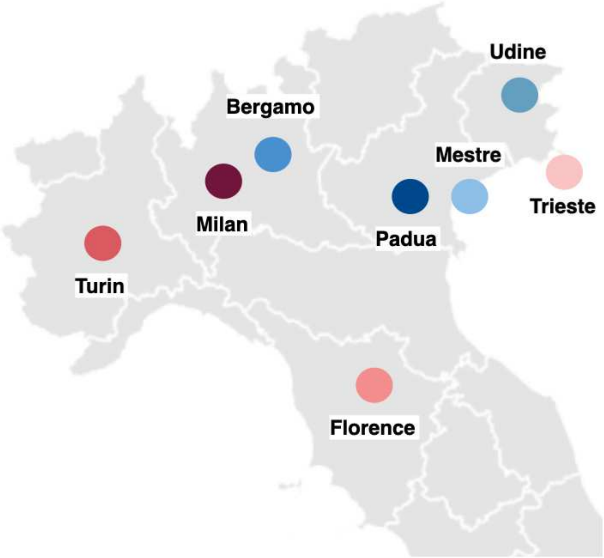
Major Cities

Milan
858 ask prices

Turin
744 ask prices

Florence
394 ask prices

Trieste
488 ask prices



Mid - Sized Cities

Padua
348 ask prices

Mestre (Venice)
246 ask prices

Bergamo
285 ask prices

Udine
404 ask prices

Figure 13: Geographic location of the eight cities in Northern Italy

The subsequent data collection phase was conducted manually, followed by a deduplication procedure aimed at removing any duplicates. In order to guarantee the thoroughness of the sample, a re-examination of the data was conducted for the purpose of verifying the comprehensiveness of the available asking prices.

Subsequently, statistical tests were performed to identify any multicollinearity between variables and to detect outliers. In the final analysis, all incomplete records, missing data and significant outliers were excluded.

During the collection phase, a variety of characteristics about **typological, technological, intrinsic and positional aspects** were meticulously documented for each property.

This integrated approach facilitates the construction of a rich and structured dataset, in which each property unit is described in terms of various aspects, providing a solid basis for the application of the HPM and for the estimation of the green premium in different urban contexts.

With regard to typological characteristics, the housing units were divided into two macro-categories: detached houses (villas) and aggregate units (apartments). The number of bathrooms and rooms per unit was recorded as an indicator of internal quality and typological level.

The internal quality of the properties was represented by classification into four categories of value: The following terms are employed: "high-end", "elite", "standard" and "low-cost". Concurrently, the state of maintenance for each property was coded into four levels: The following terms are employed to describe the condition of a property: "newly built", "refurbished", "well-maintained" and "run-down".

An additional set of explanatory variables was constituted by positional characteristics. The allocation of properties to one of three urban macro-areas – centre, semi-centre or periphery – was conducted in accordance with the official classification system employed by Osservatorio del Mercato Immobiliare (OMI) by Agenzia delle Entrate (120). Furthermore, proximity to significant local transport infrastructure, including the underground and railway, was documented to ascertain disparities in accessibility and connectivity. These factors are recognised as influential in determining market value.

In terms of energy classification, properties were categorised according to two schemes. The first is an **EPC system classified into 12 levels** from class A4 to class G according to Regulation (EU) 2017/1369 of the European Parliament and of the Council (121). This classification facilitates a more precise depiction of the variability in energy efficiency evident in the market, thereby enabling a more detailed estimation of its impact on market values.

Subsequently, to enhance the robustness of the estimates and facilitate more interpretable analyses, **a second energy class aggregation** scheme was implemented. This scheme was designed to reflect the perception of the average consumer.

The scheme utilises **simplified heuristics** and is divided into three levels. Class A (with sub-levels A1–A4) and class B represent high-efficiency properties; units with intermediate energy performance are classified C and D; and the least efficient properties are grouped into classes E, F and G.

A thorough delineation of the characteristics of the sample, together with descriptive statistics and frequency distributions, can be found in Appendix 8.1, Tables A1-A8 and A9-A16.

In order to accurately estimate the influence of energy class on property value, the study adopts the **Hedonic Pricing Model (HPM) method**. This method, which has gained wide recognition in academic literature, has been employed in numerous studies on green premiums in real estate from 2008 to 2017. Its popularity can be attributed to its robustness and its capacity to isolate the effect of specific characteristics on market value (42,122).

The premise of HPM is predicated on the notion that the market value of a property is derived from the aggregate of the values attributable to the individual attributes of the property, both intrinsic and extrinsic. In other words, each characteristic contributes differently to the overall value, and the sum of these contributions defines the final value (68).

The implementation of HPM is statistically accomplished through the utilisation of **multiple regression**, a method that facilitates the estimation of the marginal impact of each attribute on market value.

The theoretical underpinnings of the model are rooted in the seminal contributions of Lancaster (123), who posited that the value of an asset is derived from the aggregate of its distinct attributes. This notion was further formalised by Rosen (122), who developed a statistical methodology for quantifying these contributions. The application of this methodology facilitates the acquisition of a robust estimate of the effect of energy efficiency on market value, whilst concomitantly controlling for all other relevant characteristics (124).

The accuracy of hedonic estimates is contingent on three primary factors: the representativeness and quality of the sample, the judicious selection of explanatory variables, and the consistent definition of the functional specification of the model (125).

The mathematical form of the HPM model is not predetermined; consequently, the selection of variables and the construction of the model are of crucial importance for the attainment of reliable and statistically robust results.

The valuation of property values was conducted using multiple regression, applying the **Ordinary Least Squares (OLS)** methodology. The literature does not provide definitive guidance on the optimal functional form for representing property values (126), and inadequate specifications have been shown to generate systematic distortions such as spatial autocorrelation, multicollinearity and heteroscedasticity of residuals (127,128).

The present research focused on the intrinsic characteristics of the properties, paying particular attention to energy performance, type and size in terms of surface area and number of rooms. The implementation of specific spatial models to address the issue of spatial autocorrelation was precluded by two primary factors.

Firstly, the objective of the investigation is to estimate the impact of the internal characteristics of properties on market value, without broader territorial factors interfering with the measurement of the marginal contribution of each attribute (129). In summary, the objective of the analysis is to isolate the effect of energy quality and internal features, as opposed to evaluating the dynamics of property values associated with geographical location.

Secondly, the dataset already incorporates variables that indirectly capture spatial effects. An exemplification of this phenomenon can be observed in the territorial classification system employed by Agenzia delle Entrate's OMI, which divides the territory into homogeneous market areas based on property values.

This segmentation facilitates the comparison of analogous units, thereby reducing the distortion caused by spatial autocorrelation without the necessity of employing complex spatial models. In practice, the territorial subdivision functions as a proxy for location characteristics, thereby enabling the analysis to concentrate on the contribution of intrinsic characteristics to market value.

The application of OLS also requires that the explanatory variables are not excessively correlated, to avoid issues of multicollinearity (127). In order to ensure the robustness of the estimates, two complementary strategies were adopted. Firstly, during the selection of variables, the most complex indicators were simplified to retain those that best summarise the main determinants of property value. Secondly, during model verification, the Variance Inflation Factor (VIF) was calculated in order to identify any redundancies between variables and to confirm the reliability of the estimates (130).

This combination of methodological choices facilitates the accurate and independent estimation of the marginal contribution of the various characteristics of properties to market value, with particular attention to the green premium associated with energy performance, while simultaneously quantifying the influence of other intrinsic and technological characteristics, such as typological quality and state of maintenance.

Concurrently, the utilisation of aggregated spatial variables, such as the classification into homogeneous market areas, serves to reduce the necessity for complex and computationally costly spatial models. This, in turn, ensures robust and comparable estimates across diverse urban contexts, ranging from large metropolitan centres to mid-sized municipalities.

The literature on HPM for real estate reveals the variety of functional forms that have been employed to represent the relationship between property characteristics and market value. The **semi-logarithmic function** is the most widely used specification in this field. In this approach, the natural logarithm of the market value of the property is used as the dependent variable, while the independent characteristics remain on a linear scale (42).

A key advantage of this choice is that the estimated coefficients can be interpreted directly as percentage changes in market value relative to unit changes in the explanatory variables, facilitating both economic interpretation and communication of the results.

Conversely, certain studies adopt a log-log function, whereby the independent variables are also transformed into natural logarithms. This enables the coefficients to be interpreted as the elasticity of market value with respect to changes in the factors under consideration, such as energy consumption. The literature demonstrates an inverse relationship between energy consumption and market value; properties with higher consumption tend to have lower market values, as observed in the Swedish market by Wahlström (92).

The log-linear function is another common specification, particularly suitable for estimating the percentage price premium associated with different energy classes. Comparative studies have documented variations in these premiums across contexts. Comparative studies report average price premiums ranging from 4.1% (±5.4% SD) to 16.4% (±20.9% SD), with significantly higher maximum values in specific contexts: approximately 40% in Singapore under the Green Mark programme, up to 84% in some cities in southern Italy and over 114% in some areas of southern Germany.

Empirical evidence also suggests that price premiums are not stationary over time, increasing during periods of heightened sensitivity to the advantages of efficient housing and undergoing temporary reductions following economic shocks, such as the post-2008 recession (98,131).

As illustrated in Table 8, the principal functional specifications employed in the literature on HPMs are summarised, with the relative mathematical formulation for each type of curve also demonstrated.

Curve type	Purpose	Advantage	References
Semi-logarithmic	Analyse the influence of property characteristics on market value in percentage terms	Coefficients interpretable as percentage changes; reduces heteroscedasticity; captures non-linear relationships	(132)
Log-log	Assess the elasticity of market value with respect to characteristics	Coefficients interpretable as relative changes; highlights proportional effects	(92)
Log-linear	Compare market value between different energy classes and estimate green premiums	Allows percentage premiums to be calculated; highlights differences between efficient and less efficient properties	(40,59,84)
Linear	Modelling direct relationships between characteristics and market value	Simple to estimate and interpret; direct comparisons between housing units	(126)

Table 8: Functional specifications in hedonic pricing models for real estate market value

For this study, the semi-logarithmic form, which has wide recognition in economic theory, was adopted. In comparison to the most prevalent alternatives – linear and log-log – this form boasts numerous advantages. The estimated coefficients represent percentage changes in market value in response to unit changes in property characteristics, thereby highlighting the marginal effect of each attribute.

Furthermore, the semi-logarithmic function has been demonstrated to assist in the mitigation of **heteroscedasticity** issues (132–134) and enables the capture of non-linear relationships between explanatory variables and market value. This offers enhanced interpretative flexibility in comparison to linear or log-log forms. This approach ensures a more accurate and interpretable estimate of the impact of intrinsic and technological characteristics, with particular attention to the energy performance of properties.

2.5. Descriptive analysis of the dwelling

Data collection was carried out by creating an Excel dataset in which nine variables were recorded for each property listing. The variables pertain to geographical location, external and internal characteristics, technological capabilities, size, and market value of the asking prices, as reported on online property portals.

In relation to the classification of energy efficiency, the coding system employed adheres to the directives established by the European Parliament and Council (121), which delineate seven levels, ranging from A to G, based on the European Standard EN 15805. To ensure a more accurate description of the sample, the research employed a more detailed classification, divided into 12 levels, including A4, A3, A2, A1, A+, up to G.

Although the national regulations have redefined the energy performance classification scale, the use of a twelve-level scheme was retained to ensure consistency with the information reported in the market. Major Italian real estate platforms continue to employ an extended classification (from A4 to G), which represents the standard through which energy performance is communicated in property listings. Adopting twelve levels, therefore, allows the dataset to remain aligned with current market practices and provides a more accurate representation of the distribution of energy classes within the sample (cfr. Table 9).

Variables	Type of variables	Characters and units of measurement	Scale	Unit value
Zone (OMI)	Ordinal	-	Central zone	1
			Semicentral zone	2
			Suburban zone	3
Proximity to infrastructure	Ordinal	-	Up to 200 m	1
			From 201 to 500 m	2
			Over 500 m	3
Typology	Nominal	Dichotomous	Villa	1
			Apartment	2
Property class	Ordinal	-	High-end	1
			Elite	2
			Standard	3
			Low-cost	4
			Not declared	5
Number of bathrooms	Cardinal	No	Ratio scale	Numeric value
Energy class	Ordinal	-	A4	1
			A3	2
			A2	3
			A1	4
			A+	5
			A	6

			B	7
			C	8
			D	9
			E	10
			F	11
			G	12
Maintenance status	Ordinal	-	Newly built	1
			Refurbished	2
			Well-maintained	3
			Run-down	4
			Not declared	5
Gross floor area	Cardinal	m^2	Ratio scale	Numeric value
Value market	Cardinal	€/m^2	Ratio scale	Numeric value

Table 9: Dataset variables

The analysis of **frequency distributions** commences with the market value of properties, a pivotal variable for comprehending urban dynamics, both at the level of individual cities and when comparing different territorial contexts.

Major cities are characterised by polarised markets, which are typified by the presence of well-defined luxury segments and long tails towards high values. In contrast, mid-sized cities have markets that are more concentrated in the lower-middle ranges, with higher levels of accessibility and less local variability. In both types of cities, the distributions are positively asymmetrical; however, the main difference concerns the presence and size of the high-end segments, which are significantly more relevant in major cities (cfr. Figures 14 and 15).

In **major cities**, most properties are found in the mid-range category, ranging **from 1,500 to 4,000 €/m^2**. The lower price ranges, which are below 1,500 €/m^2, are marginal, while those above 5,000 €/ m^2 are found almost exclusively in cities such as Milan and Florence, indicating the existence of luxury or particularly selective markets. The distribution of values is positively asymmetrical, with few units reaching very high values, and the majority concentrated in the middle ranges.

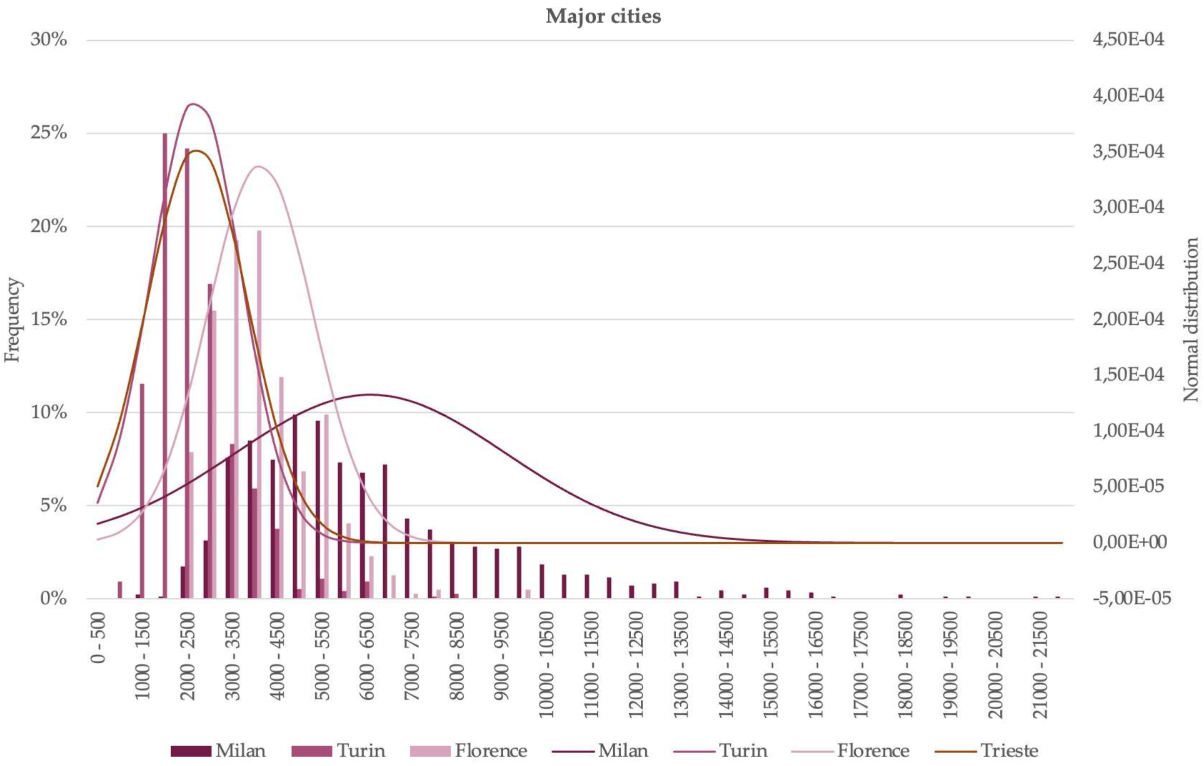


Figure 14: Frequency distribution of asking prices in the major cities' property market, with market values expressed in €/m² represented along the horizontal axis

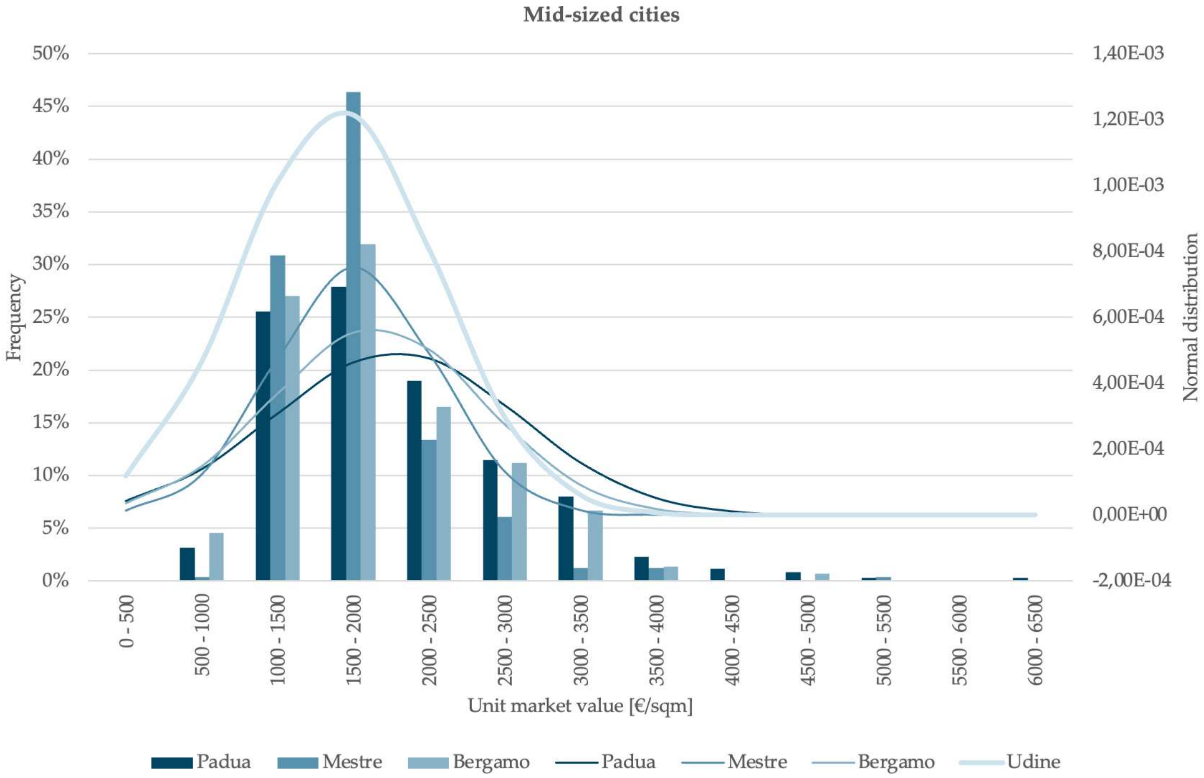


Figure 15: Frequency distribution of asking prices in the mid-sized cities' property market, with market values expressed in €/m² represented along the horizontal axis

Specifically in Milan, the real estate market is concentrated in the 4,500–5,500 €/m^2 range, with a tail exceeding 10,000 €/m^2, reflecting a particularly developed high-end segment. Florence is distinguished by the predominance of properties with a price range between 3,000 and 4,000 €/m^2, constituting over 40% of the sample. This segment exhibits higher average values and a compact distribution. In contrast, Turin and Trieste exhibit more modest values, predominantly ranging from 1,500 to 2,500 €/m^2, thereby emphasising accessible and less polarised market dynamics.

Analogous trends manifest in **mid-sized cities**, albeit adapted to the scale of local markets. Most properties are concentrated in the **lower-middle range**, typically commanding prices **between 1,500 and 2,500 €/m^2**. The upper ranges are under-represented and have a marginal weight, confirming the absence of extensive luxury segments. In such contexts, the distribution exhibits slight asymmetry, characterised by a paucity of high-value properties, with the majority situated within the middle ranges.

Specifically, in the Padua market, there is a notable concentration in the 1,500–2,500 €/m^2 range, accounting for over 50% of observations. This finding suggests a stable and relatively concentrated market. Mestre demonstrates a predominance within the 3,000–3,500 €/m^2 range, constituting approximately 46% of the sample, thereby substantiating the predominance of affordable properties and the constrained variability of market values. In Bergamo, the distribution of properties is comparable to that of Padua, with approximately 50% of properties falling within the range of 1,500 to 2,500 €/m^2.

However, a higher proportion of units are situated within the higher price ranges. A notable feature of the data is the initial predominance of values in the range of 1,000–1,500 €/m^2, which subsequently transitions to a more even distribution across the 2,000–4,500 €/m^2 range. Collectively, these two categories account for over 60% of the sample under consideration.

The results of the descriptive statistics indicate a uniformity of picture about the intrinsic characteristics, property types and maintenance status. The sample consists primarily of **multi-family properties, which are further categorised into elite and standard segments**. The maintenance status of these properties can be predominantly characterised as **refurbished or well-maintained**.

At the regional level, Milan is characterised by a relatively higher proportion of elite properties (54%), while Florence shows a prevalence of standard units (54%). In contrast, Turin and Trieste exhibit a more balanced distribution between the two segments (42% each), with a marginal presence of high-end properties.

The state of maintenance reveals further differences between major cities and mid-sized cities. In major cities, most properties can be categorised as either refurbished or well-maintained. Milan and Turin have been found to exhibit a higher average ranking, while Florence has been identified as having a higher incidence of refurbished properties.

Newly constructed units are typically in short supply, except Trieste, where they account for 12%, indicating a recent increase in construction activity. In the context of mid-sized city markets, most properties are found to be well-maintained, with a marginal share exhibiting signs of poor condition. Udine and Bergamo have a higher proportion of new builds (7% and 13%), suggesting that local markets are relatively more dynamic in terms of construction.

From a typological perspective, the primary distinction is between single-family units (villas) and multi-family units (apartments).

A significant indicator of housing quality is the number of bathrooms: in major cities, units with one or two bathrooms are predominant, while those with three or more are less common. In mid-sized markets, conversely, there is greater variability. For instance, Padua has a significant number of properties with four or five bathrooms, indicating that homes are larger on average than in major cities.

The location analysis, conducted based on the OMI classification (centre, semi-centre, periphery), highlights territorial differences. In major cities, approximately 50% of properties are in peripheral areas, a phenomenon that is particularly evident in Milan and Turin.

In contrast, Florence and Trieste demonstrate a higher degree of presence in central and semi-central areas, with Trieste reaching 47% of the sample in the historic centre. In mid-sized markets, there is a prevalence of concentration in central areas: Padua and Mestre both exceed 60%, while Udine is an exception, with 37% of properties located in the centre and a significant share in semi-central areas.

The relationship between urban location and **proximity to significant transportation infrastructure** is evident. In central areas, most properties are concentrated within a radius of 200-500 metres from major services (tram or railway stations), a trend that characterises both major cities and mid-sized cities. Properties located more than 500 metres from major services are in peripheral areas. In Trieste, this condition applies to all suburban units, while in Udine it extends to the entire sample, regardless of location.

About the classification of energy efficiency, the distribution of buildings across the 12 levels of the A4 to G scale demonstrates a predominance of those exhibiting suboptimal performance in terms of energy utilisation. Categories E, F and G represent the majority in almost all real estate markets, while high-efficiency classes (A and B) remain in the minority (cfr. Table 10).

	Major cities					**Mid-sized cities**				
	Milan	**Turin**	**Florence**	**Trieste**	**Average**	**Padua**	**Mestre**	**Bergamo**	**Udine**	**Average**
A4	0.8%	0.7%	0.0%	4.5%	1.5%	2.9%	4.5%	1.1%	5.2%	3.4%
A3	0.9%	0.1%	0.3%	1.4%	0.7%	0.3%	0.4%	1.1%	0.5%	0.6%
A2	1.4%	0.1%	0.3%	1.8%	0.9%	0.6%	0.4%	0.4%	1.2%	0.6%
A1	1.3%	1.6%	1.8%	3.7%	2.1%	1.7%	0.8%	2.5%	1.0%	1.5%
A+	0.7%	0.4%	1.3%	1.6%	1.0%	0.0%	1.6%	1.4%	2.0%	1.3%
A	2.7%	2.6%	1.0%	1.6%	2.0%	1.7%	0.8%	2.8%	1.0%	1.6%
B	2.6%	3.4%	3.0%	4.9%	3.5%	1.7%	1.6%	7.0%	6.4%	4.2%
C	2.3%	6.9%	0.8%	5.9%	4.0%	2.6%	2.8%	8.1%	7.7%	5.3%
D	9.9%	16.5%	3.3%	11.1%	10.2%	9.8%	7.3%	9.1%	12.9%	9.8%
E	14.7%	22.8%	7.6%	20.3%	16.4%	19.0%	12.6%	18.2%	22.5%	18.1%
F	21.1%	18.5%	17.3%	23.8%	20.2%	25.9%	28.5%	15.1%	22.5%	23.0%
G	41.6%	26.3%	63.5%	19.3%	37.7%	33.9%	38.6%	33.3%	17.1%	30.7%

Table 10: Percentage distribution of residential units by energy class EPC

An analysis of major cities reveals a clear concentration of properties in the least efficient energy classes. The highest proportion in class G is recorded in Florence (63%), followed by Milan (42%) and Turin (26%). Class F is of particular significance in Trieste (24%), while Milan (21%), Turin (19%) and Florence (17%) show lower values (cfr. Figure 16).

The intermediate classes D and E demonstrate a more heterogeneous distribution. The city of Turin has been found to achieve 17% in class D and 23% in class E; conversely, Florence and Trieste have been found to have values ranging from 3% to 11% for class D and from 8% to 20% for class E.

A negligible proportion of the building stock is represented by the most efficient classes (A and B). The highest incidence of the condition was observed in Trieste (19.7%), followed by Milan (10.4%). In both Trieste and Turin, however, the percentage of buildings in efficient energy classes remains below 10%.

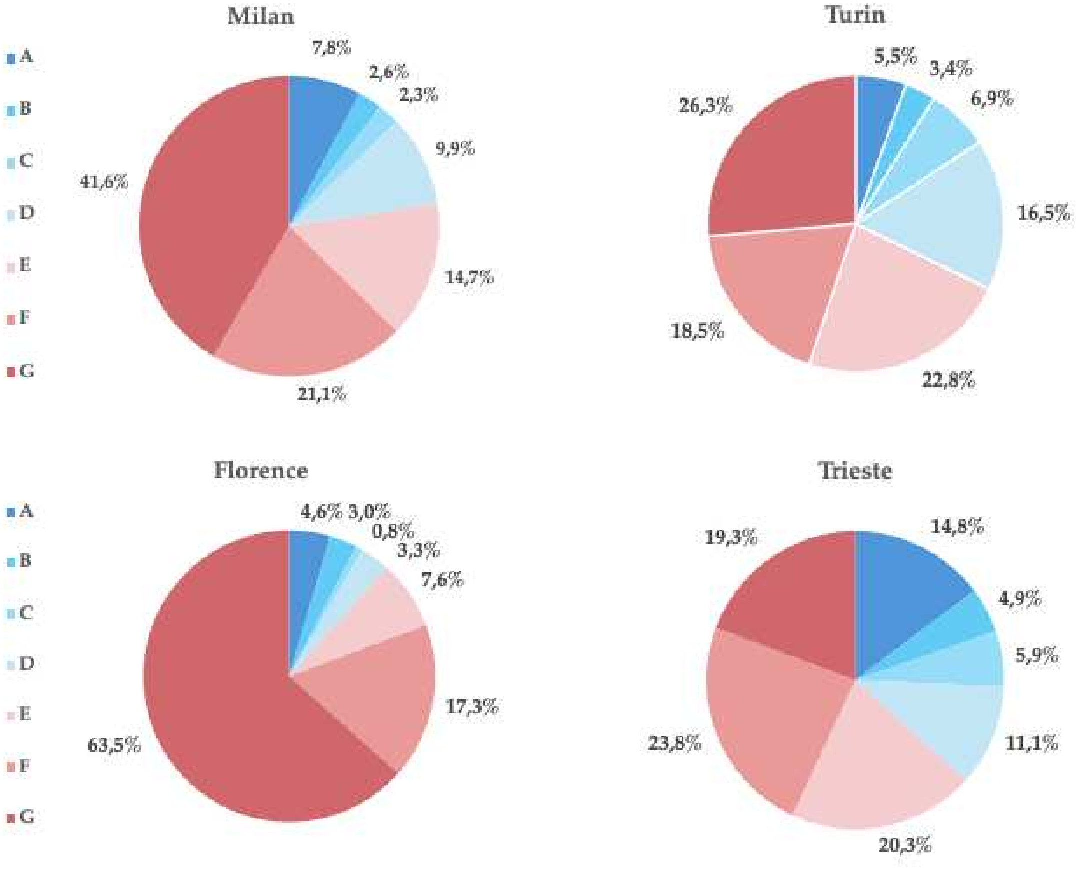


Figure 16: Percentage distribution of dwellings by energy class in major cities. (The category "Class A" aggregates the classes A3, A2, A1, A+, and A.)

In mid-sized cities, the distribution of energy classes is largely analogous to that observed in major cities, with a prevalence of buildings in the least efficient classes (F and G). Mestre has the highest percentage in class G (39%), followed by Padua (34%) and Bergamo (33%), while Udine has the lowest percentage (17%). For class F, the highest values are observed in Mestre (28%) and Padua (26%), compared to lower percentages in Bergamo (15%) and Udine (23%).

The intermediate classes D and E demonstrate a greater degree of variability. Udine has the highest incidence (D 13%, E 23%), followed by Bergamo (D 9%, E 18%), while Padua and Mestre have values between 7% and 12% for class D and between 13% and 19% for class E.

High-efficiency classes (A4–A) exhibit a very low incidence. Udine has been found to have a total of 5% of the total, while Padua and Mestre have been found to have around 3-4%. Finally, the city of Bergamo has been found to have less than 1-3%. Class B is also under-represented, ranging from 2% in Padua and Mestre to 7% in Bergamo (cfr. Figure 17).

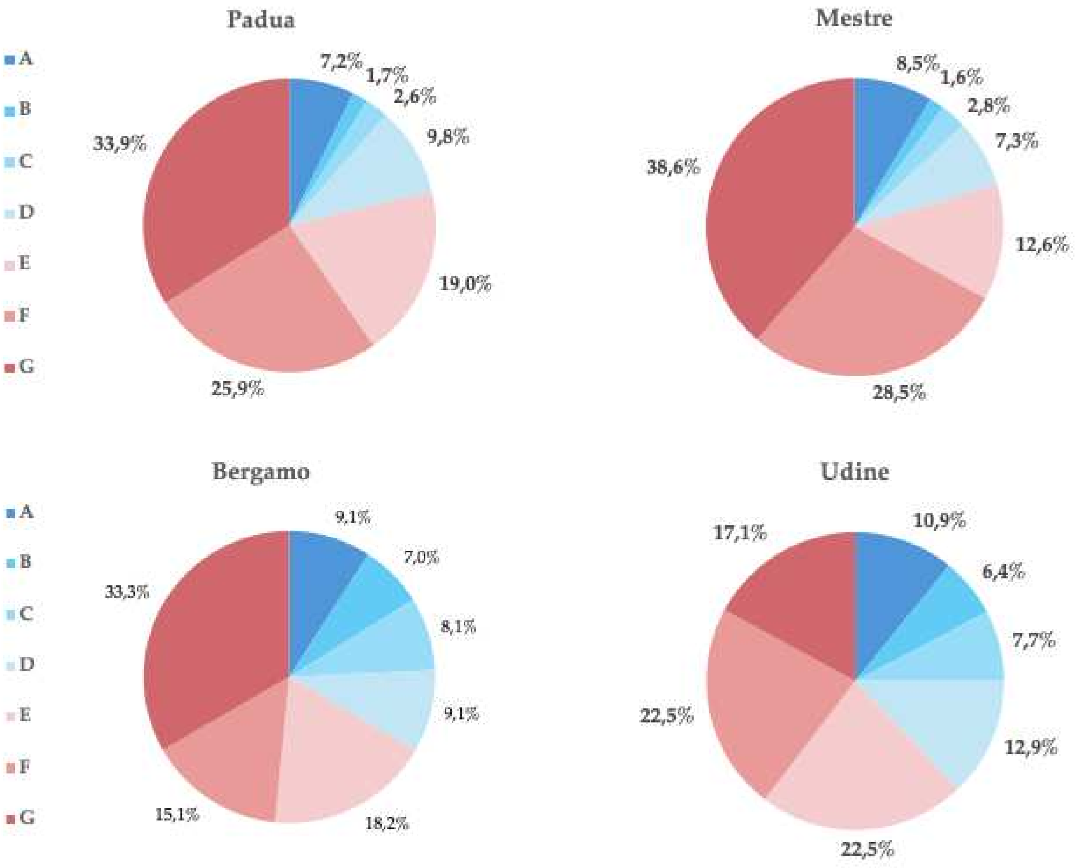


Figure 17: Percentage distribution of dwellings by energy class in mid-sized cities (The category "Class A" aggregates the classes A3, A2, A1, A+, and A.)

An analysis of the mean market values reveals that, within major cities, approximately 74% of buildings are classified as being in the least efficient energy classes (E, F, G), a figure that is remarkably consistent with the proportion observed in mid-sized cities (72%). Specifically, class G accounts for 38% of buildings in major cities and 31% in mid-sized cities; class F accounts for 20% and 23%, respectively, while class E represents 16% and 18%.

The intermediate classes (C and D) together account for 14–15% of the sample, with similar values observed in both contexts: approximately 10% in class D and 4–5% in class C. The incidence of energy-efficient classes (B to A4) is even lower, at 12% in major cities and 13% in mid-sized cities.

A clear concentration in the lower-performing bands is evident, with only a marginal proportion of buildings belonging to the highest energy classes. Most of the building stock is found in the low-efficiency categories.

These results are consistent with the national picture (91), where the last three EPC classes (E, F, G) account for a total of 68% of the total (29% in E, 23% in F and 16% in G), while the intermediate and more efficient classes represent smaller shares (12% in D, 6% in C and 14% overall between B and A) (cfr. Figure 18).

Figure 18: Distribution of sampled properties by EPC class in Italy, major and mid-sized cities

The analysis conducted enables us to systematically delineate the salient characteristics of the real estate portfolio, accentuating substantial disparities between major cities and mid-sized cities about building type, state of repair, location and energy performance.

The descriptive statistics and frequency distributions are documented in Appendix 8.1 (Tables A1–A16), forming the empirical basis for the subsequent stages of quantitative analysis.

2.6. Hedonic Prices Models

The natural logarithm of the **unit property value** (€/m^2) was adopted as the dependent variable in the econometric model used for the analysis. The transformation reduces data dispersion and allows the estimated coefficients to be interpreted as percentage changes in property value. The relationship is formalised as follows:

$$ln(V_i) = \beta_0 + \sum_{i=1}^{I} \quad \beta_i X_i + e_i \quad (1)$$

where:

- $ln\ (V_i)$ is the unit property value of property ii in logarithmic terms;
- β_0 represents the intercept, i.e. the component of property value not explained by the observed characteristics;
- β_i measures the marginal effect of the kth characteristic;
- X_i is the explanatory variable (e.g. surface area, location, energy class);
- ε_i represents the error term, capturing the variability not explained by the model.

To ensure that the inclusion of **energy performance** in the model was not contingent on arbitrary choices, the variable was represented in two distinct ways:

- **12 Level Energy classification**

  Each energy class, from A4 to G, was treated as a separate category, allowing the specific effect of each efficiency level on property value to be estimated. This representation allows for more subtle differences between classes to be captured and the impact of each efficiency level to be assessed in detail.

- **3 Level Energy classification (dummy)**

  The energy classes were grouped into three macro-categories: high performance (A-B), intermediate performance (C-D) and poor performance (E-G). The macro-classes are represented by binary variables (dummies), indicating whether the property is in each group.

The decision to incorporate a dummy representation is predicated on two primary advantages. Firstly, it aligns more closely with buyers' **perceptions**, who frequently evaluate properties within macro-classes rather than technical sub-levels. Secondly, it facilitates overcoming the class sequence, thereby highlighting any **discontinuities in market value** between the groups.

Both the 12-level classification (Model A) and the 3-level aggregated classification (Model B) were estimated using a full set of dummy variables. However, the regression tables report a single coefficient for "Energy class". This coefficient is intended to summarise the overall marginal effect of energy performance on property values. It is presented for reasons of readability and comparability across cities.

The underlying models maintain the categorical structure of the variable, and the complete set of estimated dummy coefficients can be found in the regression outputs. This reporting choice does not imply an ordinal treatment of the variable and does not affect the robustness or interpretation of the estimates.

A total of **16 distinct models** were estimated for the eight cities analysed: 8 based on the 12 Level Energy Classification (Models A) and 8 on the 3 Level Energy Classification (Models B).

For each city, the **R2 and R2 adjusted** values were calculated to assess the robustness and reliability of the results obtained. In the case of the variable represented by the **12 Level Energy Classification (Model A)**, the values are of particular significance for the major cities, with coefficients of determination of 0.627 for Milan, 0.490 for Turin, 0.612 for Florence and 0.459 for Udine. The corresponding adjusted R2 values are 0.624 for Milan, 0.487 for Turin, 0.606 for Florence and 0.453 for Udine.

The models demonstrate an R2 of 0.521 for Padua, 0.513 for Mestre, 0.363 for Bergamo and 0.429 for Udine, with adjusted R2 values of 0.513 for Padua, 0.505 for Mestre, 0.352 for Bergamo and 0.420 for Udine, respectively (cfr. Table 11).

			Overall model test			
Models A	**R^2**	**Adjusted R^2**	**F**	**df1**	**df2**	**p-value**
Milan	0.627	0.624	192.958	7	811	<.001
Turin	0.490	0.487	141.000	5	733	<.001
Florence	0.612	0.606	103.000	6	393	<.001
Trieste	0.459	0.453	68.000	6	480	<.001
Padua	0.521	0.513	59.900	6	330	<.001
Mestre	0.513	0.505	63.400	4	241	<.001
Bergamo	0.363	0.352	32.500	5	285	<.001
Udine	0.429	0.420	49.700	6	397	<.001

df1: regression; df2: residual

Table 11: Indicators of significance and robustness for HPM (12-Level Energy Classification)

Even models based on the **simplified three-level energy variable (Models B)** demonstrate stable explanatory power, thereby confirming the robustness of the results in comparison to the more detailed twelve-class specification.

In major cities, the R2 values are 0.620 for Milan, 0.494 for Turin, 0.609 for Florence and 0.459 for Trieste, while the adjusted R2 values are 0.617, 0.491, 0.603 and 0.453, respectively.

The models demonstrate analogous statistics for mid-sized cities. The R2 value for Padua is 0.516, for Mestre 0.512, for Bergamo 0.349, and for Udine 0.457. The corresponding adjusted R2 values are 0.507, 0.504, 0.337 and 0.410 (cfr. Table 12).

			Overall model test			
Models B	**R^2**	**Adjusted R^2**	**F**	**df1**	**df2**	**p-value**
Milan	0.620	0.617	188.129	7	807	<.001
Turin	0.494	0.491	143.000	5	733	<.001
Florence	0.609	0.603	102.000	6	393	<.001
Trieste	0.459	0.453	68.000	6	480	<.001

Padua	0.516	0.507	58.600	6	330	<.001
Mestre	0.512	0.504	63.200	4	241	<.001
Bergamo	0.349	0.337	30.500	5	285	<.001
Udine	0.457	0.410	31.200	6	297	<.001

df1: regression; df2: residual

Table 12: Indicators of significance and robustness for HPM (3-Level Energy Classification)

The reduction in the number of energy categories does not appear to have a significant impact on the quality of estimates between Models A and B: the R2 and adjusted R2 values remain essentially unchanged, suggesting that even a simplified classification adequately represents the impact of energy performance on property values.

Although the variable “Typology” (villas vs. apartments) was included in all model specifications, it consistently turned out to be non-significant across the eight cities. This result reflects the fact that typological differences are already captured by other structural attributes in the model—such as floor area, number of bathrooms, property class and location. Once these characteristics are controlled for, typology does not display an independent marginal effect on unit values.

The inclusion of gross floor area as an independent variable, despite using unit value (€/m^2) as the dependent variable, is an intentional and methodologically consistent choice. Omitting size would introduce specification bias, given its central role in price formation.

The logarithmic functional form reduces potential mechanical correlation, and robustness checks confirm that including floor area does not alter the estimated effect of energy performance. The negative coefficient simply reflects the well-documented “size discount” observed in real estate markets.

The findings of the regressions for major and mid-sized cities in the context of the 12-level energy variable are presented in Tables 13 and 14.

	Milan		**Turin**		**Florence**		**Trieste**	
Predictors X_i	**β_i**	**VIF**	**β_i**	**VIF**	**β_i**	**VIF**	**β_i**	**VIF**
Constant	10.307**	-	8.970**	-	9.373**	-	8.681**	-
Zone (OMI)	-0.315**	1.243	-0.220**	1.040	-0,175**	1.060	-0.054**	1.000
Proximity to infrastructure	-0.077**	1.062	-0.091**	1.020	-0.050**	1.010	-	-
Typology	-	-	-	-	-	-	-	-
Property class	-0.180**	1.409	-	-	-	-	-0.412**	1.550
Bathrooms	0.065*	2.414	-	-	0.076**	1.470	0.099**	1.420
Gross floor area	-0.002**	2.497	0.0007**	1.070	-0.003**	1.590	-0.000**	1.310
Energy class	-0.028**	1.410	-0.026**	1.650	-0.017**	1.280	-0.023**	2.190
Maintenance status	-0.037*	1.382	-0.126**	1.620	-0.100**	1.470	-0.1630**	1.960

***,* Significance at < 0.01 and < 0.05 respectively*

Table 13: Regression models (A) for Major cities (12-Level Energy Classification)

	Padua		**Mestre**		**Bergamo**		**Udine**	
Predictors X_i	**β_i**	**VIF**	**β_i**	**VIF**	**β_i**	**VIF**	**β_i**	**VIF**
Constant	9.001**	-	8.181**	-	7.973**	-	8.420**	
Zone (OMI)	-0.244**	1.150	-	-	-0.063**	1.020	-0041**	1.110
Proximity to infrastructure	-0.112**	1.040	-	-	-	-	-	
Typology	-	-	-	-	-	-	-	
Property class	NA	-	NA	-	NA	-	-0.132**	1.340
Bathrooms	0.060**	1.960	0.164	1.650	0.273**	1.830	0.149**	2.010
Gross floor area	-0.002**	2.010	-0.003	1.520	-0.001**	1.750	-0.002**	1.960
Energy class	-0.039**	1.760	-0.040	1.520	-0.044**	1.770	-0.037**	2.130
Maintenance status	-0.106**	1.780	-0.098	1.470	-0.064**	1.790	-0.103**	2.290

***,* Significance at < 0,01 and < 0,05 respectively; NA: Not Available*

Table 14: Regression models (A) for Mid-sized cities (12-Level Energy Classification)

The primary metric used to assess the reliability of hedonic models is the **statistical significance F** of the estimated coefficients. The robustness of an effect is characterised by the relative p-value, which is calculated as the probability of the observed result being due to chance. An effect is considered robust when the relative p-value is less than 0.05, indicating a very low probability that the observed result is due to chance. In all the models analysed, the coefficients demonstrated **p-values lower than 0.001**, thereby confirming the robustness of the estimates.

To assess the presence of multicollinearity between the independent variables, the **VIF** was calculated. The values obtained, which approximate one in all eight urban contexts considered, suggest the absence of high correlations between the variables. This ensures that each contributes independently to explaining the variability of property values. This outcome serves to reinforce the methodological validity of the analysis, thereby preventing distortions that may be occasioned by information redundancy.

The primary metric used to assess the reliability of hedonic models is the **statistical significance F** of the estimated coefficients. The robustness of an effect is characterised by the relative p-value, which is calculated as the probability of the observed result being due to chance. An effect is considered robust when the relative p-value is less than 0.05, indicating a very low probability that the observed result is due to chance. In all the models analysed, the coefficients demonstrated **p-values lower than 0.001**, thereby confirming the robustness of the estimates.

To assess the presence of multicollinearity between the independent variables, the **VIF** was calculated. The values obtained, which approximate one in all eight urban contexts considered, suggest the absence of high correlations between the variables. This ensures that each contributes independently to explaining the variability of property values. This outcome serves to reinforce the methodological validity of the analysis, thereby preventing distortions that may be occasioned by information redundancy.

Next, the results of the regressions for each city are presented, with the energy performance variable considered at three levels (cfr. Tables 15 and 16).

	Milan		**Turin**		**Florence**		**Trieste**	
Predictors X_i	**β_i**	**VIF**	**β_i**	**VIF**	**β_i**	**VIF**	**β_i**	**VIF**
Constant	10.245**		8.921**	-	9.331**	-	8.682**	-
Zone (OMI)	-0.315**	1.248	-0.219**	1.040	-0.175**	1.060	-0.054**	1.070
Proximity to infrastructure	-0.075**	1.071	-0.090**	1.030	-0.050**	1.010	-	-
Typology	-	-	-	-	-	-	-	-
Property class	-0.176**	1.411	-	-	-	-	-0.143**	1.550
Bathrooms	0.068*	2.409	-	-	0.077**	1.470	0.099**	1.420
Gross floor are	-0.003**	2.509	0.0007**	1.060	-0.004**	1.600	-0.000**	1.310
Energy class	-0.076**	1.417	-0.091**	1.540	-0.478*	1.220	-0.068**	2.190
Maintenance status	-0.045**	1.401	-0.124**	1.530	-0.105**	1.420	-0.193**	1.960

***,* Significance at < 0.01 and < 0.05 respectively*

Table 15: Regression models (B) for Major cities (3-Level Energy Classification)

	Padua		**Mestre**		**Bergamo**		**Udine**	
Predictors X_i	**β_i**	**VIF**	**β_i**	**VIF**	**β_i**	**VIF**	**β_i**	**VIF**
Constant	9.091**	-	8.196**	-	7.846**	-	8,431**	-
Zone (OMI)	-0.236**	1.120	-	-	-0.061**	1.010	-0,064**	1.110
Proximity to infrastructure	-0.117**	1.050	-	-	-	-	-	
Typology	-	-	-	-	-	-	-	
Property class	NA	-			-	-	-0,133**	1.340
Bathrooms	0.064**	1.960	0.172**	1.630	0.286**	1.810	0,171**	4.496
Gross floor are	-0.002**	2.010	-0.003**	1.520	-0.001**	1.760	-0,004**	0.510
Energy class	-0.164**	1.540	-0,162**	1.440	-0.114**	1.660	-0,070**	2.130
Maintenance status	-0.122**	1.620	-0-101**	1.440	-0.082**	1.710	-0,113**	2.290

***,* Significance at < 0,01 and < 0,05 respectively; NA: Not Available*

Table 16: Regression models (B) for Mid-sized cities (3-Level Energy Classification)

The analysis conducted on the eight real estate markets considered, which is statistically consistent, highlights the importance of **location characteristics** in determining unit values of asking prices. The results demonstrate a clear and systematic decrease in property values from the centre towards the periphery. This **finding confirms the hypothesis** that the hierarchy of values is closely linked to the urban structure. The conventional classification of regions into central, semi-central, and peripheral categories thus serves as an effective metric for the distribution of values across the territory.

A particular instance is observed in Mestre, where the disparities in value between central and peripheral regions do not attain statistical significance. This phenomenon is indicative of the distinct characteristics of the local market, as evidenced by the negligible impact of the variable on proximity to primary public transportation networks. In a similar vein, the proximity of a property to transport infrastructure exerts a negligible influence on property values in Bergamo. In contrast, in the other markets analysed, proximity to transport infrastructure was found to have a positive and significant effect, thereby confirming the decisive role of this factor in the formation of values.

The models also reveal the influence of typological characteristics and amenities on property values. In Turin, the unit value of prestigious and luxury buildings consistently exceeds that of mid-range or affordable homes, thereby underscoring the direct impact of typological quality. Substantial increments in valuation are concomitant with the existence of enhanced intrinsic quality characteristics within the properties, such as the number of bathrooms, thereby underscoring the pivotal role of amenities in the determination of property values.

The size of the property is a key factor in determining its value. An increase in floor space has been demonstrated to increase the total value of the property, whilst concomitantly reducing the unit value per square metre. This finding aligns with the trend that has been observed in all the urban contexts analysed. The estimated models thus provide clear empirical evidence of the law of diminishing marginal utility, showing how the unit value decreases as the size of the dwelling increases.

The analysis is completed by an assessment of the technological characteristics and state of maintenance of the properties. The findings demonstrate that **energy efficiency is a key factor** in all eight markets examined, resulting in **quantifiable increases in the marginal value of**

the property. **These effects are found to be positive and statistically significant**. This trend is evident in both the detailed twelve-level classification (Model A) and the simplified three-group version (Model B), thereby confirming the robustness of the results irrespective of the adopted classification.

Conversely, the degree of building maintenance has been demonstrated to exert a deleterious effect on unit value. Properties in poorer condition demonstrate gradual and significant decreases in value per square metre, an impact that emerges consistently in all the models analysed, thus confirming the stability of the result in the various urban markets considered.

The methodological soundness of the analysis, the statistical significance of the coefficients, and the absence of multicollinearity between the independent variables lend reliability to the models and guarantee the scientific validity of the following regression analysis.

2.7. Results

To investigate the extent of the **price premium associated with energy characteristics** and its variation according to urban size, **regression analyses** were conducted to estimate the differences in market value between properties with different levels of energy efficiency in the eight cities examined.

To determine the price premium, two energy class ranges were defined:

1. The **range G-D** denotes the disparity between an inefficient property in class G and an average efficient property in class D;
2. The **range G-A** denotes the maximum disparity between an inefficient property in class G and a highly efficient property in class A.

Price premium assessments were carried out using two different energy performance classifications:

- **12-Level Energy Classification (Models A):** the price premium is calculated separately for the three levels G, D and A of the EPC scale;
- **3-Level Energy Classification dummy (Models B):** the energy variable is grouped into three macro-categories: inefficient properties (E/F/G), moderately efficient properties (C/D) and highly efficient properties (A/B).

The differences between the estimated values are expressed as percentages. This approach enables the effect of energy performance on market value to be systematically highlighted, thereby providing a comparative measure of the price premium or depreciation associated with energy quality in the various urban markets analysed.

The results of the regression analyses based on the **12-level energy classification**, for both intervals considered (G–D and G–A), are presented in Figures 19 and 20.

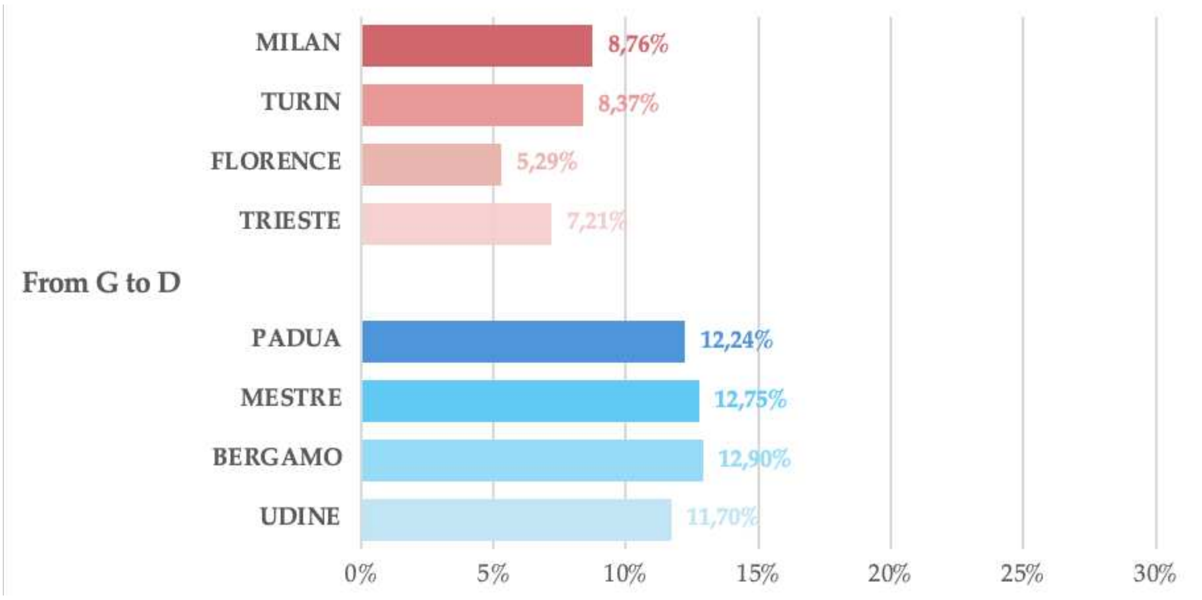


Figure 19: Green price premium between dwellings with low energy efficiency (class G) and medium energy efficiency (class D) in major and mid-sized cities – 12-Level Energy Classification

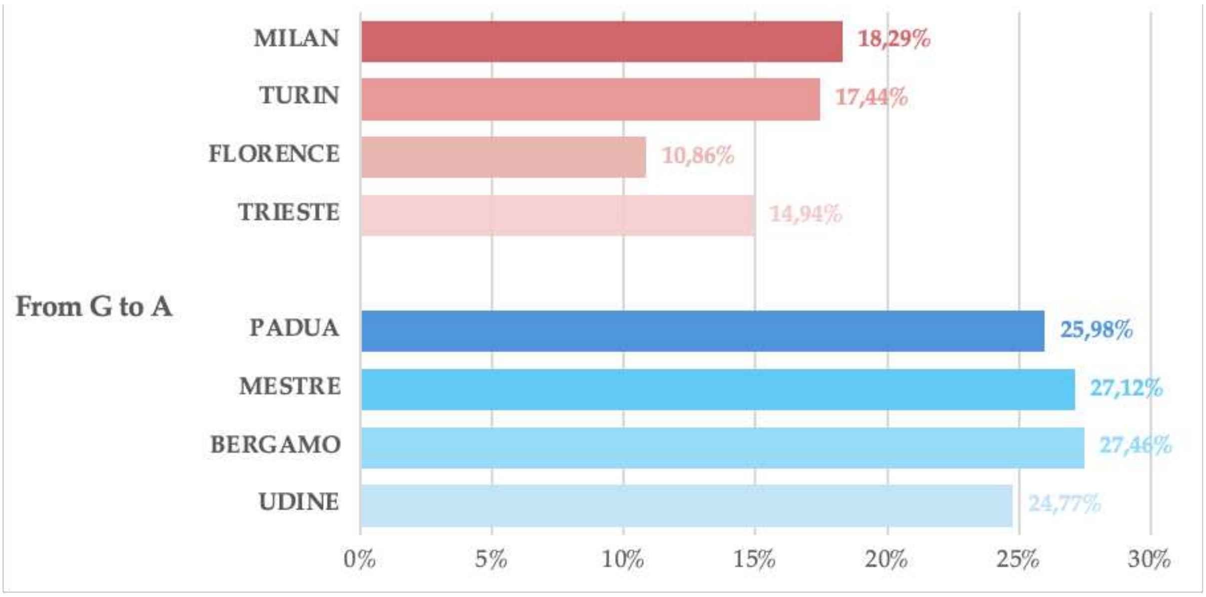


Figure 20: Green price premium between properties with low energy efficiency (class G) and high energy efficiency (class A) in major and mid-sized cities – 12-Level Energy Classification

The relative value disparity between a property in class G and a property in class D in major cities ranges from a minimum of 5.29% in Florence to a maximum of 8.76% in Milan, with intermediate values of 8.37% for Turin and 7.21% for Udine. For mid-sized cities, the differences are more pronounced: there is a percentage increase ranging from 11.70% in Udine to 13.90% in Bergamo, with 12.24% for Padua and 12.75% for Mestre.

The most significant disparities emerge from the least efficient class (G) to the most efficient class (A). In major cities, the values recorded are 18.29% in Milan, 17.44% in Turin, 10.86% in Florence and 14.94% in Trieste. For mid-sized cities, the differences are compounded, with 25.98% in Padua, 27.12% in Mestre, 27.46% in Bergamo and 24.77% in Udine.

Subsequently, the same analysis was conducted considering regression models with the **energy variable simplified into three levels (Models B).** The findings are consistent with those obtained using the 12-level classification.

In the case of the first interval between inefficient properties (class E/F/G) and moderately efficient properties (class C/D), the average difference in major cities ranges from 4.90% in Florence to 9.55% in Turin, with 7.79% in Milan and 7.00% in Trieste. In mid-sized cities, the values double, reaching 17.93% in Padua, 17.70% in Mestre, 12.13% in Bergamo and 11.68% in Udine (cfr. Figure 21).

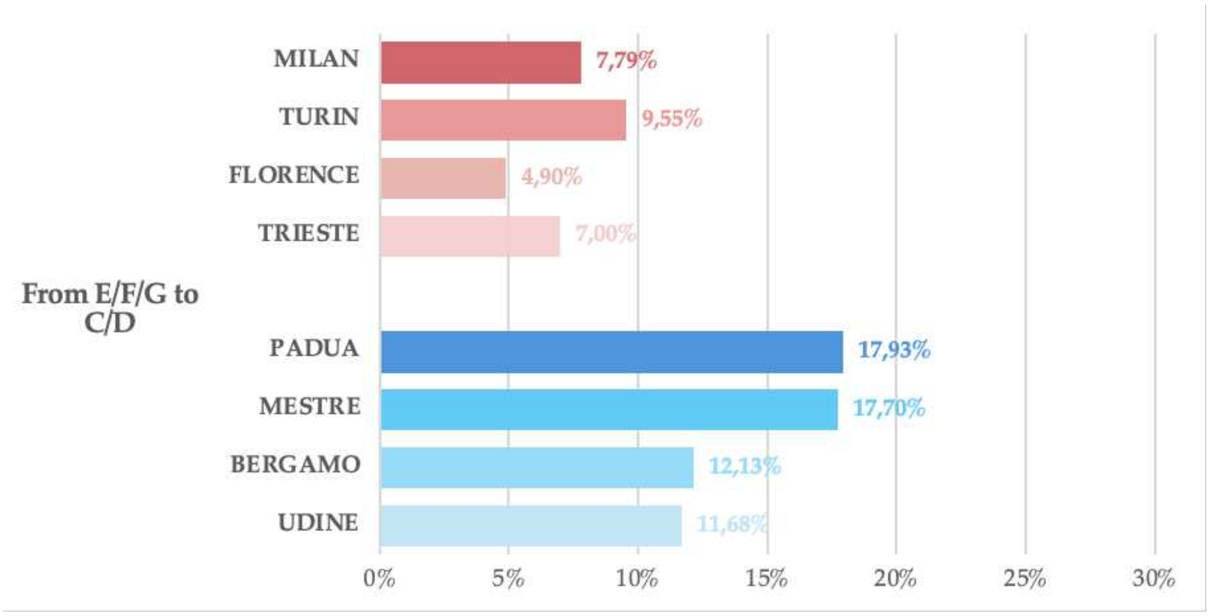


Figure 21: Green price premium between dwelling with low energy efficiency (class E/FG) and medium energy efficiency (class C/D) in major and mid-sized cities – 3-Level Energy Classification

In instances where the maximum disparity exists between inefficient (E/F/G) and highly efficient (A/B) buildings, considering the 3-level energy variable, the discrepancies are found to be considerably more pronounced. In major cities, there is an increase in the values compared to the initial interval: in Milan, for instance, the difference rises from 7.79% (from E/F/G to C/D) to 16.18% (from E/F/G to A/B). The highest percentages were recorded in Turin (20.01%), Trieste (14.57%) and Florence (10.03%).

A similar pattern is exhibited by mid-sized cities, which also demonstrate higher values in comparison to major cities. This observation is consistent with the results obtained from analyses based on the 12-level classification. The disparities between inefficient properties (E/F/G) and highly efficient properties (A/B) range from a minimum of 15.07% in Udine to a maximum of 39.07% in Padua, followed by Bergamo with 25.73%. The price premium in Udine, at 15.07%, is comparable to the values observed in major cities (cfr. Figure 22).

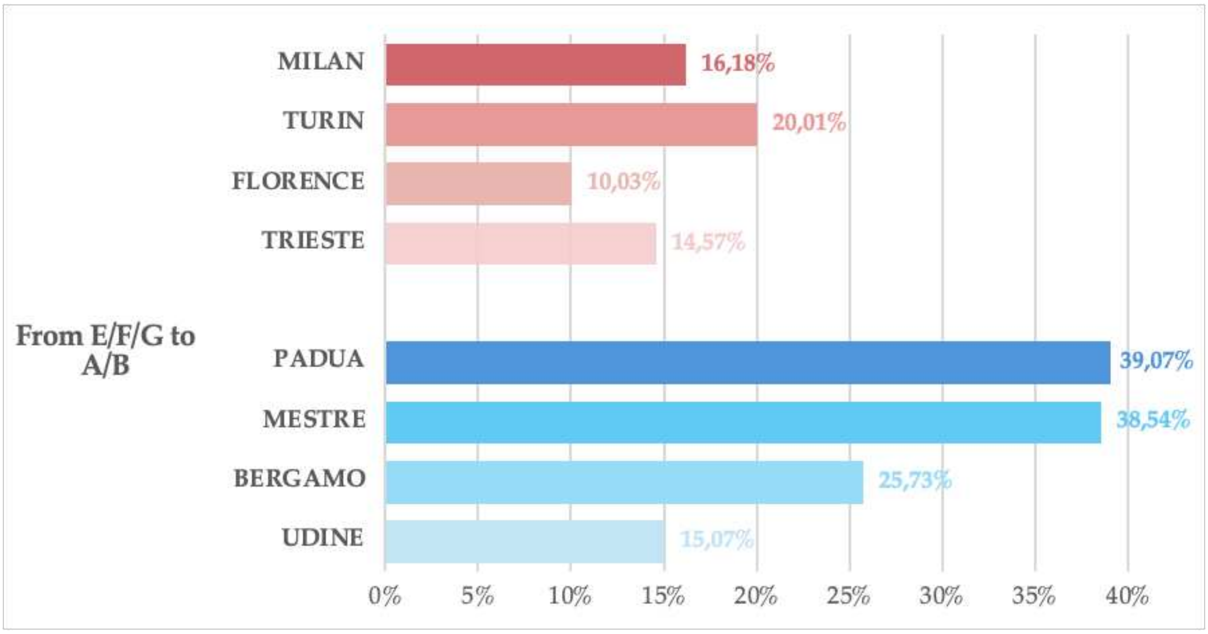


Figure 22: Green price premium between properties with low energy efficiency (class G) and high energy efficiency (class A/B) in major and mid-sized cities – 3-Level Energy Classification

As illustrated in Figure 23, there is a demonstrable correlation between the property value of a given property and its energy class, with each upgrade from G to A (G→F, G→E, G→D, G→C, G→B, G→A) corresponding to an increase in property value. The figure also demonstrates the cumulative percentage of the price premium recognised by the property market for energy-efficient properties.

Figure 23: Price premium for each energy class transition from G to A in major e mid-sized cities, with cumulative percentage

2.8. Green price premium and unjust transition

The analysis carried out allows us to answer the first research question formulated at the beginning of the study: **1a - Does the property market recognise a value differential in favour of properties with higher energy performance along the EPC scale?**

The findings corroborate the theoretical hypotheses and are substantiated by both domestic and international empirical evidence. The existence of significant disparities in property values according to energy class is indicative of the real estate market's recognition of a price premium for properties demonstrating enhanced energy efficiency. This premium is attributable to two primary factors: firstly, the **reduction in energy operating costs** and secondly, the **enhanced liquidity and marketability of such housing units**.

The study, which was based on asking prices in four major cities and four mid-sized cities in northern Italy and developed using the HPM, highlights the stratification of the residential market and provides convergent estimates of the value differences across energy performance classes.

The research also allows us to answer the more detailed research question: **1b - Do the size and vitality of the urban market influence the value of the green price premium in different territorial contexts?**

The response to this question is affirmative. While confirming the existence of a price premium, the extent of this variation is dependent upon the rank and strength of local markets. An inverse relationship has been demonstrated between the size of the value gap and the size/vitality of the market. In major cities, characterised by larger markets and high property values, superior energy efficiency generates modest value increases. In mid-sized cities, however, the gaps are significantly greater.

In consideration of the 12-level energy classification (Models A), in the event of the maximum disparity between highly efficient properties (class A) and inefficient properties (class G), the average price premium is 15.38% in major cities and nearly double that in mid-sized cities (26.33%).

A similar result can be observed for the difference between moderately efficient properties (class D) and inefficient properties (class G): the price premium averages 7.41% in major cities and reaches 12.40% in mid-sized cities (cfr. Table 17).

When the 3-level classification (Models B) is considered, slightly different values emerge, yet these are consistent with the initial analysis. In instances where the maximum disparity exists between properties in class E/F/G and properties in class C/D, the differential ranges from 7.31% in major cities to 14.86% in mid-sized cities. About the discrepancy between class E/F/G and class A/B properties, the values are 15.20% in major cities and 29.60% in mid-sized cities (cfr. Table 18).

	From G to D	**From G to A**
Major cities	5.29% - 8.76% Average: 7.41%	10.86% - 18.29% Average: 15.38%
Mid-sized cities	11.70% - 12.90% Average: 12.40%	24.77% - 27.46% Average: 26.33

Table 17: Regression models A with 12-level energy classification

	From E/F/G to C/D	**From E/F/G to A/B**
Major cities	4.90% - 9.55% Average: 7.31%	10.03% - 20.01% Average: 15.20%
Mid-sized cities	11.68% - 17.93% Average: 14.86	15.07% - 39.07% Average: 29.60

Table 18: Regression models B with 3-level energy classification

These findings corroborate the hypotheses proposed by Eichholtz et al., Addae-Dapaah and Wilkinson, and Taruttis and Weber (14,59,135), confirming that the ability of demand to discriminate between levels of technological quality depends on market conditions. In less dynamic markets, buyers tend to reward energy efficiency more strongly, whereas in highly competitive markets, the intensity of demand compresses value differentials.

A comparison with previous empirical evidence from the Italian residential sector confirms both points of convergence and context-specific variations. The magnitude of the premiums estimated in this research—around 15% in major cities and 26–30% in mid-sized cities—is broadly consistent with the values reported in other Italian studies, including Dell'Anna et al.

(96), Bisello et al. (99), all of which similarly document positive but heterogeneous price differentials associated with improved energy performance. These results also align with the wider range identified in works such as Manganelli et al. (84), which reports gaps between 29% and 41% in Bari, and with evidence from the commercial sector, where JLL (136) identifies differentials exceeding twenty percentage points.

At the same time, differences across studies should be interpreted cautiously, as they may reflect not only underlying market dynamics but also methodological and contextual factors. Variations in model specification, the set of explanatory variables, sample sizes, and the temporal frame of data collection are all known to influence the estimated magnitude of energy-related premiums. Recognising these elements is important to situate the findings within the broader empirical landscape.

In this context, the price premium assigned to efficient properties serves as a tangible incentive for owners to enhance their energy performance, thereby reducing consumption and aligning themselves with environmental directives. However, this dynamic does not affect the territory uniformly; the European energy transition exerts a greater influence on fragile contexts, characterised by weak property markets, depopulation and fewer economic resources available for deep retrofitting. Given that a significant proportion of household wealth is constituted by residential property, the transition may consequently engender regressive distributional effects, exerting the greatest impact on the most vulnerable households.

This is a crucial issue: in the absence of adequate public policies that take this aspect into account, the transition risks becoming an unjust territorial transition, as described by Rodriguez-Pose, in which the weakest territories bear the highest costs, generating resistance to environmental transition due to its differentiated economic effects (103,105,137,138).

A potentially fruitful avenue for exploration would be the exploitation of the price premium, interpreting it as an **investment opportunity**. This increase in value can be regarded as a concrete economic incentive for households, with the potential to enable them to provide financial support for deep retrofit interventions. Consequently, the price premium has the potential to encourage the broader implementation of deep retrofit interventions, which are imperative for attaining European emission reduction targets.

In addition to generating environmental advantages, deep retrofitting also has positive effects on an architectural level, promoting innovative design solutions with significant repercussions on the occupant comfort

Consequently, the subsequent chapter will examine the financial feasibility of deep-retrofitting interventions, assessing for the first time whether—and under what conditions—the price premium recognised by the market can effectively offset investment costs. This requires accounting not only for the magnitude of the premium itself, but also for two critical factors: the time needed for the value increase to materialise as a tangible economic advantage for the owner, and the risk that such an increase remains a latent value, not necessarily monetised through sale or rental. Introducing these considerations provides a coherent transition to the economic–financial analysis that follows, where the market dimension (price) is integrated with the temporal and financial dimensions of cash flow and payback.

Chapter 3

3. DEEP RETROFIT IN HOUSING AND FINANCIAL VIABILITY

3.1. Introduction

The decarbonisation of existing buildings necessitates comprehensive deep energy retrofits to achieve substantial reductions in energy consumption and GHG. **Deep retrofits** are known to incur considerable economic costs; nevertheless, they also represent an investment that has the potential to yield long-term economic, social and environmental advantages. The primary advantages include a **reduction in energy expenditures** for residential properties, an enhancement in **property values**, and a catalysis of technological innovation within the construction sector (19,139–141).

Despite their potential, the annual rate of renovation of the European building stock is approximately 1%, with only 0.2% of this attributable to deep retrofits (26). This delay can be attributed to **significant barriers** to the dissemination of these practices. The first of these concerns the current prevailing business model, known as the atomised model.

This is characterised by a fragmented approach in which multiple specialised contractors manage individual stages of the process, leaving the customer with the burden of coordinating the overall intervention. This inherent complexity has been shown to engender elevated risks of project interruption or abandonment (142).

The second obstacle pertains to the elevated initial capital requirement. In circumstances where there is an absence of certainty about the long-term cost-advantage ratio, customers often elect to abstain from investment to avoid the risk of failing to achieve adequate returns (50).

The Energiesprong model, developed in the Netherlands, represents the most advanced version of MESA. A salient feature of the project is its high degree of off-site industrialisation of the construction process, which facilitates standardised, rapid, and replicable interventions. This approach ensures high energy, environmental, and social performance, accompanied by guarantees of up to thirty years, making the model scalable and reliable (31).

However, a crucial question remains unresolved: the literature does not clarify whether deep retrofits are viable from an economic and financial point of view. Moreover, the capacity of the green price premium to fully cover the initial costs remains uncertain.

To address this gap, the chapter analyzes the economic and financial viability of deep retrofits in the residential sector, posing two main questions (cfr. Table 19).

Gap	**Research question**
The literature does not clarify whether deep retrofit interventions are financially viable. Furthermore, the ability of the green price premium to fully cover the initial costs remains uncertain.	RQ2a: Is the financial viability of deep retrofit interventions achievable, under current conditions, through business models integrated with off-site construction solutions?
	RQ2b: Do deep retrofit interventions require upfront public funding to be financially viable?

Table19: Gap 2 and sub-questions of the first research question (RQ2a and RQ2b)

The present study addresses these issues by analysing the economic and financial viability of deep retrofitting through the application of the **MESA business model**, integrated with **off-site industrialised construction solutions**.

The **innovative aspect of the research** lies in the integration of three dimensions that have historically been considered separately: the value proposition of deep retrofitting, the MESA business model and off-site industrialised construction techniques. The interaction between these factors has the potential to overcome the main economic barriers and contain the costs that have thus far limited the large-scale spread of deep retrofitting.

The chapter is organised into the following subchapters:

- **3.2 – Literature review**
  Definition of the characteristics of deep retrofits and off-site industrialised construction Pre.sentation of the main business models for residential retrofits, with a focus on the MESA model and its most advanced evolution, represented by the Energiesprong model;

- **3.3 – Materials and methodology**
  Description of the methodology adopted to estimate the profitability of the interventions, with a presentation of the demand profiles considered and the investment time horizons;
- **3.4 – Data analysis**
  Presentation of the data used, including costs, advantages and interest rates, and descriptive analysis of the typical characteristics of the average property;
- **3.5 – Financial models**
  Illustration of the time distribution of cash flows for the different demand profiles, with determination of the NPV of the investment;
- **3.6 – Results**
  Presentation of the results in terms of profitability and NPV for the various demand profiles;
- **3.7 – Discussion**
  Interpretation of the results with respect to the amount of public funding and the territorial differences in its impact on the various local contexts.

3.2. Residential deep retrofit, off-site industrialised construction and business models

3.2.1. Concept and defining features of residential deep retrofit interventions

Deep retrofitting is a building renovation that goes far beyond simple energy efficiency improvements. The term is preferable to "*deep energy renovation*" because the impacts generated are not limited to reducing consumption but also include reducing GHG, improving indoor environmental quality, increasing living comfort, accessibility and structural resilience of the building (143).

From a performance perspective, a deep retrofit is characterised by a minimum 50% reduction in the **energy intensity** of the site, accompanied by significant improvements in **comfort conditions** and indoor environmental quality (144).

The attainment of these results necessitates an **integrated approach**, entailing the simultaneous involvement of the thermal envelope, air conditioning and domestic hot water production systems, lighting and mechanical ventilation systems, in addition to the integration of technologies based on renewable sources (145).

In the context of international discourse, a uniform definition of deep energy retrofit remains elusive, a consequence of the multifaceted nature of the interventions. Since the energy crisis of the 1970s, there has been a gradual evolution in performance requirements for new buildings and renovations (144). The exhaustion of the most technically and economically accessible solutions – such as loft insulation or single-glazing replacement – has necessitated more complex and capital-intensive strategies (146).

This has resulted in interventions characterised by greater technological depth, including the insulation of perimeter walls, the enhancement of airtightness of the building envelope through the implementation of controlled mechanical ventilation systems, the adoption of low-emission technologies, and the progressive decarbonisation of energy carriers (147,148).

In the **literature**, deep retrofitting is often described more through its effects than through formal definitions (149,150). Gupta et al. (151) identify it as a set of multiple and coordinated interventions on the building envelope, ventilation, heating, lighting, and microgeneration. These interventions have been shown to be capable of producing performance improvements of between 65% and 95%. In their analysis of the social housing sector in the Netherlands, Filippidou et al. (152) emphasise the efficacy of integrating interventions on the building envelope with innovative technologies, including heat pumps and micro-cogeneration systems.

The technical and economic relevance of these interventions is confirmed by empirical evidence. A review of 26 case studies conducted in Europe documents reductions in consumption of between 51% and 88% without renewable sources, and between 72% and 94% with the integration of solar technologies. The average consumption of energy per square metre decreased from approximately 300 kilowatt hours per square metre per year to approximately 80 kilowatt hours per square metre following the implementation of the interventions (144).

Converging findings were reported from the Mustbe0 project, which evaluated the efficacy of advanced retrofit methodologies on eleven residential and educational facilities across France, Germany, the Netherlands, and the United Kingdom (153).

The impacts of deep retrofitting extend far beyond improving energy efficiency. A substantial body of research has demonstrated that comprehensive retrofitting measures can yield financial savings when compared with demolition and reconstruction. These measures have been shown to reduce household energy expenditure, contribute to the mitigation of energy poverty, and enhance occupant comfort and health (154). The literature documents a range of energy consumption reductions, averaging between 30% and 60% (155).

The effects on occupants are manifold. The **primary advantages** include enhanced thermal comfort, with average increases in winter indoor temperatures ranging from 0.5°C to 1.5°C, health advantages, including a reduction in medical visits, and a decrease in humidity and mould (156). However, there have been reports of risks associated with overheating, particularly in low-energy and passive buildings (157,158). With regard to the quality of air within buildings, the results are positive when the increased airtightness of the building envelope is combined with mechanical ventilation systems; in the absence of such systems, however, increases in CO2, radon and formaldehyde are recorded (159).

The literature also highlights how deep retrofitting can generate a **green price premium**, an increase in value on the property market for refurbished buildings. This increase in value can be attributed to two main factors: firstly, the enhancement of the property's energy performance, and secondly, the improvement in the internal quality and overall aesthetics of the building.

However, as demonstrated in several studies (32,34), this premium, although significant, is insufficient to fully cover the initial costs without adequate public support.

3.2.2. Digitalisation and off-site industrialised construction in the building sector

The Architecture, Engineering, Construction and Operations (AECO) sector is a pillar of the global economy, contributing approximately 13% to global gross domestic product (160). In Italy, the sector is of even greater importance than the European average; however, it continues to lag in terms of **productivity**, especially when compared to the manufacturing and service industries (161).

The underlying reasons for this inefficiency are attributed to deep-rooted structural factors, namely the customisation of construction projects, the complexity and difficulty of standardising processes, the **fragmentation** of the supply chain, and the predominantly **artisanal approach** to processes (162). The outcome of this phenomenon is a labour-intensive sector that is heavily dependent on the performance of the workforce and reluctant to transfer skills between the different stages of a building's life cycle (163).

Productivity is chiefly influenced by the presence of human capital and the implementation of suitable technologies (164). However, the literature indicates that the absence of a propensity for digital innovation constitutes the primary impediment to progress (165). The AECO industry's position as one of the least digitised sectors in Europe is not merely an isolated phenomenon; it is a consistent finding that has been documented by the CRESME-GSE Italy (2023) study, which revealed that a considerable proportion of Italian companies exhibited low levels of digital intensity.

Digitalisation is therefore considered a strategic lever for overcoming these constraints (166). It has been demonstrated that **digitalisation enables process integration**, operational fluidity, better information exchange, reduced human effort and increased efficiency, effectiveness and organisation throughout the value chain.

This is where off-site construction becomes relevant, representing not only a technological solution but also a **paradigm shift** in the industry. The term '**off-site construction**' refers to a set of practices that transfer a significant part of the construction process from the building site to specialised manufacturing facilities (167).

This approach was born in the context of post-war industrialisation, and it introduces industrial production logic into the construction sector (168). The aim is to overcome the structural limitations of traditional construction.

From a theoretical standpoint, the literature demonstrates several conceptual nuances. Tatum, Vanegas and Williams (168) define **prefabrication** as the transfer of activities from the construction site to external facilities, while **pre-assembly** consists of the coordinated construction of modular sub-units to be installed at a later stage.

Gibb (169) proposes an integrated view of off-site manufacturing that includes prefabrication and pre-assembly, with an industrial rather than artisanal design orientation.

Bjornfot and Sarden (170) emphasise the enhanced control of construction complexity enabled by prefabrication, attributable to the controlled production environment. Conversely, Emmitt and Gorse (171) distinguish the prefabrication of individual components and the off-site production of buildings or functionally autonomous portions, which can be transported and assembled on site.

Gibb and Isack (169) propose a typological classification of **off-site construction**, divided into four levels of increasing complexity and integration. The first category comprises fundamental components and sub-assemblies, including bricks, tiles and prefabricated structural elements. The second category, non-volumetric pre-assembly, encompasses **prefabricated structural panels**, façade elements and partially assembled plant components. The third category, volumetric pre-assembly, concerns functionally complete units, such as prefabricated kitchens or bathrooms, which require only installation and plant connections on site. The fourth category, that of modular construction, entails the concentration of the majority of operations within the factory, thereby reducing on-site activities to those of transport, assembly, and structural and plant connections of the modules.

The foundation for off-site construction is predicated on four fundamental pillars: process industrialisation, systematic quality control, integration with digital technologies and exploitation of learning economies (143).

The integration of supply chain management principles, derived from the manufacturing industry, facilitates enhanced process planning, thereby promoting economies of scale, standardisation and replicability.

The adoption of off-site methodologies offers significant advantages over traditional construction methods, including increased productivity, reduced safety risks, reduced waste, and a lower environmental impact during the construction process (172). It is evident from an examination of international experience that the sector has attained a considerable degree of technical maturity. Furthermore, it has demonstrated its capacity to adapt to local contexts and respond effectively to contemporary challenges (50).

Integration with digital technologies has rendered off-site construction an **optimal solution**, rather than a marginal one. The integration of robotics, three-dimensional printing, artificial intelligence, and high-performance computational simulations facilitates the optimisation of design, the monitoring of production processes, the reduction of quality variability, and the development of predictive maintenance systems (173). In their 2011 publication, Senaratne and Ekanayake (173) emphasised the pivotal role of advanced manufacturing environments in facilitating the integration of innovative materials and techniques.

The transition to this model necessitates a comprehensive reconfiguration of the construction supply chain, the development of new professional skills, the adoption of innovative organisational models and long-term investment strategies. The advent of off-site construction has precipitated a profound metamorphosis in the role of the worker, characterised by a shift from a conventional craftsman, engaged in manual construction work on site, to an assembler of industrialised components, capable of operating within a standardised and digitised production context.

These transformations underscore the notion that off-site construction signifies more than a mere spatial relocation of construction activities; it denotes a fundamental structural change in the production model, representing a genuine paradigm shift within the construction sector.

3.2.3. Business models for residential deep retrofit

Deep residential retrofitting can be regarded as a radical **innovation**, which requires dedicated business models capable of addressing the technical, organisational and financial complexity of the interventions and ensuring stable revenue streams over the long term (174,175). In the context of the **energy transition**, business models assume a strategic role by serving as a conduit between conventional energy supply practices and the rapid evolution of novel technologies (176–178).

According to the literature, the business model is defined as an integrated framework that incorporates the **value proposition**, the supply chain, the customer interface and the financial structure (179). From this perspective, it can be argued that the firm is the tool that coordinates the creation, distribution and capture of economic value (25,180–182). In the context of residential retrofitting, business models must encompass the green price premium of energy-efficient properties, thereby facilitating the adoption of **innovative solutions** (23,175).

The implementation of deep retrofitting necessitates the concurrent orchestration of a plethora of technological strategies, including advanced insulation measures, the integration of controlled mechanical ventilation systems, the mitigation of air infiltration, and the incorporation of high-efficiency heating systems. The successful execution of these strategies is predicated on the establishment of suitable organisational and financial frameworks (183).

In this context, the efficiency of business models is central for three reasons: i) to incentivise deep retrofitting interventions with combined effects on efficiency and comfort; ii) to stimulate innovation and competitiveness in the supply chain; and iii) to overcome the structural fragmentation of the construction sector (183).

However, the majority of studies on residential retrofitting adopt microeconomic perspectives, focusing on individual companies and neglecting a systemic view of sectoral challenges (184–189).

Consequently, recent literature identifies and analyses four predominant business models: the atomised model, the One-Stop Shop (OSS), Energy Performance Contracting (EPC) and the Managed Energy Service Agreement (MESA) (49,174,190).

The atomised model, which is currently dominant, involves the separate execution of retrofit measures by different contractors, with the owner responsible for overall coordination. This fragmentation has been shown to increase costs and management complexity, transferring both financial and operational risks to the client, and often leading to the abandonment of the project (49).

The One-Stop Shop (OSS) model has been identified as a significant development in the field, with the One-Stop Shop being defined as a system in which a single main contractor assumes responsibility for coordinating a range of activities, including energy audits, financial planning and implementation (191). Whilst the model in question has been developed with the intention of simplifying the interface with the customer, it does not fully transfer the economic risk and does not guarantee complete integration of the supply chain (49,192).

Energy Performance Contracting (EPC) introduces the concept of the Energy Service Company (ESCO), which assumes responsibility for energy performance and cost recovery through the savings generated (193). Despite offering contractual guarantees, EPC is limited in its scope due to its concentration on large-scale projects, particularly those of a public or commercial nature, and its failure to incorporate the entirety of the retrofit cycle (194).

The literature on the subject (29,49,195,196), indicates that the **Managed Energy Service Agreement (MESA)** represents the most promising model for the residential sector, as it evolves the traditional ESCO scheme. A salient feature of the latter is the direct management of the energy bill by the contractor, through an Energy Supply Contract (ESC), with payments based on actual measured and verified savings. This configuration serves to **simplify the interface** with the end user, thereby transferring the performance risk to the supplier (49,197).

MESA also facilitates the establishment of Special Purpose Vehicles (SPVs), which in turn allow for the coordination between subcontractors and customers. Furthermore, SPVs serve to isolate financial risk according to a logic similar to that of the risk fence typical of public-private partnerships (198).

The necessity for advanced capabilities in energy procurement and management is emphasised by MESA, which promotes **the integration** of renewable sources, storage systems and demand-side management strategies, thereby stimulating the development of standardised and industrialised retrofit solutions (49).

In the contemporary business environment, MESA has emerged as the most comprehensive and integrated model, ensuring contractual transparency, optimal risk management and innovation throughout the entire value chain. This configuration establishes the foundations for the emergence of learning economies, which are pivotal for the large-scale implementation of deep residential retrofits. For these reasons, the MESA model will be adopted as an analytical and operational reference in the remainder of this research.

3.2.4. The Energiesprong model: an advanced approach to residential deep retrofit

The Energiesprong model signifies the most advanced evolution of MESA systems, which were developed in the Netherlands as a structural response to inefficiencies in the deep retrofit sector. The paradigm was originally initiated by the government to rapidly renovate existing residential buildings, particularly multi-family dwellings, to achieve **net zero energy performance**. The Dutch experience has documented the transformation of over 5,000 homes into net-zero units without increasing operating costs for residents (31,199).

The Energiesprong refurbishment process involves the transformation of a residential property into a self-sufficient energy unit. This unit is capable of meeting the home's heating, domestic hot water and electricity needs while ensuring comfort levels that exceed conventional standards. The implementation of integrated and standardised technologies has enabled the realisation of these objectives. These technologies include **prefabricated facades** with high thermal performance, insulated roofs with integrated photovoltaic panels, air conditioning systems and controlled mechanical ventilation systems with digital monitoring systems. The most innovative element is the **substantial reduction in construction time**: thanks to digitised processes and off-site production techniques, the refurbishment can be completed in less than ten working days, in some cases even in a single day (30,195,200–202).

The implementation of the model requires four main operating conditions:

- **Financial accessibility** – the investment must be covered by energy savings and efficient property management.
- **Performance quality** – the company contractually guarantees long-term technical and energy performance.
- **Limited disruption** – the work is completed in a maximum of two weeks, allowing tenants to remain in their homes.
- **Long-term economic viability** – the costs are fully financed by future savings and the ordinary 30-year maintenance budget.

The economic framework underpinning Energiesprong is predicated on the concept of Total Cost of Ownership, complemented by the provision of extended performance guarantees. In accordance with the contractual agreement, contractors are obligated to ensure the maintenance of specific standards over the course of a minimum period of thirty years. These standards encompass the maintenance of a consistent internal temperature of 21°C, as well as the adherence to predetermined maximum consumption levels for domestic hot water and electricity. The contractual configuration, akin to telecommunications services with pre-set thresholds, necessitates on-site microgeneration of electricity as a technical prerequisite, thereby facilitating both cost savings and continuous performance monitoring (30,203,204).

In certain instances, the **guarantee can extend up to 40 years**, encompassing not only energy performance but also living comfort (205–207).

For proprietors and lessees, Energiesprong transfers the operational risk to the supplier through long-term energy performance contracts, thereby strengthening the certainty of the investment. The concept of E=0 certification has been demonstrated to engender a consolidation of market confidence, whilst concomitantly catalysing the establishment of a structured ecosystem for industrialised refurbishment. This development has been evidenced to establish itself as an innovative paradigm for both the construction sector and property management (49,199).

3.3. Materials and methodology

It is acknowledged that there is a value proposition associated with the superior energy efficiency of buildings. The economic viability of deep retrofit interventions is therefore assessed on a residential housing unit.

The analysis focuses on the Italian context, where real estate assets represent a structural component of household wealth (106,208) and where 70% of homes belong to the least efficient energy classes (E, F, G on the EPC scale) according to the European classification introduced by Directive 2010/31/EU (8).

The proposed methodology introduces an **innovative contribution** through the systemic integration of three distinct components (cfr. Figure 24):

- **Value proposition** deriving from the energy efficiency and maintenance status of residential properties following deep retrofit interventions;
- **MESA business model**, used as an operational framework for the integrated management of interventions;
- **Off-site industrialised construction technologies**: an innovative approach in the construction sector that involves the manufacture of components in controlled production facilities and their subsequent assembly on site, to make deep retrofit interventions faster, more standardised and more scalable.

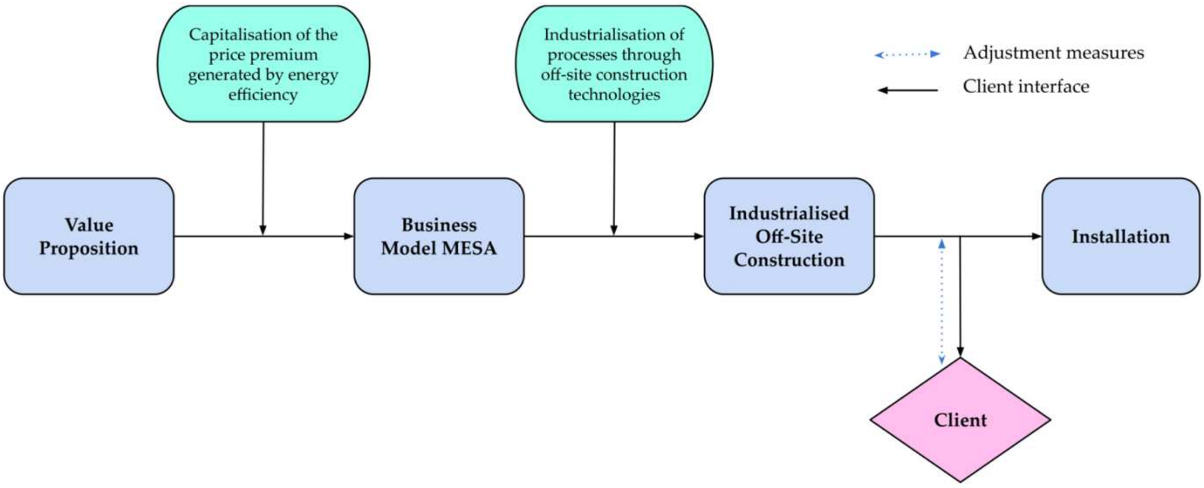


Figure 24: Methodological framework for the integration of value proposition, MESA model and off-site industrialised construction technologies

This integration signifies a substantial methodological advancement in comparison with existing methodologies. Despite the existence of studies in the literature that examine each component individually, there is an absence of research that combines these elements in a unified analytical framework applied specifically to real estate markets.

This gap assumes particular significance when considering the idiosyncrasies of the real estate market, which is characterised by information asymmetries and divergent preferences between demand (homeowners) and supply (property developers), each with disparate profitability expectations.

Following the delineation of the methodological structure, the initial step is to ascertain the value proposition engendered by the retrofit of a residential property. This value is derived from the **enhancement in energy efficiency** that has been achieved through the process of deep retrofitting. This process encompasses both technological and aesthetic improvements to the property, as well as the capitalisation of expected future **energy savings**.

In order to translate the value proposition into economic terms, it is necessary to adopt a business model that is appropriate. In accordance with Brown's classification of business models for retrofitting, the **MESA model** was selected for further investigation (49).

This business model has been demonstrated to reduce management complexity by having a single intermediary between the supply chain and the end customer, who assumes responsibility for the entire retrofitting process. Consequently, the energy transition – which has historically been characterised by its fragmentation – is reconfigured as an integrated business opportunity.

The third methodological element concerns the integration of **off-site industrialised construction technologies** into the deep retrofit project, a distinctive feature of the Energiesprong programme. This approach involves the execution of comprehensive refurbishment works, leveraging off-site construction solutions to achieve substantial enhancements in energy performance.

In addition to enhancing energy efficiency, the Energiesprong model incorporates an aesthetic renovation of the building, which can be customised by the consumer through **mass customisation** strategies (30,201,202,205). This component serves to enhance the appeal of the intervention within the market, thereby facilitating its large-scale dissemination.

The resulting framework integrates the three methodological components described and allows for the development of an overall assessment of the economic viability of industrialised deep retrofit projects.

The economic assessment was conducted considering the plurality of parties potentially interested in the identified business model. Three perspectives representing the main segments of real estate demand were identified:

1. **Owner-Occupier**

   A party that carries out deep retrofitting for personal residential use, to improve the energy efficiency of the property and reduce heating consumption. In this case, the retrofitted property is not intended for disposal, and the investment is aimed exclusively at improving the maintenance and aesthetic condition of the property;

2. **Owner-Developer**

   A person who undertakes the redevelopment for business purposes, modernising the property to increase its energy class and, through the Energiesprong approach, also renovating its aesthetic appeal, including some interior spaces (e.g. bathrooms). The aim is to resell the unit, capitalising fully on the value proposition generated;

3. **Owner-Landlord**

   A person who carries out the project to improve the energy rating and aesthetic appeal of the property. The deep retrofit aims to increase the rent charged to tenants due to the increased energy efficiency of their homes.

The three perspectives analysed reflect different investment time horizons, consistent with the strategic objectives of the respective parties:

- **Owner-Occupier:** twenty-year horizon, equal to two-thirds of the original 30-year guarantee period provided for by Energiesprong standards, reflecting a conservative approach to assessing advantages;
- **Owner-Developer:** sale planned within two years of the initial investment, to immediately capitalise on the increase in value generated;
- **Owner-Landlord:** eight-year period, corresponding to two consecutive four-year leases, identified as a realistic time frame for estimating profitability in the rental market.

From a supply-side perspective, the methodological assumption is that all demand profiles are directed towards companies that adopt the MESA business model. This is integrated with the use of off-site construction technologies to optimise property transformation processes (209–211).

The economic feasibility of retrofitting interventions was assessed using the **Discounted Cash Flow Analysis (DCF)** method. This method calculates the **Net Present Value (NPV)** by discounting costs and revenues over the time horizon defined for each investor profile.

The DCF approach, which has been adopted progressively since the mid-1960s, was developed through pioneering studies by Downs (212), Dilmore (213) and Ratcliff (214), with subsequent refinements proposed by Marshall (215).

The method is predicated on the projection of future cash flows and their discounting using a risk-adjusted discount rate, reflecting the opportunity cost of capital. This structure enables the estimation of property value and the analysis of investment viability.

In all scenarios, the hard costs of the retrofit are assumed to be fixed. The reference values were taken from the **Energiesprong France 2021** report (39) and updated with a 17% increase in line with the evolution of the Indice du coût de la construction des immeubles à usage d'habitation (ICC) recorded between 2021 and 2024 (216).

The decision to utilise French data is substantiated by two primary rationales: The report is the **only extant source** that documents in detail the costs of an intervention using off-site construction technologies. Moreover, the values are **comparable** with the Italian context, given the similarity between the two countries in terms of the industrial structure of the construction sector and the prevailing type of residential property.

In addition to the common costs, the generation of advantages from deep retrofitting projects is contingent on several factors, including the investor's profile, the objectives pursued, and the property enhancement strategies adopted.

For owner-occupier, the economic advantages are derived from the value proposition associated with the improved performance of the residential unit, both in terms of energy efficiency and maintenance. The advantage manifests in an augmentation of the property's asset value, albeit without generating direct cash flows, given the property's continued retention by the investor.

The financial advantages include savings linked to the elimination of moving costs and the cost of temporary accommodation, thanks to the Energiesprong model, which allows the work to be carried out without interrupting the continuity of living arrangements (217).

In the twenty years following the intervention, further advantages are derived from the reduction in energy costs and the deferral of maintenance costs, which are postponed until the expiry of the energy and structural performance guarantee period, generally set at 30 years (218,219).

For the owner-developer, the only advantage is the immediate capitalisation of the price premium generated by the increase in the value of the property, realised at the time of sale. The methodological assumption is that the intervention is carried out on units that are free from rental restrictions.

For the owner-landlord, the advantages are analogous to those of the owner-occupier in terms of savings on temporary property rental during the deep retrofit and deferred maintenance costs. It is important to note that the rent increase is attributable to two factors. Firstly, there has been an improvement in energy performance, and secondly, maintenance conditions have been optimised. At the conclusion of the lease period, the lessor may also capitalise on the increase in value of the property through sale, a process analogous to that of the owner-developer.

As illustrated in Table 20, a systematic classification of the advantages associated with retrofitting is presented for each investor profile. This classification differentiates between financial advantages, i.e. cash flows generated directly by the investment, and economic advantages, i.e. the increase in the property's asset value.

	Owner - Occupier	**Owner - Developer**	**Owner - Landlord**
Economic advantages	ΔV from energy efficiency improvements and enhanced maintenance condition		
Financial advantages		ΔV from energy efficiency improvements and enhanced maintenance condition	**ΔV** increase in property value due to energy efficiency improvements and enhanced maintenance condition (final capitalisation)
	Avoided rental cost for housing continuity		avoided rent cost for maintaining residential continuity
	Avoided moving cost for housing continuity		**ΔV** increase in rental income
	Avoided energy bills		
	Avoided maintenance cost due to deferred reinvestment		Avoided maintenance cost due to deferral of replacement/renewal fees

Table 20: Classification of economic and financial advantages from deep retrofit interventions across the three investor profiles

The value proposition of properties following deep retrofitting is measured by considering the difference in value between homes in habitable condition but energy inefficient (class G according to the EPC scale) and renovated properties with high energy efficiency (class A on the EPC scale).

The estimate is based on the HPM, which quantifies the specific contribution of energy efficiency characteristics to the overall value of the property (95,122).

The assessments were conducted in **four Italian cities** of varying sizes, representative of property markets with differing levels of dynamism and attractiveness: **Milan and Florence** are classified as large cities, while **Udine and Bergamo** are designated as mid-sized cities.

All four cities are located within one of the coldest climatic zones in Italy, which results in high energy consumption for heating purposes. This, in turn, leads to increased annual expenses and, consequently, a higher potential for savings from efficiency measures (109,220).

The two largest cities, Milan and Florence, are significant metropolitan hubs and economic centres of primary importance, attractive to national and international investors. In these cities, approximately 66.3% of real estate listings belong to the least efficient energy classes (E/F/G), highlighting significant potential for retrofitting.

The mid-sized cities of Udine and Bergamo, despite having less economic importance and administrative status than the large cities, have similar characteristics in terms of energy inefficiency, with 62.9% of units in the least efficient EPC classes.

The selected cities represent a substantial proportion of Italy's residential stock and mirror the European urban distribution, wherein approximately 41.8% of the population resides in large cities and 31.2% in mid-sized cities (221,222). It is imperative to consider both types of urban areas when assessing the economic viability and attractiveness of deep retrofitting interventions on a national scale.

3.4. Data analysis

The quantification of the value proposition deriving from energy retrofit interventions was carried out based on the **asking prices** collected in the previous research to determine the price premium for properties with higher energy efficiency.

In contrast to the preceding study, the valuations in this instance were conducted on a standardised property type, which is representative of the prevailing characteristics observed in the sample. The reference unit corresponds to an apartment – the dominant type of housing in Italian urban contexts – located in a semi-central area, excluding central areas subject to more stringent regulatory constraints deriving from the EPBD Directive. The property is located more than 500 metres from the main public transport hubs, to neutralise any proximity effects on the valuations.

From a construction point of view, the dwelling belongs to the ordinary category, which is the most common in the existing residential stock. It has a surface area of 70m², a parameter frequently used in energy performance studies as a standard unit of measurement. The apartment is equipped with a single toilet, a configuration that aligns with the typical characteristics of this size class.

In contrast to the preceding chapter, the value differential was estimated by comparing properties that were habitable but exhibited low energy efficiency (class G on the EPC scale) with renovated properties that were high efficiency (class A on the EPC scale). The analysis was conducted utilising hedonic regression models (223,224).

The HPM model is a methodological framework that facilitates the disaggregation of market value into its underlying components, thereby attributing an implicit marginal value to each attribute of the property unit (123,225). This methodology is particularly suitable for isolating the specific effect of the "energy efficiency" variable, thus minimising the risk of confusing this impact with that deriving from other intrinsic or locational characteristics.

The **regression analyses**, conducted separately for the cities examined, consider the energy variable with a 12-level classification. The comparative analysis enables an assessment of the intensity of the price premium and the variability of the property value differential as urban size and local market structure vary (cfr. Tables 21 and 22).

	Milan		**Florence**	
Predictors X_i	**β_i**	**VIF**	**β_i**	**VIF**
Constant	10.307**	-	9.373**	-
Zone (OMI)	-0.315**	1.243	-0,175**	1.060
Proximity to infrastructure	-0.077**	1.062	-0.050**	1.010
Typology	-	-	-	-

Property class	-0.180**	1.409	-	-
Number of bathrooms	0.065*	2.414	0.076**	1.470
Gross floor area (m²)	-0.002**	2.497	-0.003**	1.590
Energy class	-0.028**	1.410	-0.017**	1.280
Maintenance status	-0.037*	1.382	-0.100**	1.470
Vm ante unit: class G and habitable	€ 4,483		€ 3,512	
Vm post unit: class A and renovated	€ 5,503		€ 4,247	
From G and habitable to class A and renovated	€ 1,020		€ 735	
	22,75%		**20,92%**	

***,* Significance at < 0.01 and < 0.05 respectively*

Table 21: Regression models (A) for Major cities (12-Level Energy Classification)

	Bergamo		**Udine**	
Predictors X_i	**β_i**	**VIF**	**β_i**	**VIF**
Constant	7.973**	-	8.420**	
Zone (OMI)	-0.063**	1.020	-0.041**	1.110
Proximity to infrastructure	-	-	-	
Typology	-	-	-	
Property class	NA	-	-0.132**	1.340
Number of bathrooms	0.273**	1.830	0.149**	2.010
Gross floor area (m²)	-0.001**	1.750	-0.002**	1.960
Energy class	-0.044**	1.770	-0.037**	2.130
Maintenance status	-0.064**	1.790	-0.103**	2.290

Vm ante unit: class G and habitable	€ 1,525	€ 1,312
Vm post unit: class A and renovated	€ 2,118	€ 1,814
From G and habitable to class A and renovated	€ 592	€ 502
	38,82 %	**38,26 %**

***,* Significance at < 0.01 and < 0.05 respectively*

Table 22: Regression models (A) for Mid-sized cities (12-Level Energy Classification)

The econometric analysis conducted enabled the estimation of the **price premium**, defined as the positive value differential engendered by the integration of energy efficiency measures and enhancements in the maintenance state of the property. The results indicate significant territorial heterogeneity:

- **Major cities**: Milan recorded an average increase in market value of 22.75%, while Florence registered 20.92%
- **Mid-sized cities**: Udine demonstrates a substantially higher increase (38.26%), followed by Bergamo with 38.82%

As previously stated in the results of the preceding chapter, the discrepancy between the two contexts is indicative of the distinct characteristics inherent to local markets. In larger markets, property value is more dependent on location and accessibility to services, thereby reducing the relative importance of qualitative characteristics linked to energy efficiency. In contrast, in mid-sized cities, the market appears to be more sensitive to the intrinsic attributes of properties, with greater recognition given to refurbishment work that improves energy performance and the state of repair.

It is imperative to acknowledge that the price premium is only commensurate with a fully monetisable advantage in the event of the sale or rental of the refurbished property. Conversely, for owner-occupier who continue to use the property themselves, the increase in value constitutes a latent asset advantage that does not generate immediate cash flows.

In addition to this economic advantage, owner-occupier enjoy further financial advantages: The following advantages are to be expected: (i) no replacement rental costs, (ii) no moving expenses thanks to continuity of occupancy during the deep retrofit period, (iii) savings on energy bills, and (iv) no need to pay the reintegration fee for the entire duration of the guarantee.

For owner-occupier, the most significant component of the economic returns is the reduction in current energy costs. The analysis, conducted on housing units located in cold climatic zones, identified the performance parameters in terms of the Global Performance Index from non-renewable sources (EPgl,nren) and renewable sources (EPgl,ren). The monetised savings were calculated using the average energy tariffs over fifteen years for non-renewable sources, as provided by ARERA (226), and the values of the Single National Price for energy from renewable sources, as available on QualEnergia.it (227).

A further element of financial convenience is to be found in the implementation methodology of the interventions. The adoption of off-site industrialised technological solutions enables occupants to remain in their homes throughout the entire deep retrofit process, thus eliminating the indirect costs associated with moving and replacement accommodation.

The mean cost of **moving house** was estimated at approximately €3,500 in all the cities that were analysed. The financial implications of **temporary accommodation**, contingent on prevailing market conditions and an assumed relocation period of four months, have been enumerated as such: €3,775 in Milan, €3,156 in Florence, €1,749 in Bergamo and €1,501 in Udine.

The potential for avoiding such expenses thus signifies a substantial economic advantage, particularly in contexts characterised by high housing costs, such as Milan, where rental values are notably elevated.

In addition to these immediate advantages, the option of **deferring routine maintenance operations**, facilitated by the implementation of 30-year performance guarantee systems, should also be considered. This mechanism enables the deferral of recurring expenses throughout the warranty period, thereby generating savings that, on an annualised basis, are equivalent to approximately 0.30% of the construction value of the work. While this advantage may appear negligible, it becomes significant over time, particularly when capitalised over an extended period (129,218,219,228,229).

For owner-landlord in the landlord business, implementing comprehensive retrofitting measures has been shown to yield a dual advantage: a reduction in operating and maintenance costs, and an **increase in rental income**. This increase is estimated by capitalising the market value of properties in excellent condition, as reported by the Agenzia delle Entrate's OMI, applying the average capitalisation rate specific to each geographical area.

The cost framework associated with a deep retrofit includes both direct (**hard costs**) and indirect (**soft costs**) items, which remain constant in the various configurations analysed. The hard costs, estimated based on data from the Energiesprong France programme (39), amount to €1,150/m². In consideration of the escalation documented by the Indice du coût de la construction des immeubles à usage d'habitation (ICC), which, according to INSEE data, exhibited an augmentation of 17% between 2021 and 2024, the revised construction cost is established at €1,347/m².

In addition to these hard costs, soft costs include professional fees for design, construction management and safety coordination, calculated at 9% of hard costs, a contingency allowance quantified at 2%, and a business margin, i.e. the profit of the contractor or owner-landlord, estimated at 4% of hard costs. Collectively, these elements constitute a substantial augmentation to the overall financial outlay of the project, thereby reflecting the management and design intricacy that is characteristic of deep retrofit.

The unit hard costs for the project under analysis amount to 1,347 €/m², totalling €94,307. Conversely, soft costs exhibit variability in accordance with the demand profile. For the owner-landlord and the owner-developer, these costs amount to €14,146, whereas for the owner-occupier, they are reduced to €10,374, as they exclude business profit (cfr. Table 23).

	Owner - occupier Milan, Florence, Bergamo, Udine		**Owner – developer, Owner - landlord Milan, Florence, Bergamo, Udine**	
	Unit cost [€/m²]	Total cost [€*gross area]	Unit cost [€/m²]	Total cost [€*gross area]
Hard costs	1,347	94,307	1,347	94,307
Soft costs	148	10,374	202	14,146
Total costs	**1,495**	**104,681**	**1,549**	**108,454**

Table 23: Unit and total costs of the retrofit intervention with off-site construction on the representative building

3.5. Financial Models

The economic and financial analysis of deep retrofit interventions was conducted using the **DCF model**, which is recognised as one of the most robust tools in real estate economics literature for assessing the feasibility and profitability of medium- to long-term investment projects (215,230).

This methodology facilitates the estimation of the **NPV** through the discounting of positive cash flows, which comprise reduced operating energy costs, augmented rental income and deferred maintenance costs, over time. Negative cash flows, encompassing investment costs (hard costs), indirect costs (soft costs), financial charges and the anticipated return on risk capital, are also discounted.

A pivotal element of the model pertains to the **temporal distribution of cash flows**, which exhibits substantial variation depending on the profile of the economic actor under scrutiny. For the owner-occupier, the advantages primarily manifest in the form of energy and maintenance savings distributed over the entire life cycle of the property. For the owner-landlord, positive cash flows are derived from both operational savings and the rent increase capitalised over time. For the property developer, the time horizon is shorter and the value of the investment is mainly linked to the resale margin, which reflects the market's ability to incorporate the added value resulting from the redevelopment into transaction prices.

The discount rate employed to discount cash flows is the **Weighted Average Cost of Capital (WACC)**, a pivotal parameter in real estate finance as it quantifies the average cost of capital employed. WACC is a metric that calculates the cost of equity and debt based on their respective shares in the financial structure of a transaction (231–233).

The decision to utilise WACC as the discount rate is driven by the necessity to incorporate both the financial risk associated with debt, as manifested by market interest rates, and the minimum return required by investors to remunerate the utilisation of their own capital, which reflects the perceived level of risk associated with the project.

The reference formula adopted is as follows:

$$WACC = Ke\frac{E}{D+E} + Kd\frac{D}{D+E}$$

where:

- WACC is defined as the weighted average cost of capital employed in the investment;
- Ke indicates the cost of equity, i.e. the minimum return required by shareholders or investors in relation to the risk assumed;
- E is the percentage of equity in relation to total sources of financing;
- Kd represents the cost of debt, calculated as the average interest rate applied to loans;
- D is the percentage of debt in relation to the total financial structure.

WACC is therefore not merely a technical parameter, but rather it directly reflects credit access conditions, the macroeconomic context and financial operators' perception of risk. In this sense, it is imperative to ascertain the correct determination as a fundamental component of a comprehensive evaluation of the economic viability of deep retrofit interventions.

In this particular instance, the **cost of debt** was established at 3.06%, based on the average rates applied to green mortgages by the major Italian credit institutions (234).

Conversely, the **cost of equity** is contingent on the risk profile attributed to the investor. For owner-occupier, who retain the refurbished unit for the long term, an expected return of 4% is assumed, consistent with the average yield on Italian government bonds (BTPs) in 2024 (235). For owner-landlord, the cost of equity has been estimated at 6%, reflecting both greater exposure to risk and the possibility of increased returns from higher rents. Finally, for the property developer intending to sell the property within two years, the cost of equity has been set at 8%, consistent with the speculative nature and operational risk associated with a short-term horizon.

The DCF methodology facilitates the assessment of the economic viability of energy retrofit measures by quantifying the investment's capacity to generate added value in comparison to WACC over a stipulated timeframe.

For **owner-occupier**, the time horizon considered is twenty years, which corresponds to the operational life cycle of the refurbished property. The financial structure that has been assumed provides for greater leverage, with 80% of the capital represented by debt and 20% by equity, to maximise the leverage effect on the cash flows generated. WACC for this profile is 3.25% (cfr. Figure 25).

	Temporal horizon	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Costs	Hard costs	🟥																			
	Soft costs	🟥																			
Advantages	Avoided rent cost	🟩																			
	Avoided moving cost	🟩																			
	Avoided energy bills	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Avoided maintenance cost	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Net operating income (×10^3) [€]																					
	Milan	-95,4	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0
	Florence	-96,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0
	Bergamo	-97,4	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0
	Udine	-97,7	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0

Figure 25: The DCF model is applied to the case of an owner-occupier of a residential property undergoing deep retrofit, with the structure of cash flows and discounting using WACC highlighted

For the **owner-developer**, the investment is designed with a two-year time horizon. This is equal to the period needed to complete the work and proceed with the sale of the property. The investment is made immediately after the deep retrofit has been completed. This allows the developer to capitalise on the value proposition deriving from the retrofit.

In this instance, the financial structure is deemed to be more prudent, with leverage set at 70% debt and 30% equity. This strategy is intended to reduce financial exposure and ensure capital viability. WACC calculated for the developer is 4.45% (cfr. Figure 26).

	Temporal horizon	1	2
Costs	Hard costs	🟥	
	Soft costs	🟥	
Advantages	ΔV: from G and habitable to class A and renovated		🟩
Net operating income (×10^3) [€]			
	Milan	-10,85	7,14
	Florence	-10,85	5,14
	Bergamo	-10,85	4,14
	Udine	-10,85	3,51

Figure 26: The DCF model is applied to the case of an owner-developer of a residential property undergoing deep retrofit, with the structure of cash flows and discounting using WACC highlighted

For the **owner-landlord**, an eight-year timeframe is assumed, corresponding to two consecutive four-year lease periods. This is considered a realistic assumption for the purpose of assessing profitability in the rental market. The financial structure provides for a leverage ratio of 70% debt and 30% equity, thus ensuring a balanced approach to financial risk and capital viability. WACC for the owner-landlord is 3.94% (cfr. Figure 27).

	Temporal horizon	1	2	3	4	5	6	7	8
Costs	Hard costs	🟥							
	Soft costs	🟥							
Advantages	ΔV: from G and habitable to class A and renovated								🟩
	Avoided rent cost	🟩							
	Increase in rental income		🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Avoided maintenance cost	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Net operating income (×10³) [€]									
	Milan	-10,4	0,28	0,28	0,28	0,28	0,28	0,28	7,42
	Florence	-10,5	0,22	0,22	0,22	0,22	0,22	0,22	5,37
	Bergamo	-10,6	0,23	0,23	0,23	0,23	0,23	0,23	4,37
	Udine	-10,7	0,17	0,17	0,17	0,17	0,17	0,17	3,69

Figure 27: The DCF model is applied to the case of an owner-landlord of a residential property undergoing deep retrofit, with the structure of cash flows and discounting using WACC highlighted

3.6. Results

NPV analysis shows **negative outcomes**, with variations observed depending on the investment perspective adopted and the city under consideration.

For owner-occupiers, who directly bear the costs and advantage from the energy savings resulting from the operation of the property, NPV values are relatively consistent between major cities and mid-sized cities. Specifically, Milan records a loss of €-56,875, Florence €-57,493, Bergamo €-58,900 and Udine €-59,153, indicating a notable uniformity in the results obtained.

In the case of the owner-developer, who assumes the immediate sale of the property at the end of the intervention, the differences between cities are more marked. In major cities, NPVs are less negative, at €-37,066 in Milan and €-57,015 in Florence, while in mid-sized cities, losses increased considerably, with €-67,009 in Bergamo and €-73,323 in Udine.

The effect of urban size is even more pronounced for owner-landlords, whose NPV shows greater heterogeneity. In major cities, the results are relatively better, with Milan recording €-13,115, the least negative value in the entire sample, and Florence €-38,159. In mid-sized cities, profitability decreases significantly, reaching €-49,412 in Bergamo and €-59,397 in Udine, demonstrating how the ability to generate rental income is strongly influenced by the urban context (cfr. Table 24).

Investor perspective	**Cities**	**NPV**	**Financial deficit**
Owner - occupier	Milan	-56,875	54,3%
	Florence	-57,493	54,9%
	Bergamo	-58,900	56,3%
	Udine	-59,153	56,5%
Owner - developer	Milan	-37,066	34,2%
	Florence	-57,015	52,6%
	Bergamo	-67,009	61,8%
	Udine	-73,323	67,6%
Owner - landlord	Milan	-13,115	12,1%
	Florence	-38,159	35,2%
	Bergamo	-49,412	45,6%
	Udine	-59,397	54,8%

Table 24: NPV and financial deficit of the deep retrofit project in major and mid-sized cities, according to three ownership profiles

NPVs obtained from the analysed models are negative in all the cities under consideration, indicating that the renovation costs exceed the expected advantages. This renders investment in deep energy retrofitting financially unviable without recourse to public subsidies or additional private resources. It is therefore vital to ensure the intervention's economic and financial viability by seeking external support.

The **investment deficit,** understood as the proportion of the total cost of the intervention that is not offset by the anticipated advantages, corresponds to the ratio between the NPV and the total cost of the investment (cfr. Table 21).

For owner-occupiers, the values are relatively similar between major cities and mid-sized cities. The deficit ranges from 54.3% in Milan, Italy's strongest metropolitan city, to 56.5% in Udine, with Florence at 54.9% and Bergamo at 56.3%.

A lower deficit is demonstrated by major cities in comparison to mid-sized cities for owner-developers. Milan continues to demonstrate the highest level of performance, with a deficit of 34.2%, closely followed by Florence with 52.6%. In mid-sized centres, on the other hand, the figures are higher and more varied: The deficit in Bergamo is 61.8%, while Udine has a deficit of 67.7%.

A particularly salient example of this phenomenon is observable in the context of owner-landlords, where the disparities between major cities and mid-sized cities become even more pronounced. Milan demonstrates the most favourable outcome, exhibiting a deficit of 12.1%, while Florence exhibits a substantially higher deficit of 35.2%. In mid-sized centres, profitability decreased significantly, with Bergamo at 45.0% and Udine at 54.0%, confirming that the ability to generate rental income is strongly influenced by the urban context (cfr. Figure 28).

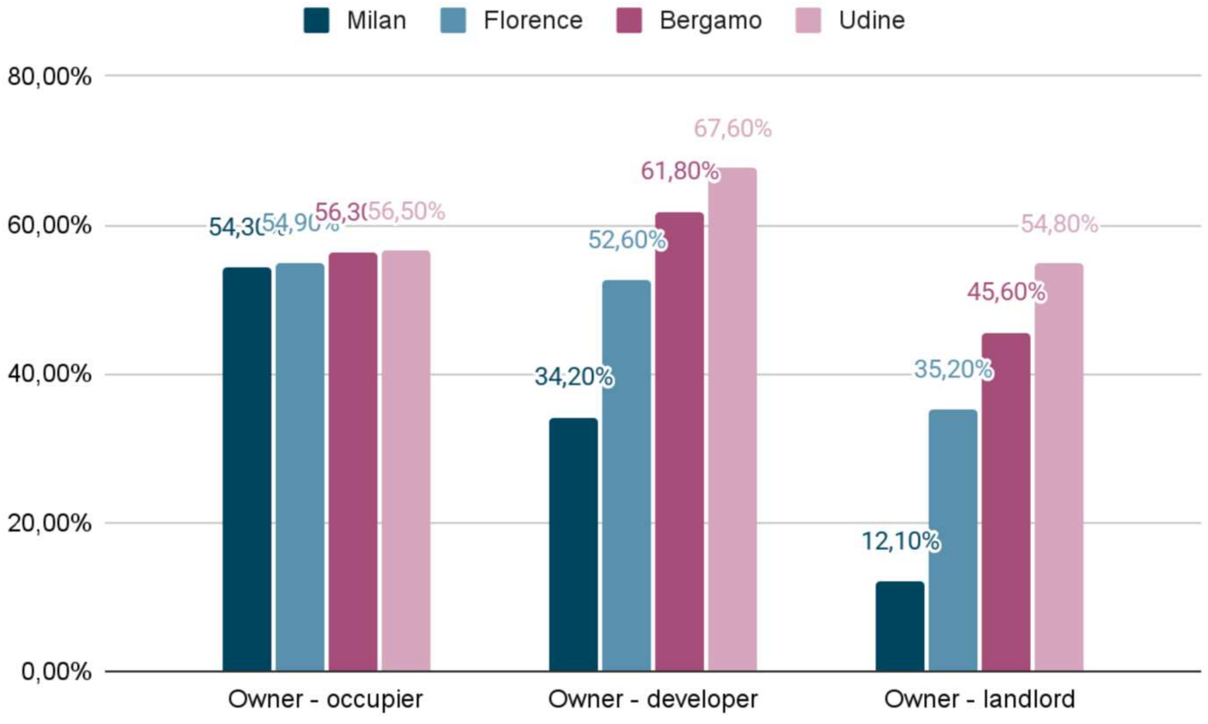


Figure 28: Financial deficit of the deep retrofit project in major and mid-sized cities, disaggregated by three ownership profiles

NPV and financial advantage for owner-occupiers demonstrate a **substantial alignment between the cities**. In this investment profile, the costs and advantages of deep retrofitting are independent of the specific characteristics of local property markets, except insofar as the costs associated with finding replacement accommodation during the construction phase are concerned. These costs are determined by the continuity of occupancy required by Energiesprong interventions.

The financial implications of the intervention depend on the geographical location and the attributes of the property, with rental fees playing a crucial role in determining the overall costs. In metropolitan areas such as Milan and Florence, which are characterised by generally high rents compared to mid-sized cities, the absence of additional costs for **replacement accommodation** partially reduces the investment deficit. However, this effect results in a marginal alteration in the overall NPV, which persists in being negative in absolute terms.

However, a notable distinction emerges for **owner-developers** intending to market the residential unit after the retrofit's completion. In this case, the disparities between large urban centres and mid-sized cities are evident, as the NPV is determined exclusively by the **capitalisation of the price premium** resulting from the improvement in the energy and maintenance quality of the property.

In major cities, the capitalisation of the price premium applies to **higher market values**. Consequently, although the percentage of the price premium is lower than in mid-sized cities, the absolute value recovered through capitalisation is higher. This enables a more substantial return on investment in deep retrofitting, thereby rendering the intervention more economically viable in large cities than in mid-sized centres.

This dynamic is clear in the case of Milan, where significantly high property prices allow the capitalisation of energy improvements to generate a higher NPV, thereby reducing the deficit of the intervention. Conversely, in cities such as Bergamo or Udine, characterised by less dynamic property markets and lower property values, capitalisation is more limited, and the investment deficit is much greater.

About **owner-landlords**, the results demonstrate a more intricate and diversified pattern in comparison to other investment profiles. The financial viability of the intervention is contingent upon the capacity to transfer the enhanced value arising from the energy and quality enhancement of the property to landlords, in addition to direct energy savings and any tax advantages that may be available.

In major cities, characterised by stronger property markets, landlords can transfer a greater share of the **added value to rents**, thereby significantly increasing revenues and reducing the investment deficit. In cities such as Milan and Florence, where average rents are higher, the increase in rent resulting from energy improvements can offset the costs incurred to a greater extent than in mid-sized cities. Specifically, in Florence, approximately one-third of the investment remains in deficit, while in Milan, the situation is closer to a balance between costs and advantages, with a residual deficit of 12%.

Conversely, in mid-sized cities such as Bergamo and Udine, the economic balance is considerably further away, with around 50% of the investment not recoverable. In such contexts, the capacity to elevate rental rates is constrained, and the capitalisation of the price premium manifests in markets characterised by substantially diminished values. This phenomenon engenders an inadequate impact on attaining the financial balance of the intervention.

3.7. Unviable deep retrofit and the need for upfront public funding

The analysis conducted addresses the second research gap in the literature and provides an answer to Research Question **RQ2a: Is the financial viability of deep retrofit interventions achievable, under current conditions, through business models integrated with off-site construction solutions?**

The findings indicate that the economic and financial advantages yielded by energy retrofitting measures are systematically lower than the costs incurred. It can thus be concluded that, even under the assumption of full capitalisation of the value proposition through the most efficient MESA business model and the utilisation of off-site construction technologies, deep retrofitting interventions are not financially self-sufficient investments.

It is evident that the enhancement of the energy efficiency of buildings, whilst undoubtedly beneficial in terms of reducing energy consumption and associated costs, is not necessarily sufficient to guarantee the economic viability of the investment. For the owner-occupier, approximately 50% of the investment remains uncovered by the advantages generated. In the case of owner-developers, the unrecovered share of the investment varies significantly, ranging from 30% in major cities to 70% in mid-sized cities. For owner-landlords, the residual deficit ranges from 12% to 50%, depending on the urban context.

This economic and financial imbalance **confirms literature** (34,82) that the value proposition associated with improving the energy performance and intrinsic characteristics of residential properties – even assuming the maximum value differential between units in energy class G and class A – **is insufficient** to guarantee the economic and financial viability of the interventions.

Moreover, the economic viability of retrofitting is contingent on the urban context, exhibiting variations in accordance with the magnitude of the city and the configuration of the property market. In major cities, characterised by dynamic markets and high property values – such as Milan and Florence – deep retrofits are relatively more viable and have lower deficits.

This phenomenon can be attributed to **two key factors**. Firstly, there is the enhanced capacity to capitalise on the price premium at the time of property disposal. Secondly, there is the possibility of transferring a greater proportion of the increase in value resulting from energy and quality improvements to the tenant.

Conversely, in mid-sized cities – such as Bergamo and Udine – where property values are lower, the economic viability of retrofitting is much more pronounced. In such contexts, the efficacy of capitalising on the price premium is constrained, and the capacity to transfer added value to tenants is diminished, culminating in less profitable investments with considerably higher deficits.

The analysis also provided an answer to Research Question **RQ2b: Do deep retrofit interventions require upfront public funding to be financially viable?**

The response to this question is **affirmative**. It is an irrefutable fact that deep retrofits require **initial public support** to achieve economic balance. The amount of support required varies significantly depending on the characteristics of local property markets, being greater in mid-sized cities, where lower property values reduce the ability to capitalise on the added value generated by the intervention.

In the absence of upfront public contributions, deep retrofits cannot be sustained by **market mechanisms alone.** The analysis shows that the value created by efficiency improvements—although recognised by the market—is subject to both **temporal** and **monetisation constraints**. On the one hand, the increase in property value requires time to materialise as an effective economic return for the owner, typically occurring only at the moment of sale or, to a lesser extent, through higher rents. On the other hand, there remains the concrete possibility that part of this increase constitutes a **latent value**, which is not immediately (or fully) realisable, particularly in weaker or stagnant markets.

Acknowledging these two dimensions is essential for understanding why deep retrofit interventions, even when supported by advanced construction technologies and efficient business models, fail to reach financial equilibrium. It also provides a coherent transition to the next chapter, where the focus shifts from market-based value creation to the **economic–financial feasibility** of retrofitting, integrating the price dimension with the temporal structure of cash flows and the payback dynamics. This broader analytical framework enables the identification of the subsidy levels required to close the investment gap and highlights the conditions under which public funding can effectively leverage private investment.

Chapter 4

4. REDUCING CONSTRUCTION COSTS IN OFF-SITE INDUSTRIALIZED BUILDING APPLIED TO BUILDING RENOVATION: EMPIRICAL EVIDENCE FROM ENERGIESPRONG PROJECTS IN FRANCE

4.1. Introduction

A review of the literature on deep retrofits indicates that **construction costs** remain the primary barrier to the large-scale adoption of these technologies. Despite the implementation of energy-efficient measures and off-site construction techniques, such interventions often fail to achieve financial viability, making **external public support** necessary (32,236,237).

A proposed strategy for reducing the unit costs of these interventions is to invest in the **development and refinement of industrialised off-site construction technologies**, alongside greater investment in innovation and standardisation (238).

It is widely acknowledged that the accumulation of experience and technological efficiency serve to enhance the efficacy of production processes, thereby resulting in a reduction in costs. This phenomenon, termed the **learning effect**, has been documented across a wide range of industrial and technological domains, particularly within innovative contexts where initial costs are substantial in the early stages and subsequently decrease over time because of accumulated experience.

The acquisition of experience in associated domains, such as manufacturing and renewable energy, validates the efficacy of learning-by-doing mechanisms. Initially, high costs are diminished as production levels rise, processes undergo technological enhancement, and organisational competencies are strengthened (239,240).

From this standpoint, it is conceivable that greater industrialisation of off-site industrialised construction, based on prefabrication and standardisation, could trigger similar cost reduction dynamics in the off-site construction sector (241). Consequently, the research focuses on deep retrofit interventions carried out with off-site technologies. The scope of the research selects projects from the Energiesprong programme for social housing in France, which is the second largest European market for industrial building retrofits after the Netherlands in terms of the number and volume of projects carried out (31). The data collected enables the creation of a **cost reduction curve** based on cumulative units.

The literature on this subject is limited in scope. There is a paucity of studies that have analysed, both theoretically and empirically, the extent of construction cost reductions in both traditional technology-based interventions and those carried out using off-site building technologies.

The objective of this chapter is to empirically verify the extent to which the increase in retrofitted units can lead to a reduction in unit construction costs linked to learning economies.

Empirical verification of the existence of learning processes is significant, as it demonstrates how costs traditionally considered fixed can be progressively reduced through the adoption of technological innovations and new methods of industrial organisation.

The objectives of the research are **twofold** (cfr. Table 25):

- to verify whether the increase in interventions, accompanied by processes of standardisation and consolidation of skills, has led to a reduction in construction costs;
- to identify the factors underlying this cost reduction.

Gap	**Research question**
There is a lack of studies investigating cost reductions in off-site construction industries because of learning economies	RQ3a: Is it possible to empirically document a reduction in construction costs linked to learning-by-doing mechanisms in deep retrofit projects carried out with off-site construction solutions?

Table 25: Gap 3 and sub-question of the third research question (RQ3a)

The chapter is organised as follows:

- **4.2 – Learning economies: theoretical foundations, mathematical formalisation and learning rates**
  Presentation of the main theoretical references on learning curves, with an in-depth analysis of the mathematical formulations and cost reduction rates observed in the various production sectors;

- **4.3 – Methodology and data**
  Detailed description of the methodology adopted, including econometric models, sample selection criteria and statistical analysis tools used;
- **4.4 – Data analysis: descriptive statistics**
  Presentation of descriptive statistics relating to the costs of the interventions, highlighting the main characteristics of the sample and the variables considered;
- **4.5 – Models**
  Elaboration of cost learning curves for different types of buildings, accompanied by robustness analysis and estimation of the sample's learning rates;
- **4.6 – Results and reduction drivers**
  Analysis and discussion of the factors that have contributed to cost reduction and the obstacles that have limited its potential.

4.2. Learning economies: theoretical foundations, mathematical formalisation and learning rates

4.2.1 Theoretical principles of the learning curve: from Wright's original intuition to recent developments

Innovations require significant initial investments, both for the acquisition of new technologies and infrastructure, and for learning new processes and training staff. Consequently, production costs are elevated in the initial stages. However, as experience is accumulated and production scale is expanded, there is a tendency for operational efficiency to increase and unit costs to gradually decrease.

This phenomenon is known as the **learning effect**, formalised through the **learning curve** (or experience curve). The curve delineates the systematic relationship between the cumulative quantity of output produced and the reduction in unit costs or processing times. It is evident that, in general terms, the curve demonstrates how an increase in production experience results in a gradual enhancement of operational efficiency, consequently leading to a **reduction in average costs** or the time required per unit of output (242).

The adoption of learning curves has become pervasive across all sectors, particularly within emerging and innovative domains such as the management of novel products and services

(243), where curves are employed to **optimise processes and costs**, or industrial training through virtual reality simulations (244).

The starting point is Ebbinghaus (245), who formalised the relationship between learning and forgetting in experimental psychology, providing a conceptual framework that would later be translated into the manufacturing sector. Wright (246) transferred these principles to the domain of aeronautics, thereby establishing the empirical regularity that links accumulated experience and cost reduction. This seminal contribution can be regarded as the founding act of industrial literature.

Ayres (247) built upon this **initial systematisation**, consolidating and reinforcing the mathematical formalisation of the model, thus allowing it to be generalised to different production contexts. Sahal (248) also fits into this trajectory, emphasising the relationship between learning dynamics and technical progress, broadening the interpretative scope of the framework and paving the way for subsequent theoretical and applicative developments.

During the period spanning from the **1970s to the 1990s**, the focus of attention was directed towards the **operational and organisational methodologies** through which learning materialised. Anderson (249) investigated the performance improvements resulting from repetitive activities; Adler & Clark (250) extended the analysis from the individual to the organisation, highlighting the effects on productivity; Dar-El & Rubinovitz (251) introduced the concept of industrial forgetting, while Pananiswaml & Bishop (252) explored the impact of task complexity on learning rates. At this same stage, Teplitz (253) and later Uzumeri & Nembhard (254) applied the principles of the curve to the allocation of tasks based on individual learning profiles.

Since the 2000s, literature has undergone a phase of **diversification** that can be traced back to three main lines of development: operational, methodological and predictive. The initial strand, of an **operational** line contemplates the utilisation of learning curves as a mechanism for enhancing the management of production and organisational processes. In this context, studies by Lapré, Mukherjee & Van Wassenhove (255), Nembhard & Uzumeri (256) and Nembhard & Osothsilp (257) highlight the organisational **determinants of learning** and the transferability of skills, while Vits & Gelders (258) and Hamade et al. (259) explore the design of training programmes and the **factors** that accelerate technical learning processes

These contributions are complemented by those in the ergonomic and cognitive fields, such as Wickens et al. (260) and Pananiswaml & Bishop (252), who analyse the **mechanisms of retention** and recovery of skills following interruptions, thus broadening our understanding of the limits and potential of human capital.

The second line, which is **methodological** in nature, focuses instead on the development of theoretical models and analytical tools capable of describing and quantifying learning processes. This perspective incorporates studies that introduce supplementary dimensions into the framework, such as forgetting, task complexity, and group dynamics.

The third line, which has a **predictive** nature, examines the use of curves as a tool for forecasting future costs and performance. The seminal work of Martino (261) was among the first to propose its application for forecasting purposes. This concept was subsequently developed by Alberth (262) and Nagy et al. (263) through empirical validation and hindcasting methodologies. This research trajectory ultimately culminates in the stochastic approach pioneered by Farmer & Lafond (28), which introduces probabilistic models, thereby marking the transition from deterministic to distributional forecasts.

The literature highlights a strong **application-oriented approach**, particularly evident in the studies by Lapré, Mukherjee & Van Wassenhove (255), Smunt & Watts (264), Chen et al. (265) and Jaber & El Saadany (266). These illustrate how curves can be used to define standards, monitor objectives, forecast production times and volumes, estimate waste and optimise processes.

Subsequent **management extensions** — including inventory optimisation, batch sizing, supplier selection and logistics planning (routing, order picking) — emerge from the work of Azadegan & Dooley (267) and Grosse & Glock (268).

At the strategic level, contributions from Abernathy & Wayne (269), Plaza & Rohlf (270) and Nadeau et al. (271) emphasise the role of curves in pricing decisions, new product launches, investments in innovation and organisational design.

In recent developments, the application of learning curves has been extended to emerging and **technology-intensive contexts**. As demonstrated by Rahman & Kirby (243), the utilisation of these systems has been shown to facilitate the management of innovative products and services. In contrast, Li, Siniosoglou, Sarigiannidis & Argyriou (244) have indicated that immersive virtual reality simulations have the capacity to accelerate technical learning and reduce the training curve.

In the field of **construction**, Micelli et al. (241) present **the first empirical** research aimed at investigating the **dynamics of cost reduction in the off-site sector**. The study, which was conducted on deep retrofit interventions, highlights a trend towards decreasing unit costs as the number of interventions increases and industrialised processes become more established.

When considered as a whole, these studies provide a multidisciplinary and constantly evolving picture in which learning curves play a dual role (28,242,272,273): on the one hand, as a descriptive tool capable of capturing empirical regularities in improvement processes; on the other, as a tool capable of guiding operational, organisational and strategic choices.

Their adaptability to different contexts — from cognitive psychology to renewable energy, from traditional manufacturing to innovative services, and from training in virtual environments to building retrofits — attests to their theoretical significance and practical utility for research.

Table 26 presents the main contributions in the literature on learning curves.

Author(s)	**Year**	**Sector/Context**	**Methodological Contribution**	**Theoretical Impact**
Ebbinghaus	1885	Experimental Psychology	First formalisation of learning and forgetting curves	Theoretical foundation for industrial applications
Wright	1936	Aeronautics	Learning curve: constant reduction of unit costs for each doubling of cumulative production	Foundational principle in industrial literature
Ayres	1969	Industrial Economics	Advanced mathematical formalisation of experience curves	Consolidation of the theoretical framework
Sahal	1979	Technological Innovation	Integration of technical progress and cost dynamics	Linking learning and innovation
Anderson	1982	Industrial Production	Analysis of performance improvements in repetitive tasks	Microfoundations of operational learning
Adler & Clark	1991	Industrial Organisation	Organisational learning and productivity effects	Extension from individual to organisational level
Dar-El & Rubinovitz	1991	Work Engineering	Modelling knowledge loss after interruptions	Introduction of the concept of industrial forgetting

Author(s)	Year	Sector/Context	Methodological Contribution	Theoretical Impact
Pananiswaml & Bishop	1991	Industrial Ergonomics	Impact of complexity on learning rates	Determinants of learning effectiveness
Martino	1993	Technological Forecasting	Experience curves for estimating future costs	Predictive application of the framework
Wickens et al.	1998	Cognitive Psychology	Retention and recovery of skills after breaks	Cognitive mechanisms of forgetting and recovery
Nembhard & Uzumeri	2000a	Manufacturing Production	Organisational factors in learning and retention	Determinants of group learning effectiveness
Nembhard & Osothsilp	2002	Industrial Production	Role of prior experience in learning processes	Transferability of competencies
Vits & Gelders	2002	Operational Management	Training structure and learning rates	Optimal design of training programmes
Hamade et al.	2007	Manufacturing	Identification of factors accelerating technical learning	Optimisation of learning conditions
Alberth	2008	Renewable Energy	Cross-validation of predictive accuracy	Empirical validation methodologies
Jaber & Guiffrida	2008	Industrial Production	Integrated models of learning and forgetting	Joint dynamics of acquisition and loss
Nagy et al.	2013	Renewable Energy	Hindcasting methodologies for forecasting robustness	Standards for predictive evaluation
Farmer & Lafond	2016	Stochastic Modelling	Geometric random walk with drift for probabilistic cost estimation	Transition from deterministic to distributional forecasting
Rahman & Kirby	2023	Emerging Products and Services	Application of learning curves to optimise processes and costs	Performance optimisation in innovative contexts
Li, Siniosoglou, Sarigiannidis & Argyriou	2025	Industrial VR Training	Immersive simulations to accelerate technical learning	Reduction of learning curves and enhancement of practical skills
Micelli et al.	2025	Off-site Construction, Deep Retrofit	Experimental analysis of unit cost reduction in industrialised deep retrofit projects	Empirical evidence of learning curves in off-site industrialised construction

Table 26: Main contributions to the literature on learning curves

4.2.2. Learning curve models: a review

The transition from the theoretical conceptualisation of the learning effect to its **mathematical formalisation** marked a crucial stage in the development of studies on the subject. The necessity to identify and quantify the learning rate of learning curves resulted in the development of a variety of models, characterised by differing levels of complexity and increasing specificity of application.

The Wright curve (246) is regarded as the most **pioneering** and widely **adopted** model. It was originally developed in the **aeronautical sector** to formalise the principle that unit production costs decrease by a constant percentage each time cumulative production doubles.

The methodological robustness and versatility of this model have permitted its application at both the individual level, to monitor the learning of individuals, and at the collective level, to analyse team dynamics and organisational processes. This has resulted in a proliferation of alternative names in the specialist literature, such as the so-called progress functions (274), start-up curves (275) and improvement curves (276).

Wright's studies identified the three most common functional forms: the Power Law Model, the Learning Curve Model and the Logarithmic Cost Function.

The **Power Law Model**, defined by the function $C(Q) = C_0 \cdot Q^b$ (where C is the unit cost and Q is the cumulative quantity), is primarily applied in highly standardised industrial sectors, where increased production generates persistent and significant reductions in unit costs. The model operates under the assumption of constant learning economies over time, rendering it particularly well-suited for processes characterised by mature technological components (246,263,277).

The **Learning Curve Model** is specified as $C(Q) = C_0 \cdot Q^{log2\,(1-r)}$, where α is the learning elasticity. The model has been demonstrated to be suitable for technologically advanced sectors, including but not limited to renewable energy, aerospace and electronics. In such sectors, the accumulation of production experience leads to systematic improvements and rapid cost reductions in the early stages (278–280).

The **logarithmic cost function**, expressed as $C(Q) = a + b\ ln(Q)$, is a model which describes gradual and decreasing cost reductions in industrial contexts where scalability is limited and there are significant fixed costs. The application in question is employed within sectors characterised by diminishing returns to learning, wherein enhancement of efficiency is realised through incremental optimisations as opposed to radical innovations (281,282).

Subsequent years witnessed the development of more sophisticated models for specific **industrial contexts**. As posited by **Stanford-B**, the integration of experience through the introduction of an additional parameter serves to enhance predictability in the early stages of production. This is a particularly salient point during the period in which data scarcity engenders uncertainty about cost estimation (283,284).

De Jong's model (285) differentiates between **two components** of production costs or times: a learning-sensitive part, which decreases with the accumulation of experience, and an incompressible part, which remains constant regardless of production, generally associated with machinery, automated processes or standardised activities. The model facilitates a more authentic depiction of efficiency dynamics in mixed production contexts, wherein not all processes are subject to an identical learning rate.

As illustrated in Table 27, the principal learning curve models are presented, accompanied by their respective formulae and applications.

Model	Main Application	References
Wright (1936)	Advanced technology sectors, repetitive processes	(246,280)
Stanford-B (1947)	Complex production with prior experience	(283,284)
de Jong (1957)	Mixed processes with incompressible components	(285)
S-Curve	Entire learning cycle: initial phase, growth, saturation	(284)
Power Law Model	Standardised industrial sectors, persistent economies of scale	(273)
Learning Curve Model	Technologically advanced sectors, rapid initial learning	(246,280)
Logarithmic Cost Function	Sectors with limited scalability, diminishing returns	(286–288)

Table 27: Overview of the main learning curve and unit cost models

In the field of construction cost analysis, the logarithmic cost function has been identified as a particularly pertinent mathematical formulation for the study of learning dynamics. The methodological approach adopted renders it especially **well-suited** for the analysis of production processes characterised by structural constraints and heterogeneous cost components (242,273).

The logarithmic formulation facilitates the concurrent depiction of two distinct phases: the initial rapid learning phase, distinguished by substantial marginal cost reductions, and the subsequent consolidation phase, where improvements become progressively more marginal. These phases are considered typical characteristics of innovative and repetitive processes, as evidenced by empirical observations in energy retrofit projects. In these projects, technological innovation is coupled with process standardisation, resulting in the generation of complex, multi-phase learning dynamic.

4.2.3. Measuring the learning rate in the energy and construction sectors

The learning rate is a fundamental metric for quantifying the **percentage reduction** in costs or production time when doubling the quantity produced, reflecting the efficiency accumulated through operational experience (289,290).

A review of the scientific literature indicates **significant heterogeneity** in learning rate values across industrial sectors and technologies. This can be attributed to variations in the complexity of production processes, the rate of technical knowledge accumulation, and the efficacy of technological innovation diffusion mechanisms.

Mature and standardised sectors are subject to gradual and progressive cost reductions, characterised by relatively low but stable learning rates over time. Conversely, **innovative or rapidly developing technologies** demonstrate significantly higher learning rates, thereby confirming the close relationship between technological complexity, methods of accumulating operational experience, and the speed of industrial learning processes.

Within the domain of energy, a discernible dichotomy exists between conventional technologies and their more pioneering counterparts. **Renewable sources** have been shown to exhibit higher learning rates, with reported values ranging from 14% to 34%. The results indicate that wind energy exhibits a lower variability, ranging from 3% to 17%, attributable to the technological maturity achieved and the diversification of applications. Specifically, **onshore wind power** exhibits learning rates ranging from -11.4% to 20%, with initial negative coefficients indicating that inefficiencies or operational challenges can temporarily reverse the conventional learning curve. This phenomenon generally resolves itself as experience accumulates.

Technologies associated with energy demand management, such as smart thermostats and home energy management systems (HEMS, which automatically regulate energy consumption), demonstrate an average learning rate of approximately 18%, with standard deviations of ±9% attributable to differences between technology clusters and specific methods of implementation and market penetration.

Solar photovoltaics represent a prime example of a technology characterised by high and relatively stable learning rates, ranging from 15% to 25%. Residential **photovoltaics** has been shown to achieve values of up to 33%, thus demonstrating the efficacy of adapting to the needs of the residential segment and the optimisation of technical solutions in significantly accelerating learning processes. In contrast, the industrial production of photovoltaic panels ranges between 20% and 32%, indicating higher cost reduction rates in comparison to numerous mature and established technologies (cfr. Table 28).

Technology	**Learning Rate (%)**	**Observations**
General wind energy	3 – 17	High variability (240)
Onshore wind	-11.4 – 20	High variability (291)
Energy demand technologies	18 ± 9	Medium variability, differences across technology clusters (292)
Photovoltaic solar	15 – 25	Medium variability (293–296)
Residential photovoltaic solar	33	Particularly high reduction rate (293)
Photovoltaic panels costs	14.2	Average module costs (240)
Photovoltaic panels (production)	20 – 32	Medium variability (239,240)
Renewable energy technologies	14 – 34	High variability (297)
Deep retrofit unit construction costs	5 – 12	High variability (241)

Table 28: Learning rates reported in the literature for different technologies

Micelli et al. (241) initially proposed a cost reduction curve through experimental calculation. The authors developed an experimental **learning curve** relating to construction costs per housing unit undergoing **deep retrofitting** with industrialised technologies.

The curve is based on a limited amount of historical and forecast data provided by the Observatoire Coûts, Qualité et Impact des rénovations EnergieSprong of Energiesprong France (39). The report remains the only official document providing data on the actual costs of deep retrofits employing off-site industrialised construction, as well as estimates of cost reductions based on production scale and accumulated experience.

The curve displays a logarithmic profile, which is consistent with the learning curves formalised by Wright (1936). The initial average construction cost of €1,700/m² for the first ten units is reduced to approximately €1,400/m² for 100 units and €1,024/m² for 1,280 units, thereby demonstrating a systematic decline in unit costs. For higher production volumes, up to over 40,000 retrofitted units, the cost stabilises at around €549/m², with lower values estimated for further volume increases.

The curve demonstrates a variable learning rate, which is contingent on the scale of production. In the initial production doublings (from 5 to 10, 10 to 20, up to 80 → 160 units), the reduction in unit costs is between approximately 5% and 7%, while in subsequent doublings the marginal reduction increases progressively to approximately 14–15% in the final intervals (cfr. Figure 29).

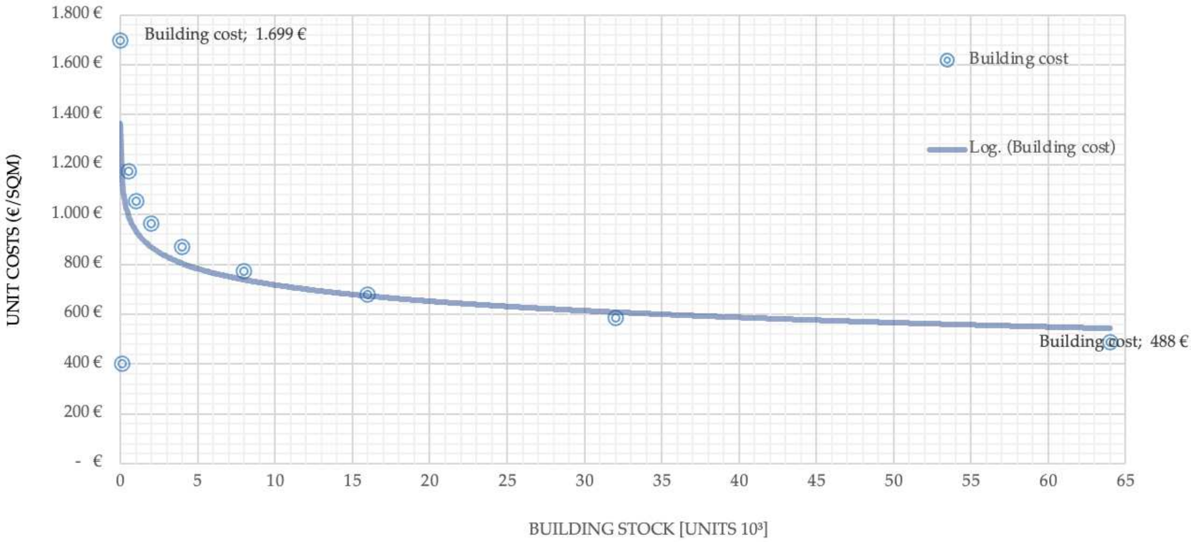


Figure 29: Trend of hard costs as a function of the cumulative number of units undergoing deep retrofit using off-site industrialised construction

To summarise, an analysis of the literature indicates that learning curves have a robust theoretical foundation and have been formalised through various mathematical formulations. Among these, the logarithmic formulation is the most established. As demonstrated in extant research, particular learning rates have been identified for discrete production sectors, thereby validating the efficacy of curves in predicting the progression of costs and performance.

The paucity of empirical studies on off-site industrialised construction defines the objective of this research, which aims to investigate, for the first time, the existence of learning dynamics and construction cost reductions in this specific context, thus helping to fill a significant gap in the literature.

4.3. Methodology and data

4.3.1. Reasons for selecting the French sample

The analysis focuses on deep retrofit interventions carried out with industrialised constructions in **social housing** buildings in France.

The projects were developed with the **most ambitious offsite programme**, Energiesprong, for which France is the second largest market in the world in terms of volume of interventions, with approximately 350,000 m² of redeveloped surface area (31). The utilisation of the French case enables the continuation and comparison with the preceding empirical analysis conducted by Micelli et al. (241), which was based on data from the Energiesprong France Report. This ensures methodological continuity and consistency for the development of this study.

In addition to this continuity, the French context exhibits characteristics that justify its selection for comparison. Firstly, the technical documentation relating to Energiesprong projects is extensive and accessible through public sources, allowing for the accurate reconstruction of production processes, technological solutions and intervention costs. Secondly, certain structural indicators demonstrate a significant degree of comparability between France and Italy (298):

- **Age of the building stock:** more than 55% of residential buildings in both countries were constructed before 1970, predominantly in masonry or reinforced concrete;
- **Share of social housing:** France has a larger social-housing sector (around 17% of the stock), compared with Italy (approximately 4%); this difference helps contextualise the role of public policy in supporting standardised large-scale retrofits;
- **Average construction costs:** according to Eurostat and national cost manuals, the average cost of residential interventions is broadly comparable, with France slightly

above Italy. Traditional on-site renovations in Italy average around **€1,200/m²**, close to the Energiesprong France benchmark of **€1,150/m²** (including both on-site and off-site components);

- **Level of industrialisation:** both countries are undergoing a transition towards more standardised construction processes. While France exhibits a more advanced level of industrialisation, Italy is progressively integrating off-site technologies, making the comparison methodologically relevant.

Taken together, these elements make the French case a suitable reference for analysing the potential of industrialisation to reduce unit costs in deep retrofit projects and for assessing the replicability of the model in European contexts characterised by a similar building stock.

The empirical investigation aimed at estimating the learning curve was conducted through two sequential phases:

- The selection of the interventions that were carried out.
- The identification of unit construction costs and units constructed is imperative for the purpose of conducting a comprehensive analysis of the relationship between cumulative production and the reduction in construction costs.

4.3.2. Selection of deep retrofit projects

The present study examines all projects completed by **EnergieSprong France from 2018 to date**, using the database published by Pellegrino et al. (202) and the publication by Gauzin-Müller et al. (200) as its main sources. The reliability of these sources is reinforced by systematic integration with data from peer-reviewed scientific literature and grey literature.

The integration of the various documentary sources enables the reconstruction of the entire set of **32 projects** completed or under construction in the period 2018–2025. The interventions encompass a variety of building types, including terraced single-family homes (maison individuelle), apartments in collective buildings (logement collectif), university residences (bâtiment étudiant) and school buildings (cfr. Figure 30).

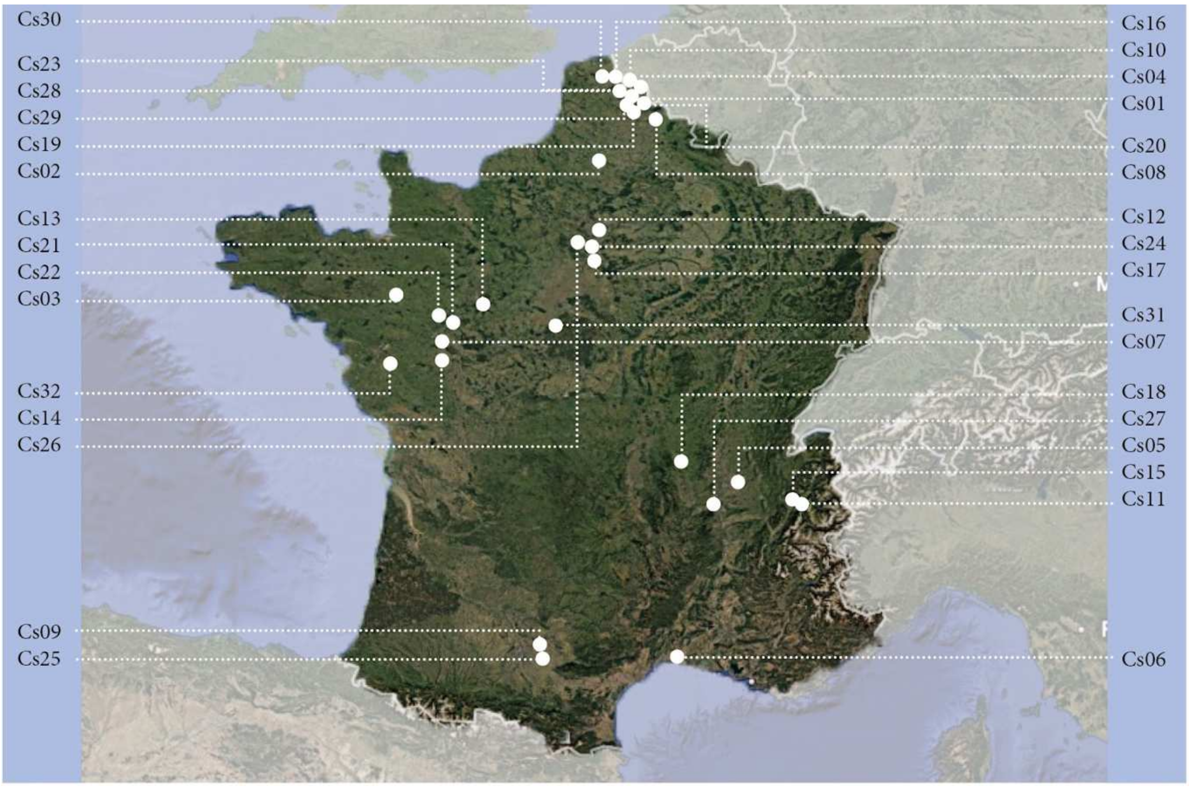


Figure 30: Location of the 32 deep retrofit projects in France (2018–2025)

The data is systematised by creating a **structured dataset** in Excel, organised into five main areas: project identification, building characteristics, economic and financial aspects, energy efficiency and performance, and social and housing aspects.

A comprehensive account of the Energiesprong programme in France, encompassing its areas of application, the types of buildings involved, and the operators involved, can be found in Annex 7.1. Summary sheets relating to the 32 projects, accompanied by iconographic representations, are presented in Appendix 8.2.

The 32 projects surveyed **exclude** those without complete data on construction costs, a crucial variable for reliably estimating the learning curve, as well as projects still in progress, without a final economic balance sheet. Projects involving exceptional costs related to energy infrastructure, resulting indoubling of construction costs, were also excluded, as were projects involving school buildings or other non-residential types. The rationale for excluding these projects was that they were considered marginal to the objective of the analysis and not comparable with the curve constructed for the housing sector.

To summarise, 19 projects meet the eligibility criteria. These projects fall into two categories: **single-family homes** and **apartments** in multi-storey buildings. The Energiesprong model is most applicable to these two categories of French public housing (38,202).

For each of these projects, a dataset comprising eight variables is constructed (cfr. Table 29).

ID	Municipality	Year of intervention	Type of intervention	Gross floor area (m²)	N° of retrofitted units	Change in energy class	Total cost (€)
ID1	Hem	2018	House	840	10	F – A	1,576,550
ID2	Longueau	2018	House	984	12	F – A	2,325,071
ID3	Ossé-Châteaugiro	2019	House	244	4	E – A	618,909
ID4	Wattrelos	2022	House	14,654	160	F – A	18,534,490
ID7	Angers	2022	House	2,860	32	D – A	3,861,352
ID9	Toulouse	2023	Apartment	6,000	254	E – A	2,037,936
ID10	Montmélian	2023	Apartment	6,197	99	D – A	5,704,336
ID12	Le Mans	2024	Apartment	15,520	251	E – B	11,606,849
ID13	Maine-et-Loire et Sarthe	2024	House	24,510*	296	nd – A	20,760,567
ID14	Chambéry	2024	Apartment	25,200	244	E – A	31,635,149
ID15	Hallouin	2024	Apartment	4,796*	70	F – A	31,931,729
ID16	Brétigny-sur-Orge	2024	House	1,530	18	-	5,931,590
ID17	Saint-Haon-le-Chatel et Villerest	2024	Apartment	1,250	12	F – A	1,680,617
ID20	Pays de la Loire	2025	House	36,931*	446	nd – A	40,000,000
ID21	Hem, Roubaix et Croix	2025	House	16,150	207	E – B	28,800,000
ID29	Bretonnières	2025	Apartment	4,933*	72	-	8,303,400
ID30	Nantes	2025	Apartment	6,029*	88	-	8,303,400
ID31	Pluvigner	2025	House	3,643*	44	-	6,366,000
ID32	Saint-Herblain	2024	Apartment	3,310	46	C – B	5,000,000

Values with (*) have been reconstructed

Table 29: Overview of location, building type, floor area, number of units, total investment, and unit construction costs for the 19 selected interventions

4.3.3. Determination of construction costs and units for learning curve modelling

The unit cost of each intervention was determined using a method divided into sequential phases. Firstly, the total cost documented by primary sources was broken down into two components: **hard costs**, corresponding to construction hard costs, and **soft costs**, including professional fees, company margins, overheads and contingency costs.

In most cases, the sources merely reported the total cost incurred by the **Maître d'Oeuvre (MOE)**, without distinguishing between the two components. To address this lacuna, the share attributable to soft costs was estimated through a comparison based on disaggregated data available for some projects, technical reports provided by the MOEs and information collected through questionnaires administered to operators in the sector. The method yielded an average soft cost share of 13% for single-family homes and 10% for apartments.

Once the hard cost component had been isolated, the hard costs were normalised by eliminating the 9% tax incidence applicable in France, thus obtaining an indicator representative of hard construction costs alone.

Subsequently, the entire dataset was discounted to the base year 2025 using the French Index of Total Construction Costs (ICC), as published by INSEE (216).

The reconstruction of the unit cost necessitated the determination of the total usable floor space for each project. In certain instances, this data was not available, as only the number of housing units was reported. The estimation of the missing floor space was achieved through the utilisation of statistical interpolation, utilising the weighted average floor space of analogous projects within the sample as a reference point. The procedure yielded an average surface area per housing unit of 84 m^2 for single-family homes, with a range between 61 and 92 m^2, and 77 m^2 for apartments, with a range between 62 and 103 m^2.

From a **technological standpoint**, the examined sample evinces a high degree of performance homogeneity. The objective of all the interventions was to achieve the EnergieSprong standard, which requires a transition from energy class E or F to class A on the EPC scale. This is to be accomplished by means of complete thermal insulation of the building envelope, the installation of photovoltaic systems sized to ensure energy self-sufficiency, and the provision of a contractual "E=0" performance guarantee.

The learning curve was plotted based on two key factors: the reconstructed unit construction costs for each project and the cumulative number of units built.

The methodology comprised the construction of three distinct curves: two curves broken down by building type, respectively for single-family homes and apartments, and an aggregate curve representative of the entire sample.

In order to facilitate the comparison of the various types, the financial implications about maisons individuelles were standardised by implementing an additional surcharge, as stipulated in the technical price lists for designated building types (299).

The **quantitative phase** constitutes the core of the research. The study's primary focus is on the analysis of data and the development of an empirical curve, the purpose of which is to demonstrate the reduction in construction costs in industrialised deep retrofitting projects. This is undertaken to verify the existence of learning dynamics in the off-site industrialised construction sector.

Concurrently, a **qualitative phase** was initiated with an integrative and supportive function, aimed at enriching and contextualising the interpretation of the quantitative results. However, this qualitative phase did not represent the central focus of the research. To this end, a **questionnaire** was prepared and administered to the main technical and managerial actors involved in the projects, with particular attention to the Maîtres d'Œuvre (MOE).

The questionnaire, consisting of 35 questions divided into seven thematic sections, collects information on the type and characteristics of the interventions, organisational roles and coordination methods, cost structure and sources of financing, energy performance, social impacts and perceived drivers of construction cost reduction (see Appendix 8.3).

The response rate is 14.8%, which may appear low; however, the methodological relevance of the survey is guaranteed by the fact that the respondents represent over 60% of the total volume of interventions surveyed, thus ensuring a high statistical representativeness of the sample. While not the primary focus of the research, the qualitative responses collected have the potential to enhance the discussion phase by identifying the main drivers that have supported the learning curve and that could favour further reduction in the future.

4.4. Data Analysis

4.4.1. Descriptive statistics of deep retrofit projects

The geographical distribution of the sample reflects the geographical spread of the Energiesprong model across France, with a concentration in the **northern and western regions** of the country. A significant proportion, amounting to 26%, is concentrated in Pays de la Loire, followed by Hauts-de-France with 21%. A substantial share of 16% is allocated to Auvergne-Rhône-Alpes, with Brittany accounting for an additional 16%. A modest 11% is designated for Occitanie, while the remaining 5% is distributed between Loire and Maine-et-Loire/Sarthe.The climatic conditions of the regions under consideration, characterised by severe winters and substantial heat consumption, serve to accentuate the merits of deep retrofitting, which results in considerable reductions in energy consumption and a substantial enhancement in living comfort.

In all cases, the deep retrofit process involved an efficient combination of technological solutions and interventions on the building envelope. From a plant engineering perspective, **photovoltaic systems** with an average production of approximately 6,000 kWh per year per unit, high-efficiency heat pumps for heating and domestic hot water and controlled mechanical ventilation systems with heat recovery were installed. About the external building envelope, the following interventions were made: the application of passive-standard insulation cladding, the replacement of windows and doors with triple-glazed units, the improvement of airtightness and the elimination of thermal bridges.

From an **energy perspective**, 70% of the buildings in the sample demonstrated a three-class jump, transitioning from class E or F to class A or B on the EPC scale. Furthermore, a significant proportion of the sample, specifically 25%, demonstrated an improvement in classification from class D to A or B. In contrast, only a minor percentage of the properties, amounting to 5%, exhibited an increase in classification from class C to A or B.

Quantitatively, the mean reduction in energy consumption per housing unit is approximately 70%. The energy requirements before renovation, ranging from 9 to 25 MWh per year per unit, are systematically reduced to values between 4.9 and 6.8 MWh.

In addition to enhancing energy performance, the deep retrofit projects have resulted in comprehensive redevelopment of the buildings. At an **architectural level**, the façades have undergone a process of restyling, and the courtyards and outdoor spaces have been renovated. Within the confines of the buildings, a programme of refurbishment and renovation was initiated. This encompassed the electrical and ventilation systems, with kitchens and bathrooms being refurbished, appliances being replaced with energy-efficient models, and volumetric extensions being added where permitted by urban planning regulations.

It is noteworthy that all interventions are accompanied by long-term energy performance guarantees, typically spanning a period of between 25 and 30 years.

The sample analysed includes **19 deep retrofit interventions**. Of these, 10 concern single-family homes, for a total of 1,229 retrofitted units, while 9 concern apartments, for a total of 1,136 units. The interventions considered in this study encompass a **total area of 174,066 m²**, encompassing **2,365 units**.

A thorough examination of the aggregate investment expenses reveals that the undertakings entailed a total dedication amounting to approximately **€235 million**. The distribution of investments between the two categories of buildings is approximately equal: €129 million was allocated to single-family homes, while €106 million was allocated to apartments.

The weighted average unit cost, discounted to 2025, is also similar between the two segments, ranging from €1,071/m² for single-family homes to €1,171/m² for apartments (cfr. Table 30).

ID	Type of intervention	Numbe of retrofit residential units	Total gross floor area (m²)	Total cost (€)	Weighted average building cost updated to 2025 (€/m²)
10	Single-family homes	1229	100,831	128,774,529	**1017**
9	Apartment	1136	73,235	106,203,417	**1171**
19	**Total**	**2365**	**174,066**	**234,977,946**	**1091**

Table 30: Summary of deep retrofit interventions

In terms of size, single-family homes have a weighted average surface area of 84m² per unit, ranging from 61 to 92m², while apartments are slightly smaller, with an average size of 77m² and values ranging from 62 to 103m².

A thorough analysis of the scale of the interventions reveals a heterogeneity in size. For single-family homes, the number of units involved in each project varies from a minimum of 4 to a maximum of 446. The distribution is asymmetrical, with a median of 32 units and first and third quartile values of 12 and 160 units, respectively.

The variability in size is significant for apartments, ranging from 12 to 254. The median value is 88 units, with the first and third quartiles at 46 and 244 units, respectively. The distribution indicates that most interventions pertain to complexes comprising up to 100 apartments, while larger operations frequently involve more than 200 units distributed across multiple buildings (cfr. Tables 31 and 32).

Single-family homes

ID	**Municipality**	**Number of Units**	**Total Cost (€)**	**Construction Costs Updated to 2025 (€/m²)**
ID1	Hem	10	1,576,550	1,667*
ID2	Longueau	12	2,325,071	1,888*
ID3	Ossé-Châteaugiron	4	618,909	2,027*
ID4	Wattrelos	160	18,534,490	1,011*
ID7	Angers	32	3,861,352	1,199*
ID13	Maine-et-Loire et Sarthe	296	20,760,567	1,005*
ID16	Brétigny-sur-Orge	18	5,931,590	878*
ID20	Pays de la Loire	446	40,000,000	843*
ID21	Hem, Roubaix et Croix	207	28,800,000	1,425*
ID31	Pluvigner	44	6,366,000	435*
Total		**1,229**	**128,774,529**	**1,017.9 (weighted average)**

Values with (*) have been reconstructed

Table 31: Total and unit construction costs for single-family

Apartments				
ID	**Municipality**	**Number of Units**	**Total Cost (€)**	**Construction Costs Updated to 2025 (€/m²)**
ID9	Toulouse	254	2,037,936	1,345*
ID10	Montmélian	99	5,704,336	1,534*
ID12	Le Mans	251	11,606,849	1,095*
ID14	Chambéry	244	31,635,149	1,038*
ID15	Hallouin	70	31,931,729	977*
ID17	Saint-Haon-le-Chatel et Villerest	12	1,680,617	712*
ID29	Bretonnieres	72	8,303,400	1,298*
ID30	Nantes	88	8,303,400	834*
ID32	Saint-Herblain	46	5,000,000	1,411*
Total		**1,136**	**106,203,417**	**1,171.2 (weighted average)**

Values with (*) have been reconstructed

Table 32: Total and unit construction costs for the apartment

A thorough analysis of **unit construction costs** per square metre, discounted to the year 2025, reveals discernible economic distinctions between the two categories of buildings. Single-family homes demonstrate high variability, with values ranging from 435 to 2,027 euro/m², representing an average of approximately 1,212 euro/m², a weighted average of 1,018 euro/m² and a median of 1,082 euro/m², accompanied by a standard deviation of 490 euro/m².

The data reveal that approximately 50% of the cases fall within the range of €800-1,200/m², while there are still situations with extremely low or high unit costs, indicating the strong heterogeneity of this segment (cfr. Figure 31).

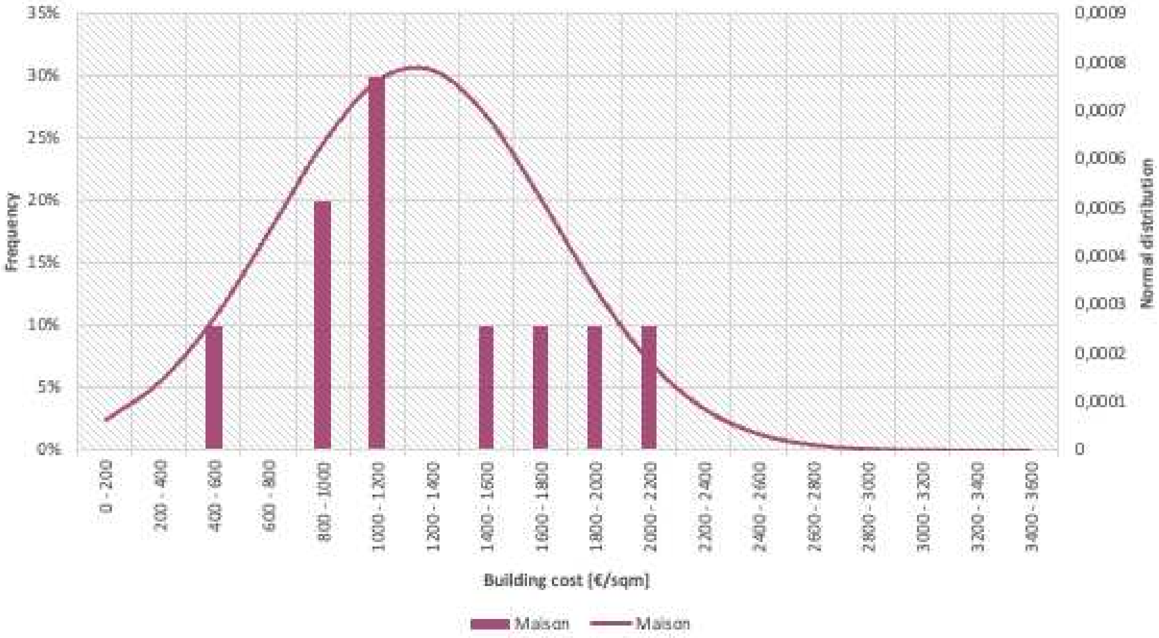


Figure 31: Distribution of building costs for single-family homes

In the context of apartments, unit costs are characterised by greater compactness and symmetry, with a range of €712 to €1,534/m². The mean and median values are found to be substantially aligned at €1,156 and €1,101/m², respectively. This results in weighted average cost of €1,171/m² and a standard deviation of €267/m².

Most cases are observed to fall within the range of €800 to €1,200/m², with no occurrence of exceptional values, thereby indicating a higher degree of cost uniformity within the multi-storey buildings segment (cfr. Figure 32).

The observed differences are indicative of disparate economic dynamics. In single-family homes, the discrepancy between the mean and the median underscores diminished production efficiency and the challenge of standardising interventions on heterogeneous and diminutive-scale edifices.

In residential properties, the convergence of indicators suggests a more stable and predictable distribution of costs, a phenomenon favoured by economies of learning and the standardisation of construction processes. This observation confirms the maturity of the application model and the optimisation of operating procedures.

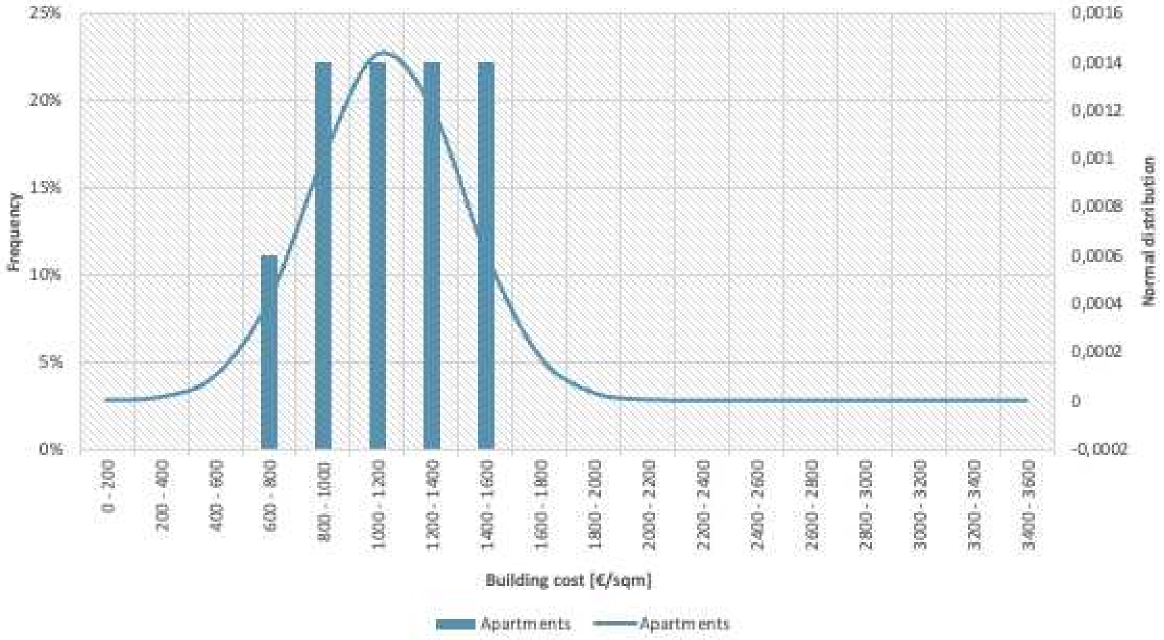


Figure 32: Distribution of building costs for apartments

A thorough analysis of the **construction period** reveals that the interventions are predominantly focused on buildings constructed during the period of expansion of social housing, which was characterised by low energy standards. The sample comprises of approximately 40% buildings constructed in the 1950s and 1960s, with a further 35% dating back to the 1970s and 1980s; only a small proportion are more recent buildings constructed since the 2000s.

The interventions were executed **between 2018 and 2025**, albeit with disparate implementation timelines. A total of 72% of the sample was completed within the three years 2023-2025, thereby confirming a significant acceleration in the dissemination of the Energiesprong model. This recent increase in concentration is indicative of two key developments. Firstly, there has been a gradual consolidation of the technical and organisational skills necessary to operate on a larger scale. Secondly, there has been an increase in financial resources allocated to support these operations.

The composition of the implementing entities demonstrates the predominance of social housing operators, which are responsible for 65-70% of the interventions. The following entities have been identified as being particularly involved: OPAC, MASH, 3F and Habitat 44. The residual 30-35% is attributable to specialised private operators, including Vilogia, Néotoa, Podéliha and Cristal Habitat.

4.4.2. Responses of MOEs to the questionnaire

The empirical **survey conducted on MOEs** aimed to examine in depth the technical and economic characteristics of deep retrofit interventions carried out using off-site construction technologies, with particular attention to the cost structure, their distribution over time and the factors that influence their reduction, both observed and potential.

The responses from the MOEs corroborate the descriptive analysis that emerged from the desk analysis of the projects, demonstrating that the most prevalent types of deep retrofit interventions pertain to single-family homes and apartments in multi-storey buildings, predominantly intended for social housing, aligning with French public policy priorities on energy efficiency and institutional demand.

The scale of the interventions is bimodal, ranging from small-scale pilot projects (4–10 units) to large-scale redevelopment programmes (over 400 units), with surface areas ranging from a few hundred to several tens of thousands of square metres.

Furthermore, the responses furnish us with the ability to delineate the **duration of interventions** facilitated by off-site technologies.

- **Design phase**: The period between 6–25 months is characterised by the influence of bureaucratic and administrative complexity, as well as the coordination of multiple stakeholders that is characteristic of the public sector;
- **Construction phase**: Assembly times for housing units are typically between 12 and 18 months, with an average duration of 2–3 weeks. However, the systematic utilisation of prefabricated components has the potential to reduce this timeframe to a few days.

Delays of between one and eight months were observed, primarily due to authorisation issues, design revisions during construction and external shocks, such as the emergence of the novel Coronavirus (SARS-CoV-2) pandemic.

The responses demonstrate that the degree of **industrialisation** of the interventions is situated along a continuum, ranging from partial solutions that are confined to specific building components, to comprehensive approaches that encompass systematic prefabrication of the building envelope and roof. According to the MOEs, this variability is indicative of a process of technological and organisational maturation, with a gradual transition towards more industrialised production models.

The **unit construction costs** of the projects reported by the MOEs that responded to the questionnaire range from €70,000 to €90,000 per housing unit, with variations mainly related to the scale of production and the level of industrialisation adopted.

The respondents were invited to indicate the **composition of hard costs** in their projects, highlighting the main technical components that contribute to the overall cost (cfr. Table 33).

Technical Component	Percentage Share	Observed Variability
Prefabricated insulated façades	30–40%	±5%
Building services (HVAC, DHW)	40–45%	±3%
Roofs with photovoltaic systems	10–15%	±4%
Structural adaptations and site works	5–15%	±7%

Table 33: Composition of hard costs in projects reported by MOEs

Soft costs are estimated to account for 10-15% of the total, exerting a more significant influence on design and construction management. This is attributable to the multidisciplinary complexity of the interventions and the necessity for advanced competencies in the oversight of innovative industrialised processes.

The open-ended responses to the questionnaire demonstrate that all operators with recent or mature projects recognise a trend towards cost reduction, which can be attributed to four factors. The initial issue pertains to the **accumulation of human capital and organisational skills**: approximately 40% of respondents indicate that pilot batches necessitate operational calibration phases, with average delays of approximately two months for six-unit projects. These delays can subsequently be optimised and scaled up to production cycles of 400 units.

The second factor pertains to the **standardisation of processes and components**, a practice indicated by 21% of operators, which has been demonstrated to reduce assembly times. The third factor pertains to the **serialisation** of interventions, reported by 18% of participants, which facilitates enhanced operating speeds per unit, while small-scale projects continue to demonstrate elevated unit costs. Finally, the fourth factor pertains to logistics optimisation and the implementation of **lean management** principles, a practice reported by 21% of respondents. This approach is designed to reduce inefficiencies and downtime, thereby enhancing the efficiency of production flows and the supply chain.

The responses indicate that **further cost reductions** could result from stabilising the project pipeline, consolidating production volumes, and strengthening coordination between public and private entities.

In this context, "tailor-made" industrialisation, perceived as effective by operators, which combines process standardisation with adaptation to local specificities, represents a promising strategy, especially for technologically advanced components such as energy modules and high-performance prefabricated facades.

The prospective analysis indicates that there are margins for optimisation concentrated on components with greater potential for standardisation, namely: prefabricated facades, through industrialisation and supply chain optimisation; photovoltaic modules, through price reduction and integration with prefabricated roofing; and HVAC and DHW systems, thanks to kit standardisation and modularisation.

4.5. Models

4.5.1. The empirical learning curve of off-site industrialised construction Costs

The analysis of learning economies was conducted with construction costs discounted to 2025 and the chronological order of implementation of the interventions taken into account, with the aim of verifying the relationship between the reduction in unit costs and the accumulation of production, in line with the theoretical principles of industrial learning processes.

The learning curves were developed separately for the **two types of intervention** — single-family homes and apartments —to highlight the specificities in the cost reduction mechanisms between the two segments. The learning curves were then **aggregated** so as to allow the comparison of empirical results with the theoretical evidence found in the literature.

As illustrated in Table 34, the weighted unit construction cost is shown as a function of cumulative production.

	Single-family homes	Apartment	Aggregated
Cumulative units	**Unit construction cost (€/m²)**	**Unit construction cost (€/m²)**	**Unit construction cost (€/m²)**
5	1888	1534	1832
10	1888	1534	1832
20	1711	1534	1703
40	1411	1534	1420
80	1096	1534	1213
160	1011	1389	1181
320	851	1345	1027
640	1081	1166	1262
1280	985	1024	1058
2560	-	-	997

Table 34: Unit construction costs by building type as a function of cumulative production

The analysis of single-family homes demonstrates a **substantial decrease in unit costs**, particularly evident in the initial stages of the production process. The unit cost initially amounts to €1,888/m², as documented for the initial five units, and subsequently reduces to a minimum of €851/m² upon reaching 320 units.

However, it should be noted that this trend is not linear; at the threshold of 640 units, there is a 27% increase, from €851/m² to €1,081/m². This increase can be attributed to several factors, including the execution of extraordinary works on buildings with more complex characteristics, the increase in the prices of construction materials during the construction period, as well as possible organisational inefficiencies related to the management of larger and more complex construction sites.

Notwithstanding this discontinuity, the cumulative reduction at the conclusion of the sample is **approximately 48%,** thereby confirming a significant learning effect, albeit characterised by diminishing returns in the more advanced stages of production.

A comparison of the dynamics exhibited by the **apartment** segment with those of single-family homes reveals marked differences. The apartment's initial costs, which amount to

€1,534/m^2, remain largely constant across the first five cumulative production thresholds (5, 10, 20, 40 and 80 units). This apparent stability can be attributed to the fact that the initial project, which was conducted in Montmélian, encompassed 99 units, thereby effectively impeding the progression of learning rates until approximately 80 units were attained.

As the number of units under consideration exceeds 160, the cost curve demonstrates a more regular downward trend, reaching a minimum of €1,024 /m^2 at the 1,280-unit threshold, with an overall reduction of 27%.

The **aggregate curve** occupies a median position between the two building types. The initial unit cost, which is €1,832 /m^2, shows a progressive reduction until it reaches €1,027/m^2 at the threshold of 320 units. However, in this case too, there is an anomalous increase of 22.9% at the threshold of 640 units, attributable to the inclusion of projects such as Montmélian and Bretonniers, characterised by unexpected costs linked to particularly costly plant efficiency measures. These projects have temporarily elevated the mean value, thus disrupting the standard trend of the learning curve.

After this, the curve stabilises at approximately **€997/m^2 for 2,560 units**, indicating an overall **reduction of 45.6%** in comparison to the initial value. The observed trend is consistent with the dynamics predicted by learning curves, indicating a progressive decrease in unit costs as production experience increases.

To estimate the **learning effects,** three functional forms that have been widely adopted in the literature to model the relationship between unit cost and production volume were compared: the Power Law Model, the Learning Curve Model and the Logarithmic Cost Function.

The comparative analysis demonstrated that the **logarithmic function** is the most appropriate for this case. This specification, which is employed extensively in the empirical literature on both conventional and renewable energy systems, facilitates the estimation of technological learning rates in relation to the deep retrofit interventions carried out (241,286–288).

The function delineates an empirical relationship between unit cost (y) and cumulative volume of retrofitted dwellings (x). According to this relationship, an increase in production scale leads to a reduction in unit costs at a rate that decreases progressively until it reaches a limit value.

The graphs depicting the learning curves for the three types under consideration are presented in Figures 33, 34 and 35.

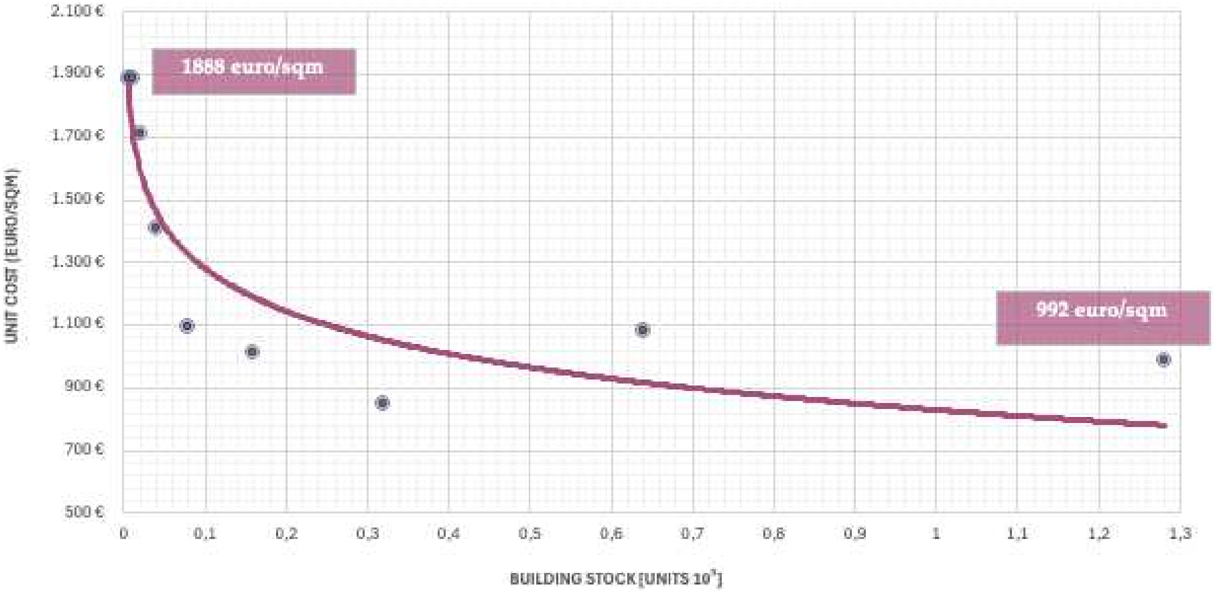


Figure 33: Unit construction costs for single-family homes by number of retrofitted units, with overlaid logarithmic regression curve

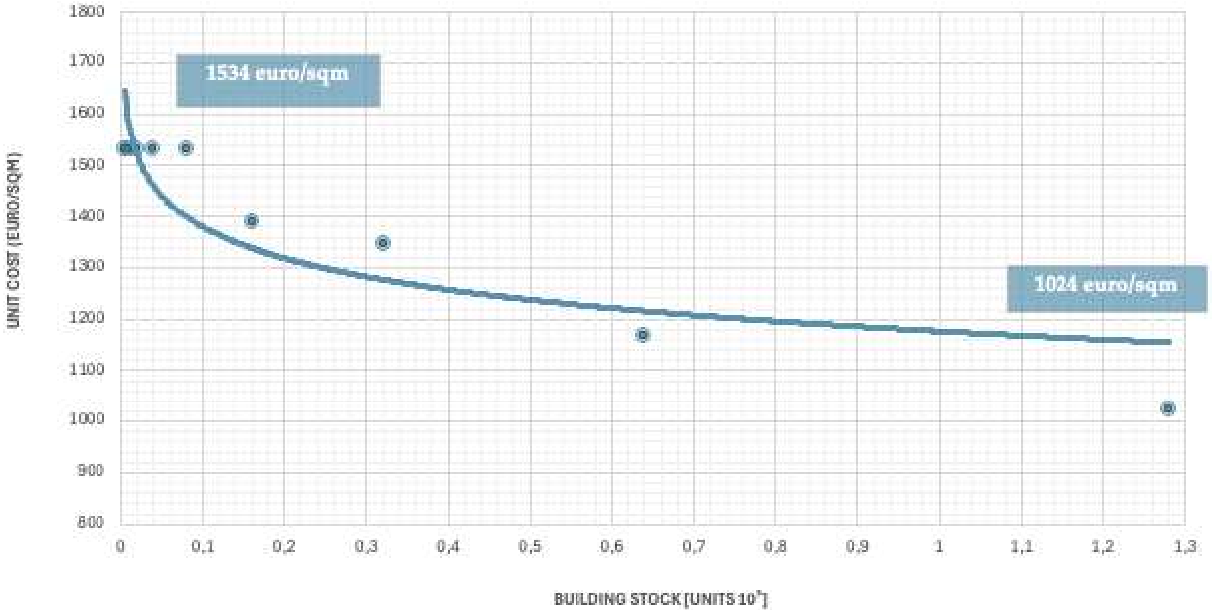


Figure 34: Unit construction costs for apartment by number of retrofitted units, with overlaid logarithmic regression curve

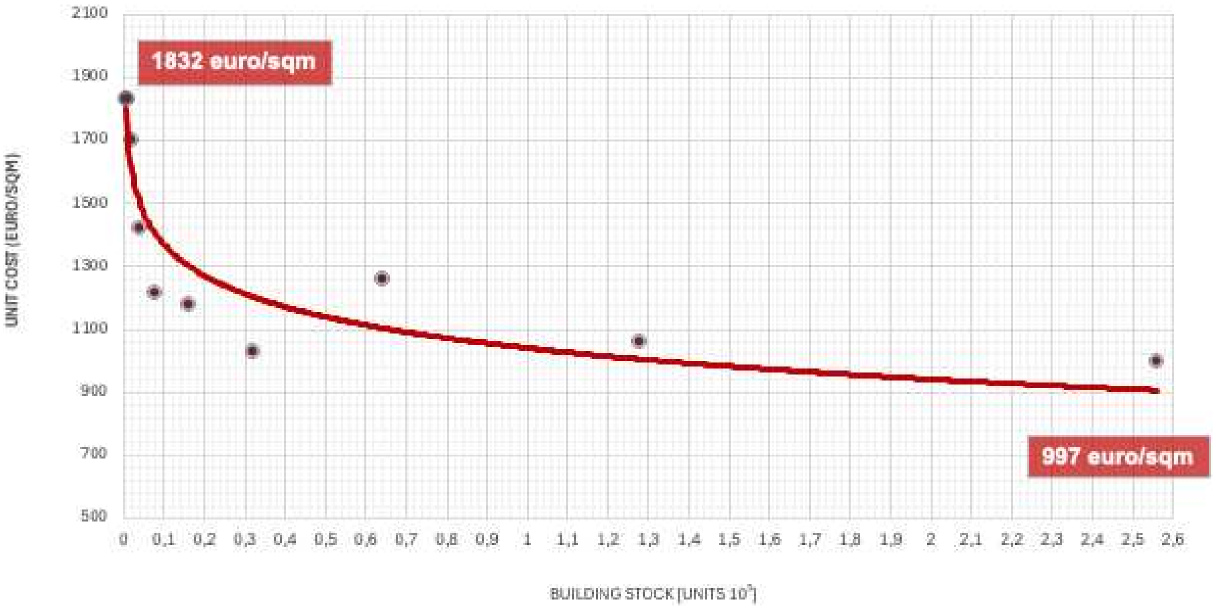


Figure 35: Unit construction costs for aggregated houses by number of retrofitted units, with overlaid logarithmic regression curve

The disparities in unit costs underscore the heterogeneity in learning dynamics across different building types. Single-family homes demonstrate a more rapid reduction in the early stages, presumably due to the enhanced potential for learning economies and greater design variability in this segment. This variability enables the introduction of technical and organisational innovations over a shorter timeframe.

Conversely, apartments exhibit a more linear and regular cost trajectory, consistent with standardised construction processes and a higher average number of units per building. This tendency is conducive to stable learning economies but more gradual cost reductions.

In both cases, a significant reduction in costs is evident in the initial stages of production, with a subsequent stabilisation as production progresses. This observation aligns with the theoretical principle of learning with diminishing returns, suggesting that as production volumes increase, the cost-reduction advantages become more pronounced.

The empirical validation of the logarithmic models adopted was conducted through the analysis of three main statistical indicators (cfr. Table 35).

Typology	n	R^2	R^2 adj	F	t coeff. ln(x)	p-value (ln(x))
Single-family homes	9	0.826	0.801	33.2	-5.76	< 0.001
Apartment	9	0.775	0.743	24.1	-4.91	< 0.001
Aggregated	10	0.841	0.821	42.2	-6.50	0.00019

Table 35: Statistical analysis of learning coefficients (β) and learning rates by building type

The first of these aspects pertains to the **coefficients of determination R^2 and adjusted R^2,** which are utilised to ascertain the proportion of variability in unit costs that is explained by the regression. The values obtained for single-family homes are R^2=0.826 and R^2adj=0.801; for apartments, R^2=0.775 and R^2adj=0.743; and for the aggregate dataset, R^2=0.841 and R^2adj=0.821.

The elevated nature of these values serves to **substantiate the hypothesis** that the logarithmic function reliably captures empirical variability, thereby negating the influence of the relatively modest number of observations. This assertion is further substantiated by the uniformity observed in the adjusted values.

The second indicator is the **F-statistic**, which measures the overall significance of the regression. The estimated values, which equalled 33.2 for single-family homes, 24.1 for apartments, and 42.2 for the aggregate dataset, respectively, far exceeded the critical thresholds commonly adopted in the literature. This **attested to the statistical validity** of the models and confirmed that the estimated logarithmic relationships **significantly explained** the dynamics of unit costs.

The third evaluation criterion is based on the **t-test of logarithmic coefficients**, which allows us to verify whether the effect of production accumulation on costs is statistically different from zero. The values obtained, equivalent to -5.76 for single-family homes, -4.91 for apartments, and -6.50 for the aggregate dataset, are all deemed to be highly significant ($p < 0.01$). This outcome provides substantial confirmation of the existence of a learning effect, which is statistically significant in all building types considered.

A comprehensive review of the literature reveals that the logarithmic function is an adequate and statistically robust specification for describing the evolution of unit costs in off-site industrialised construction. The high significance of the coefficients and the consistency of the R^2 and F-statistic values confirm the **robustness of the model**, while the consistency of the results between segments and the aggregate dataset reinforces the overall validity of the conclusions.

4.5.2. The learning rate of off-site industrialised construction costs

To estimate the learning effects in deep retrofit processes, the **learning rate (LR)** was calculated using empirical data from the sample. In accordance with the seminal work of Wright (1936), the learning rate is defined as the percentage change in unit costs following a doubling of cumulative production, under the assumption of a continuous relationship between cost and total output.

As illustrated in Table 36, the unit construction costs and marginal reductions (learning rate) for each doubling of production are shown, as are the cumulative reductions, with the data divided into single-family homes, apartments and aggregate values.

The analysis demonstrates that single-family homes exhibit a high learning rate in the initial stages of production, with a marginal reduction of 9.4% observed when transitioning from 10 to 20 units. Subsequent increases in production, up to 80 units, result in further decreases ranging from 17% to 22%. This initial rapid learning process is indicative of the potential for experimentation with more flexible and diversified construction and organisational procedures. For units above 160, the reductions continue, albeit with decreasing intensity (–7.8% between 80 and 160 units and –15.8% between 160 and 320).

The minimum reduction is €851/m², representing a cumulative reduction of 54.9% compared to the initial value of €1,888/m². However, between 320 and 640 units, there is a 27% increase in costs (from €851 to €1,081/m²), which temporarily interrupts the downward trajectory and reduces the average learning rate to around 9.5%. The unit cost stabilises at 1,280 units, with an overall **cumulative reduction of 47.8%** being achieved. This is equivalent to €985/m². This trend indicates that, while maintaining high LR values, single-family homes are subject to significant fluctuations linked to contingent factors and design variability.

	Single-family homes			Apartment			Aggregated		
Cumulative units	**Unit Cost (€/sq m)**	**Marginal Reduction (%)**	**Cumulative Reduction (%)**	**Unit Cost (€/sq m)**	**Marginal Reduction (%)**	**Cumulative Reduction (%)**	**Unit Cost (€/sq m)**	**Marginal Reduction (%)**	**Cumulative Reduction (%)**
5	1888	-	-	1534	-	-	1832	-	-
10	1888	0%	-	1534	-	-	1832	-	-
20	1711	-9.4%	-9.4%	1534	-	-	1703	-7.0%	-7.0%
40	1411	-17.5%	-25.3%	1534	-	-	1420	-16.6%	-22.5%
80	1096	-22.3%	-41.9%	1534	-	-	1213	-14.6%	-33.8%
160	1011	-7.8%	-46.5%	1389	-9.5%	-7.7%	1181	-2.6%	-35.5%
320	851	-15.8%	-54.9%	1345	-3.2%	-10.0%	1027	-13.0%	-43.9%
640	1081	+27.0%	-42.7%	1166	-13.3%	-19.5%	1262	+22.9%	-31.1%
1280	985	-8.9%	-47.8%	1024	-12.2%	-27.0%	1058	-16.2%	-42.2%
2560	-	-	-	-	-	-	997	-5.8%	-45.6%

Table 36: Unit construction costs and marginal and cumulative reductions by cumulative production for single-family homes, apartments, and overall aggregate

In the case of apartments, the initial doubling does not result in any alterations, with costs remaining constant at €1,534/m² up to 80 units. It is only from 160 units onwards that the initial marginal reductions are observed (-9.5%), with subsequent decreases of between 3.2% and 13.3% in the following phases, reaching €1,024/m² at 1,280 units, equivalent to an **overall reduction of 27%**. The mean learning rate for apartments, estimated at approximately 4.6%, is thus lower than that for single-family residences. However, it is more consistent and uniform, which is consistent with the greater standardisation of processes and the high number of units per building.

The aggregate curve is indicative of intermediate dynamics: initially, it shows rapid reductions (–7.0% at 20 units and –16.6% at 40 units), followed by an overall decline to 43.9% at 320 units. Anomalies are also evident in the range between 320 and 640 units, with a 22.9% increase in costs, thereby temporarily reducing the cumulative reduction from 43.9% to 31.1%. The downward trajectory of the market has been confirmed with a final figure of 2,560 units, representing a 45.6% cumulative reduction in costs to €997/m². The mean LR of the aggregate curve is 6.9%, which indicates a moderate yet substantial overall learning effect.

In summary, the data confirm that in off-site industrialised construction processes, there is a clear **reduction in unit costs as production experience accumulates**, although the cumulative decrease varies across segments and production levels.

For **single-family houses**, at 1,280 cumulative units, the reduction reaches approximately **47.8%** of the initial cost, although it should be noted that these are more susceptible to fluctuations. For residential **apartments**, at the same level of 1,280 cumulative units, the reduction is more moderate and linear, at **27%.** The **aggregate curve**, which incorporates both segments and has been extended to 2,560 cumulative units, demonstrates an overall **cumulative cost reduction of 45.6%,** thereby substantiating the **existence of a substantial learning effect**.

4.6. Results and drivers of cost reduction in industrialised off-site deep retrofit

The analysis conducted fills the second gap in the literature and answers Research Question **RQ3a: Is it possible to empirically document a reduction in construction costs linked to learning-by-doing mechanisms in deep retrofit projects carried out with off-site construction solutions?**

In order to answer this question, the research analyses 19 deep retrofit projects carried out in the French social housing sector. This constitutes the first systematic contribution aimed at investigating learning curves in the field of off-site industrialised construction.

The quantitative analysis indicates a statistically **significant reduction in unit construction costs**, which is positively correlated with an increase in the cumulative volume of refurbished units. This phenomenon manifests in two distinct ways. Firstly, when considered at a disaggregated level, that is, on an individual building type basis. Secondly, in the context of aggregate data. These findings serve to confirm the theoretical hypothesis of the existence of learning economies within the industrialised retrofit sector.

Single-family homes have undergone the most substantial reduction, with a 47.8% decrease in costs, from €1,888/m² to €985/m². A more modest yet still significant reduction of 27% is demonstrated by the apartments. The aggregate curve demonstrates an average decrease of

45.6%, which is consistent with theoretical expectations for processes characterised by a strong component of industrial standardisation (cfr. Table 37).

	Learning rate	Average learning rate	Cumulative Reduction
Single-family home	7.8% – 22.3%	6.4%	47.8%
Apartment	3.2% – 13.3%	6.6%	27.0%
Aggragated	-2.6% – 16.6%	5.8%	45.6%

Table 37: Learning rates and cumulative reductions for single-family homes, apartments, and aggregated production

The heterogeneity in cost reduction rates between building types is indicative of the specificities of their respective production processes and their divergent potential for standardisation. The apartments exhibit increased design uniformity and higher unit volumes per building. They demonstrate linear and regular learning curves, with gradual yet consistent reductions over time.

Single-family homes demonstrate more volatile dynamics, marked by considerable initial reductions followed by temporary increases. This phenomenon can be attributed to higher design variability and standardisation challenges. This volatility is indicative of the influence of contingent factors, such as local architectural specificities, fluctuations in material prices and logistical complexities linked to the territorial dispersion of interventions.

The learning rates observed are consistent with those reported in the literature for mature industrial sectors: The mean percentage for single-family homes was 9.5%, for apartments 4.6%, and for the aggregate dataset 6.9%. These values fall within the typical range of standardised processes (289,290).

A comparison with other high-tech building components, such as the industrial production of residential **photovoltaic panels** — characterised by learning rates between 20% and 32% (3,28,290)— shows significantly higher values than those observed in off-site deep retrofitting. This outcome is consistent with the finding that the production of industrialised technological components, such as photovoltaic panels, advantages from greater economies of scale and highly standardised processes, generating faster cost reduction rates than many established technologies.

This comparison suggests that **construction costs in deep off-site retrofitting are indeed decreasing**, albeit at **slower learning rates than other highly innovative building technologies**, such as photovoltaic panels. It appears that, although there is significant room for optimisation, the industrialised retrofitting production process is at an intermediate stage of technological maturity, characterised by more gradual cost reductions.

A **comparison with the forecast curve by Micelli et al. (2025)** (241) demonstrates a similar logarithmic trend, albeit with some quantitative differences. The forecast assumed initial learning rates of between 5% and 7% in the first doublings, with marginal increases of up to 14–15% in subsequent phases. Empirical evidence indicates that single-family homes exhibit slightly higher values, while apartment values are lower. The learning rate of the aggregate curve demonstrates variability between 7% and 13% as production levels rise, ultimately converging towards an average value of 6.9%.

At the threshold of 1,280 units, the forecast curve estimated a unit cost of €1,024/m², while the aggregate empirical data reached €1,058/m², with a difference of €34/m² (approximately 3.3%), confirming that the observed behaviour is substantially consistent with theoretical estimates. The greater overall reduction in comparison to forecasts is probably attributable to the composition of the sample, characterised by a prevalence of flats, which have lower unit costs and more stable learning curves, thus influencing the aggregate average value.

The cost reductions that have been observed in empirical studies can be explained by several effects that have also been identified by the MOEs. Firstly, the progressive accumulation of specific skills in the design and construction phases has been demonstrated to allow companies and design studios to operate more efficiently, thereby reducing errors, processing times and production waste. The standardisation of processes, in conjunction with the replicability of procedures and the serialisation of components, fosters economies of scale, thereby rendering operations more predictable and stable. Concurrently, logistical optimisation, facilitated by the centralisation of demand, the rationalisation of packaging, and the planning of material flows, enables the containment of transport and management costs. Cumulative operational experience has also been demonstrated to contribute to more efficient resource management, with a consequent minimisation of downtime and inefficiencies on site. In conclusion, the reduction of waste and unused material, made possible by more controlled construction practices and industrialised processes, is a further factor in reducing unit costs.

The synergistic interaction of these elements helps explain the empirically observed reductions, confirming that the combination of accumulated expertise, standardised processes and logistical optimisation is the main driver of cost reductions in industrialised off-site deep retrofitting. Single-family homes, while demonstrating greater variability in reductions than apartments, advantage from analogous mechanisms, with particularly evident effects in the early stages of production. In apartments in multi-storey buildings, economies of scale and process serialisation help to stabilise learning curves.

Empirical evidence demonstrates that off-site deep retrofitting engenders substantial and progressively escalating reductions in unit costs, underpinned by the synergy between accumulated technical expertise, process standardisation, demand coordination and production flow optimisation.

These elements are essential conditions for ensuring the scalability, economic efficiency and replicability of the industrialised model in the retrofitting of social housing stock, with potential applications also in private markets, provided that production volumes are sufficient to generate significant learning economies.

Chapter 5

5. DETERMINATION OF THE FINANCIAL THRESHOLD IN DEEP RETROFIT PROJECTS

5.1. Introduction

The large-scale adoption of deep energy retrofits is a crucial tool for **decarbonising existing buildings**, as it generates simultaneous environmental, economic and social advantages (300). Nevertheless, the dissemination of such interventions is hindered by substantial structural impediments that constrain their widespread implementation (301).

The primary impediment is of an economic nature: deep retrofit projects frequently prove to be financially unviable due to elevated **construction costs** and the pervasiveness of inefficient and **fragmented business models** (32,236,241,302).

As demonstrated in the preceding chapters of this thesis, to effectively initiate the energy renovation of the building stock and contribute to achieving European objectives, it is necessary to adopt an innovative business model, namely the **MESA model**, enhanced using off-site industrialised construction technologies.

The MESA model, an evolution of the traditional ESCO scheme, is considered by the literature to be the most promising for the residential sector (49). The system provides the customer with a unified reference point, thereby facilitating the management of interventions. Concurrently, the integration of off-site solutions has been demonstrated to engender cost reductions, attributable to the standardisation of processes and technological enhancement (238).

The progressive reduction in construction costs can be attributed to two key factors: **learning processes**, which engender production efficiency, and **technological improvements**, and economies of scale, which are activated with the increase in the number of refurbished units (28,240,242)

Consequently, the development of bespoke cost reduction curves for the construction sector is imperative. In the preceding chapters, it has been demonstrated how off-site technologies have already undergone a decrease in unit costs because of industrialisation and standardisation.

Learning curves facilitate the estimation of cost reduction trends and the assessment of the scalability of interventions. They also enable the **identification of a cost level** at which interventions become financially viable.

The subsequent step, which is the objective of this chapter, is to utilise these curves to identify the break-even point, i.e. the unit cost level at which the economic and social advantages of deep retrofitting equal the costs incurred. This knowledge is essential to understand when and under what conditions deep retrofitting can become a competitive investment.

However, the current study has revealed that further research is required to determine the number of units that need to be retrofitted to achieve a sufficient reduction in costs, and the unit cost values at which the break-even point will be reached. This inherent uncertainty complicates the assessment of medium- to long-term profitability, thereby hindering investment decisions. For financial operators, the absence of reliable data on economic return prospects engenders elevated risk and exacerbates credit access conditions for households (51,52).

This observation underscores a research gap, namely the paucity of studies that accurately analyse the financial break-even point of deep retrofit projects executed using off-site construction technologies, with consideration for the impact of learning curves on the progressive decline in construction costs (cfr. Table 38).

Gap	**Research question**
There is a lack of studies on learning curves and cost reduction in deep retrofitting, particularly about off-site industrialisation and economies of scale.	RQ3b: Is it possible to determine the threshold construction cost value at which deep retrofit interventions are financially balanced?

Table 38: Gap 3 and sub-question of the third research questions (RQ3b)

The innovative element of the research lies not only in the integration of the value proposition of deep retrofitting, the MESA model and off-site technologies, but above all in the assumption that technological innovation, standardisation and industrialisation of the supply chain can generate a dynamic and progressive process of cost reduction.

The interaction between learning processes and technological innovation is a pivotal factor in overcoming current economic barriers, reducing costs and promoting the large-scale diffusion of deep retrofitting. This, in turn, makes it accessible and viable for both households and businesses (34,263).

From a **methodological perspective**, this standpoint is especially pertinent in sector that has historically exhibited a reluctance to embrace innovation and is characterised by low productivity (161,165). The elevated demand for deep retrofitting, further accentuated by European directives, necessitates a transformation in the business model and industrial investments capable of modernising the construction sector and containing costs (186,189).

Applying this logic to the case studies previously analysed - Milan, Florence, Bergamo and Udine - enables the identification of the unit cost values that allow interventions to achieve economic and financial balance, as well as the level of external contribution required in different territorial contexts and for various demand profiles.

The research design is divided into the following subchapters:

- **5.2 – Materials and methodology**
  Description of the methodology, demand profiles and data used for dynamic assessment aimed at identifying financial balance thresholds as construction costs gradually decrease;
- **5.3 – Dynamic assessment and financial viability threshold**
  Analysis of the profitability of deep retrofit interventions, with the identification of threshold values for different demand profiles and territorial contexts;
- **5.4 – Analysis of the financial deficit and up-front external contribution**
  Estimate of the financial deficit and up-front external contribution requirement, calculated in relation to the level of construction costs;
- **5.5 – Construction cost threshold for financially viable deep retrofit interventions**
  Interpretation of the results, with indication of the break-even cost values for the various demand profiles and territorial contexts.

5.2. Materials and methodology

The literature highlights the fact that the property market attributes a premium price to energy-efficient buildings. This is because energy costs are reduced and there is an improvement in aesthetic and functional characteristics following deep retrofitting.

On this basis, the preceding chapters have developed a methodological framework to capitalise on the value proposition within innovative business models. In particular, the **MESA model** has been identified as the optimal configuration for deep retrofit interventions (49).

Concurrently, the systematic implementation of **industrial standardisation** and optimisation logic in off-site construction has demonstrated, as evidenced by the French case study, that learning-by-doing processes result in a progressive decline in construction costs. The French experience demonstrates that the accumulation of operational experience and the enhancement of production processes, precipitated by technological learning effects, can engender substantial reductions in unit costs.

Evidence suggests that a decline in the primary cost item is associated with an enhancement in the profitability of deep retrofit interventions. This, in turn, results in reduction in the financial deficit and a diminished necessity for upfront external contributions.

Consequently, it can be hypothesised that the learning curve will persist, and that subsequent cost reductions will be associated with the augmentation of off-site construction and an escalation in the number of refurbished units. The cost of interventions is anticipated to diminish further until the financial break-even point is attained.

The preceding chapter presented a static cost assessment based on currently available technologies and prevailing market values. In contrast, this chapter presents a **dynamic assessment** based on the assumption of a progressive reduction in unit costs resulting from increased efficiency in off-site construction, thanks to economies of technological learning.

The objective of the analysis is to ascertain the economic-financial balance point the point at which the profitability of the interventions reaches the break-even threshold. The assessment was supplemented with a simulation that considers the progressive reduction of public support, modelled according to the dynamics of industrial costs and the specificities of local residential markets.

The objective of the dynamic assessment is twofold:

- to identify the **threshold value** beyond which the interventions are financially viable for the three demand profiles (owner-occupier, owner-developer and owner-landlord);
- to verify whether the **real estate markets of the cities** under consideration (major cities: Milan and Florence; mid-sized cities: Bergamo and Udine) involve different financial balance threshold values for deep retrofit interventions.

From a methodological perspective, the analysis proposes a dynamic assessment based on the assumption that the investor elects to undertake comprehensive retrofitting works, capitalising on the maximum potential premium price recognised by the market. This is achieved by adopting the most innovative business model (MESA) and off-site construction technologies.

The methodology employed in this study maintains constant variables (revenues, times, rates) while systematically varying construction cost. This approach enables the observation of how profitability is influenced by changes in unit costs. This methodological approach facilitates the estimation of the dynamic evolution of the NPV for each investor profile, thereby enabling the identification of the cost levels at which the interventions become financially viable (cfr. Figure 36).

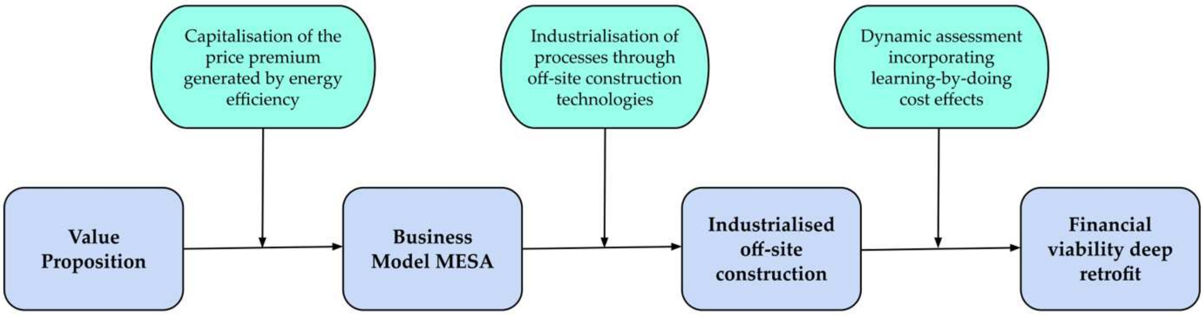


Figure 36: Methodological framework for integrating the value proposition, MESA model, off-site technologies, and economies of scale and learning to assess the financial viability of deep retrofit projects

Finally, the adoption of a system consistent with the analytical framework presented in the preceding chapters – incorporating procedures, costs, data and demand profiles – ensures the comparability of results and the internal consistency of the entire analysis.

The **DCF method** has been adopted once again, thus enabling **the NPV** to be estimated by discounting the differential flows of costs and advantages over the specific time horizon of each investor archetype.

The financial analysis encompasses three distinct profiles: the owner-occupier, with a time horizon of 20 years and a focus on housing quality and energy efficiency; the owner-developer, with a time horizon of 2 years and a focus on capital gains; and the owner-landlord, with a time horizon of 8 years, corresponding to two standard contract cycles.

The analysis considers the following advantages: energy savings, reduced maintenance costs, increased rental income and capitalisation of the energy premium price when the property is sold. This approach facilitates the capture of the full range of economic advantage that are derived from deep retrofit interventions and enables the assessment of their impact on the overall financial viability of the projects concerned.

5.3. Dynamic assessment and financial viability threshold

The cumulative cost reduction curve per unit built allows for the identification of the **threshold value of hard costs** at which deep retrofitting becomes financially viable.

The assessment was conducted based on the unit cost value of €1,347/m², as identified in Chapter 3. This indicated that, at that level, deep retrofitting would not be financially viable.

The employment of the DCF model, calibrated to the dynamics of progressive cost reduction, facilitates the estimation of the evolution of NPV over time and the identification of the break-even points for each demand profile.

The results of the analysis, presented in Tables 39, 40 and 41, demonstrate a direct correlation between the decline in construction costs and the augmentation in NPV, with varying values contingent on the investor profile and the characteristics of the reference market.

Hard costs	Owner - occupier			
	Milan	Florence	Bergamo	Udine
1,347 €/m^2	-56,875 €	-57,493 €	-58,900 €	-59,153 €
1,200 €/m^2	-46,051 €	-46,670 €	-48,077 €	-48,330 €
1,100 €/m^2	-38,701 €	-39,320 €	-40,726 €	-40,980 €
1,000 €/m^2	-31,351 €	-31,969 €	-33,376 €	-33,629 €
900 €/m^2	-24,000 €	-24,619 €	-26,026 €	-26,279 €
800 €/m^2	-16,650 €	-17,269 €	-18,675 €	-18,928 €
700 €/m^2	-9,300 €	-9,918 €	-11,325 €	-11,578 €
600 €/m^2	-1,949 €	-2,568 €	-3,975 €	-4,228 €
500 €/m^2	5,401 €	4,782 €	3,376 €	3,123 €
400 €/m^2	12,751 €	12,133 €	10,726 €	10,473 €

Table 39: NPV for the owner-occupier in the cities of Milan, Florence, Bergamo and Udine, as a function of construction cost reductions resulting from learning effects

Hard costs	Owner - developer			
	Milan	Florence	Bergamo	Udine
1,347 €/m^2	-37,066 €	-57,015 €	-67,009 €	-73,323 €
1,200 €/m^2	-25,212 €	-45,161 €	-55,155 €	-61,469 €
1,100 €/m^2	-17,162 €	-37,111 €	-47,105 €	-53,419 €
1,000 €/m^2	-9,112 €	-29,061 €	-39,055 €	-45,369 €
900 €/m^2	-1,062 €	-21,011 €	-31,005 €	-37,319 €
800 €/m^2	6,988 €	-12,961 €	-22,955 €	-29,269 €
700 €/m^2	15,038 €	-4,911 €	-14,905 €	-21,219 €
600 €/m^2	23,088 €	3,139 €	-6,855 €	-13,169 €
500 €/m^2	31,138 €	11,189 €	1,195 €	-5,119 €
400 €/m^2	39,188 €	19,239 €	9,245 €	2,931 €

Table 40: NPV for the owner-developer in the cities of Milan, Florence, Bergamo and Udine, as a function of construction cost reductions resulting from learning effects

Hard costs	Owner - landlord			
	Milan	**Florence**	**Bergamo**	**Udine**
1,347 €/m²	-13,115 €	-38,159 €	-49,412 €	-59,297 €
1,200 €/m²	-1,508 €	-26,553 €	-37,806 €	-47,791 €
1,100 €/m²	6,374 €	-18,671 €	-29,924 €	-39,909 €
1,000 €/m²	14,256 €	-10,789 €	-22,042 €	-32,027 €
900 €/m²	22,138 €	-2,907 €	-14,160 €	-24,145 €
800 €/m²	30,020 €	4,975 €	-6,278 €	-16,263 €
700 €/m²	37,902 €	12,857 €	1,604 €	-8,381 €
600 €/m²	45,784 €	20,739 €	9,486 €	-499 €
500 €/m²	53,666 €	28,621 €	17,368 €	7,383 €
400 €/m²	61,548 €	36,503 €	25,250 €	15,265 €

Table 41: NPV for the owner-landlord in the cities of Milan, Florence, Bergamo and Udine, as a function of construction cost reductions resulting from learning effects

The comparative analysis indicates that the NPV is not a linear function of construction costs. Rather, it reflects the interaction between market dynamics, the ability to capitalise on energy advantages, and the duration of the investment horizon. The hierarchy of the markets analysed is such that Milan is ranked as the most favourable context for all investor profiles, followed by Florence. However, it is asserted that Bergamo and Udine require more substantial cost reductions to ensure profitability, particularly for investors focused on capital gains or leasing.

For **owner-occupiers,** the dynamics of values are relatively homogeneous across the territory, with the **break-even point at around €600/m²** in all the urban contexts examined. The progressive reduction in costs generates an increase in the NPV, which varies from approximately €3,000 in Udine to €5,400 in Milan for a cost level of €500/m², reaching values above €10,000 at €400/m² in all the markets analysed.

The findings suggest that for owner-occupiers, the primary factor influencing financial viability is the reduction of construction costs. Regional variations play a negligible role in determining the overall profitability of the project.

For **owner-developer**, the profile shows **marked territorial heterogeneity**, with profitability strongly influenced by the urban context and the ability to capitalise on a price premium during the resale phase. Milan shows a convergence towards break-even already at the level of €900/m² (NPV: -€1,062), reaching positive values below €800/m², while Florence achieves break-even at around €600/m²..

In mid-sized markets, Bergamo demonstrates a positive NPV at €500/m² (€ 1,195), while Udine exhibits a negative NPV up to this threshold (€5,119), attaining economic viability only at lower cost levels. The territorial divergence is further accentuated at the €400/m² level, with Milan achieving an NPV of over €39,000, compared to only €2,900 in Udine.

The findings underscore the capacity of markets with higher property values to capitalise on price premiums and generate positive NPVs, even in the presence of low construction costs. In contrast, less dynamic markets necessitate substantially lower costs to attain profitability.

For owner-landlord, territorial variations persist in significance, although the protracted investment timeframe (eight years) permits a steady appreciation of the advantages accruing from the intervention. Milan has already achieved a positive NPV in excess of €1,200/m², reaching €6,374 at the level of €1,100/m². Florence attains economic viability within the €800-900/m² range, with an NPV of approximately €5,000 at €800/m². Bergamo attains profitability at below €700/m², while Udine remains in deficit up to €600/m² (€-499), achieving positive values only at €500/m².

At notably lower cost levels (€400/m²), a marked divergence between markets becomes evident. Milan exceeds €61,000, Florence stands at €36,500, Bergamo at €25,000 and Udine at €15,000.

5.4. Analysis of financial deficit and up-front external contribution

As a preliminary step, a dynamic assessment of the costs and profitability of the interventions for the various demand profiles must be conducted. A secondary yet crucial aspect pertains to the **financial deficit**, which constitutes the proportion of the investment that is required to be covered by an external contribution made in advance.

The investment deficit, understood as the proportion of the total cost of the intervention that is not offset by the anticipated advantages, corresponds to the ratio between the NPV and the total cost of the investment.

The results obtained in this study appear to provide robust confirmation of the theoretical hypothesis that the profitability of interventions is strongly influenced by the interaction between the investor profile and the structural characteristics of the local market.

For **owner-occupiers**, the results show an inverse relationship between construction costs and financial deficit. At the maximum cost level considered (€1,347/m²), the deficit ranges from 54.3% in Milan to 56.5% in Udine, with Florence (54.9%) and Bergamo (56.3%) in an intermediate position and an overall territorial difference of less than three percentage points. As efficiency and standardisation increase, the deficit gradually decreases until it reaches values close to zero at around €600/m², the threshold at which the NPV tends to become non-negative.

Sensitivity analysis confirms a regular trend: reductions of €100/m² in hard costs lead to an improvement in the deficit of between 4 and 7 percentage points, with slightly more pronounced variations in contexts with lower property values. The decrease in the deficit is consistent in the higher cost ranges, as between €1,347 and €1,000/m², there is an overall reduction of approximately 15–20 percentage points in all cities.

A similar trend emerges in the lower cost ranges: between €700 and €500/m², the deficit is reduced by a further 20 percentage points or so, from values between 17–21% (at €700/m²) to values between –8 and –14% (at €500/m²), depending on the city.

Overall, the sensitivity of the owner-tenant profile to changes in unit cost is high and shows a similar trend in all the markets analysed. Regional differences remain limited across the entire range of cost variations, indicating that the reduction in unit costs has a substantially uniform impact on economic results in different urban contexts (cfr. Table 42 and Figure 37).

Hard costs	Owner - occupier			
	Milan	Florence	Bergamo	Udine
1,347 €/m²	54.33 %	54.92 %	56.27 %	56.51 %
1,200 €/m²	49.39 %	50.05 %	51.56 %	51.83 %
1,100 €/m²	45.28 %	46.00 %	47.65 %	47.95 %
1,000 €/m²	40.35 %	41.14 %	42.96 %	43.28 %
900 €/m²	34.32 %	35.21 %	37.22 %	37.58 %
800 €/m²	26.79 %	27.78 %	30.04 %	30.45 %
700 €/m²	17.10 %	18.24 %	20.82 %	21.29 %
600 €/m²	4.18 %	5.51 %	8.53 %	9.07 %
500 €/m²	-13.90 %	-12.31 %	-8.69 %	-8.04 %
400 €/m²	-41.03 %	-39.04 %	-34.51 %	-33.70 %

Table 42: Variation of the financial deficit for the owner-occupier in the cities of Milan, Florence, Bergamo and Udine, as a function of construction cost reductions resulting from learning effects

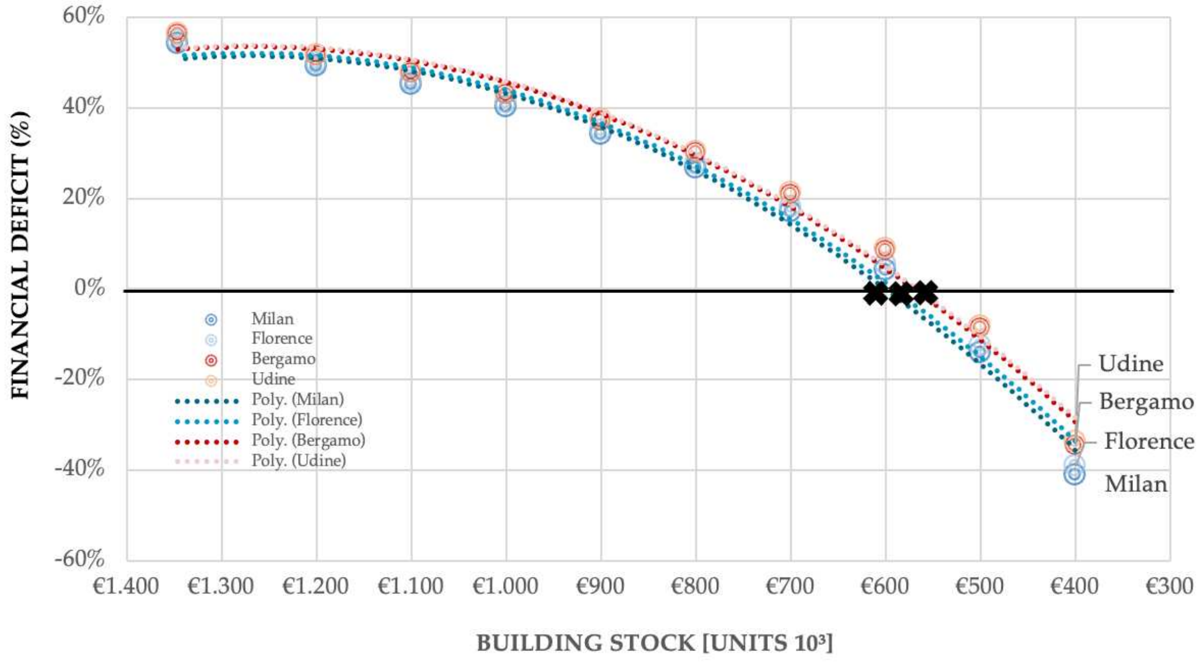


Figure 37: Trend of the unit NPV of the investment as a function of the reduction in unit retrofit cost using off-site technologies for the owner-occupier

For the **owner-developer**, the analysis shows a significantly greater sensitivity to construction costs than the owner-occupier profile, with very marked regional differences. In markets with high demand intensity – particularly Milan – the financial deficit rapidly decreases as unit costs fall, becoming negative in the €900–800/m² range.

This result reflects the primary market's ability to incorporate the price premium associated with improved energy performance at the property sale stage, generating a sufficient increase in value to offset a substantial part of the investment.

Sensitivity analysis confirms the model's strong responsiveness in major cities: reductions of €100/m² in hard costs lead to improvements in the deficit of between 7 and 12 percentage points for Milan, with progressively smaller variations further down the urban scale. Florence shows a similar trend, albeit with a lower capacity to absorb the added value generated by energy efficiency, placing the transition to negative values between €800 and €700/m².

In **mid-sized cities**, such as Bergamo and Udine, the economic structure of the market significantly limits the capacity to absorb investment. Even with significant cost reductions, the deficit remains positive up to lower cost levels: in Bergamo, it still exceeds 15% at €600/m², while in Udine, the improvement only becomes significant below €500/m².

In these cities, a reduction of €100/m² in construction costs leads to less marked improvements than in larger markets – generally between 5 and 8 percentage points – highlighting a more attenuated sensitivity linked to the capacity for local property development.

Overall, the sensitivity of the owner-developer profile is high in cities with high property values and tends to decrease in mid-sized contexts, where the viability of interventions is more dependent on further reductions in unit costs.

The **financial viability threshold** is around €800/m² in Milan, €700/m² in Florence, €500/m² in Bergamo and around €400/m² in Udine, with a sensitivity structure that directly reflects the hierarchy of local property values (cfr. Table 43 and Figure 38).

Hard costs	Owner - developer			
	Milan	Florence	Bergamo	Udine
1,347 €/m²	34.18 %	52.57 %	61.79 %	67.61 %
1,200 €/m²	26.10 %	46.75 %	57.10 %	63.63 %
1,100 €/m²	19.38 %	41.91 %	53.20 %	60.33 %
1,000 €/m²	11.32 %	36.10 %	48.52 %	56.36 %
900 €/m²	1.47 %	29.00 %	42.80 %	51.51 %
800 €/m²	-10.85 %	20.13 %	35.65 %	45.45 %
700 €/m²	-26.69 %	8.72 %	26.45 %	37.66 %
600 €/m²	-47.80 %	-6.50 %	14.19 %	27.27 %
500 €/m²	-77.36 %	-27.80 %	-2.97 %	12.72 %
400 €/m²	-121.70 %	-59.75 %	-28.71 %	-9.10 %

Table 43: Variation of the financial deficit for the owner-developer in the cities of Milan, Florence, Bergamo and Udine, as a function of construction cost reductions resulting from learning effects

Figure 38: Trend of the unit NPV of the investment as a function of the reduction in retrofit costs using off-site technologies for the owner-developer

For the **owner-landlord** profile, the results show an intermediate pattern compared with the two previous cases, yet territorial differences remain statistically significant. At the maximum cost level (€1,347/m²), the initial deficit ranges widely across cities: Milan exhibits the lowest value (12.1%), Florence positions at mid-range (35.2%), while Bergamo (45.6%) and Udine (54.8%) display markedly higher deficits.

As construction costs decrease, the deficit contracts at different speeds depending on the market. In Milan, values become negative already at €1,100/m², reflecting the strong capacity of the rental market to absorb efficiency-related value increases. Florence reaches break-even between €800 and €900/m², while in secondary markets this threshold is substantially harder to achieve: Bergamo approaches economic viability only at around €700/m², and Udine does so at €600/m², turning positive at €500/m².

The sensitivity analysis highlights pronounced gradients across cities. Reductions of €100/m² in hard costs generate improvements in the deficit ranging from 8 to 15 percentage points in Milan and Florence, while the same cost variation produces more modest adjustments in Bergamo and Udine, where deficits remain persistently elevated until lower cost thresholds are reached. The divergence across markets becomes particularly evident at €400/m²: Milan records a substantial financial surplus (-191%), Florence reaches -113%, Bergamo -78%, and Udine -47%. This widening gap illustrates how market size, rental price levels and the depth of rental demand shape the ability of each context to translate cost reductions into financial viability (Table 44, Figure 39).

Overall, the owner-landlord profile displays a sensitivity pattern that is strongly conditioned by the territorial structure of rental markets. High-value cities exhibit rapid improvements in economic performance as construction costs fall, while mid-sized markets require significantly deeper cost reductions to reach positive returns. These results confirm that, for investment strategies based on rental income, territorial variables play a decisive role in determining whether deep retrofit interventions can achieve financially sustainable outcomes.

The findings of this study underscore the pivotal role of territorial variables, encompassing market size, rental levels, and rental demand structure, in generating economically viable returns, particularly for investments that employ strategies of enhancement through rental income (cfr. Table 44, Figure 39).

Hard costs	**Owner - landlord**			
	Milan	**Florence**	**Bergamo**	**Udine**
1,347 €/m^2	12.09 %	35.19 %	45.56 %	54.77 %
1,200 €/m^2	1.56 %	27.49 %	39.14 %	49.47 %
1,100 €/m^2	-7.20 %	21.09 %	33.79 %	45.07 %
1,000 €/m^2	-17.71 %	13.40 %	27.38 %	39.79 %
900 €/m^2	-30.56 %	4.01 %	19.54 %	33.33 %
800 €/m^2	-46.61 %	-7.73 %	9.75 %	25.25 %
700 €/m^2	-67.26 %	-22.82 %	-2.85 %	14.87 %
600 €/m^2	-94.79 %	-42.94 %	-19.64 %	1.03 %
500 €/m^2	-133.33 %	-71.11 %	-43.15 %	-18.34 %
400 €/m^2	-191.14 %	-113.36 %	-78.42 %	-47.41 %

Table 44: Variation of the financial deficit for the owner-landlord in the cities of Milan, Florence, Bergamo and Udine, as a function of construction cost reductions resulting from learning effects

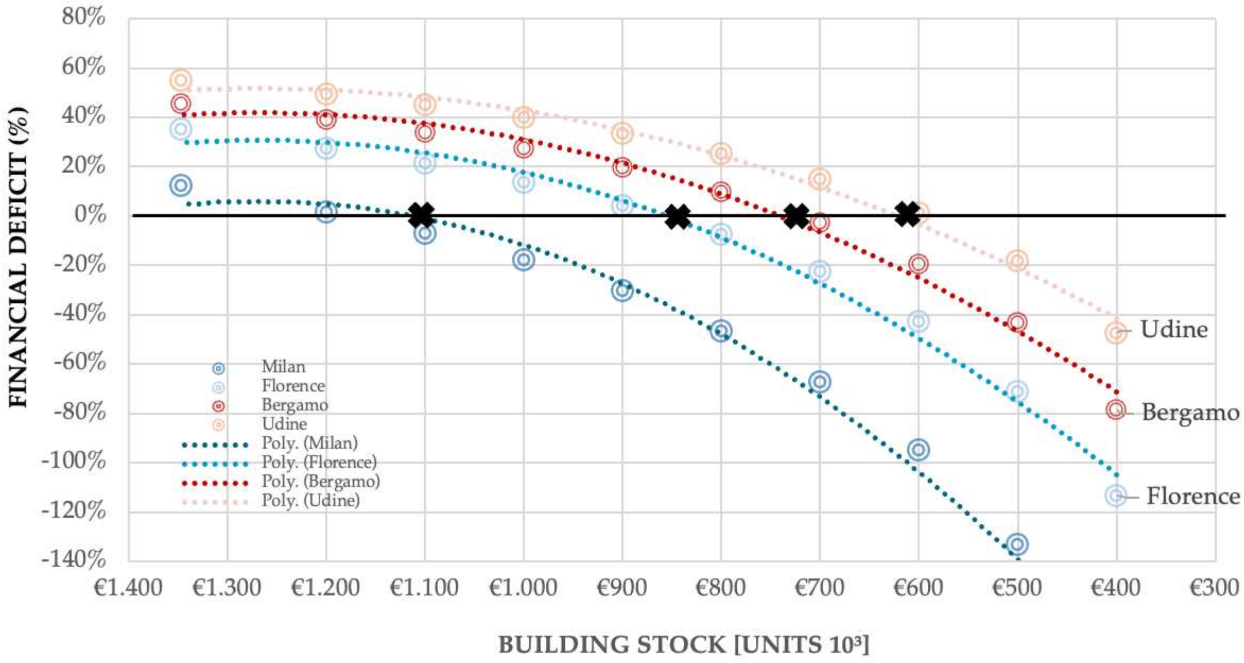


Figure 39: Trend of the unit NPV of the investment as a function of the reduction in retrofit costs using off-site technologies for the owner-landlord

The comparative analysis of the deficit confirms a **clear territorial hierarchy**: Milan has the greatest capacity to sustain investments at higher cost levels, followed by Florence in an intermediate position, while Bergamo and Udine require more substantial cost reductions to achieve economic viability.

The actual profitability of a given property is determined by the interaction between two factors: namely, the reduction in construction costs and the property values in different urban contexts. In markets with lower property values, such as Bergamo and Udine, the activation of public support instruments or the adoption of targeted cost containment strategies are necessary conditions to ensure the financial viability of deep retrofit interventions. In cities with higher property values, such as Milan and Florence, these constraints are less stringent.

Across investor profiles, the **sensitivity analysis** reveals distinct patterns: for owner-occupiers, the financial deficit decreases steadily as costs fall, with limited territorial variation; for owner-developers, the response to cost reductions is markedly stronger, especially in major cities where the premium can be capitalised at sale; for owner-landlords, the sensitivity is intermediate, with rental market conditions amplifying territorial disparities. Overall, the responsiveness to cost reductions increases moving from owner-occupiers to owner-developers, while owner-landlords exhibit asymmetric sensitivity shaped by local rental demand. These differences highlight how both market structure and investor type jointly condition the feasibility of deep retrofit investments.

5.5. Construction cost threshold for financially viable deep retrofit interventions

The analysis conducted addresses the third gap identified in the literature, relating to the possibility of achieving significant reductions in construction costs through learning economies in off-site construction. In the field of construction, quantifiable cost reductions attributable to learning effects in off-site construction are already being observed.

It is now assumed that these effects may continue over time, leading to further reductions in construction costs until a critical threshold is reached, at which point deep retrofits become financially viable, with a balance between costs and revenues.

In this specific context, the research provides an answer to Research Question **RQ3b: Is it possible to determine the threshold construction cost value at which deep retrofit interventions are financially balanced?**

The assessment was conducted using a DCF model calibrated on the decreasing dynamics of hard costs, thus allowing the evolution of the NPV to be estimated and the critical break-even thresholds for each investment profile to be identified. An analysis of the markets in Milan, Florence, Bergamo and Udine reveals a hierarchical structure in terms of investment attractiveness. Milan is the most favourable context, followed by Florence. However, Bergamo and Udine require more substantial cost reductions to achieve financial viability.

The analysis demonstrates that there are **different viability thresholds** for different investor profiles and territories. It is evident that owner-occupiers, who directly capitalise on energy savings, achieve financial viability with construction costs below €500/m² in all the contexts considered, without the need for upfront public subsidies.

Conversely, profiles oriented towards property enhancement demonstrate heightened sensitivity to local market dynamics. Developers achieve viability with thresholds between €800 and €600/m² in large cities and between €500 and €400/m² in mid-sized cities. Owner-landlords have higher thresholds, at approximately €1,100/m² for Milan, €800/m² for Florence, €700/m² for Bergamo and €500/m² for Udine.

In this context, the systematic adoption of **off-site industrial processes** for the deep energy retrofitting of buildings is imperative. This approach is pivotal in reducing the amount of public funding required, and in scenarios where construction costs are less than €500/m², it has the potential to eliminate the need for public funding. This, in turn, promotes a more efficient use of public resources and stimulates technological innovation in the sector.

The findings further substantiate the observation that the value proposition exhibits considerable variation across different territories. The values thus obtained can be used to estimate the percentage of public funding required to ensure the economic viability of interventions in different contexts, and to calibrate targeted incentive policies.

To achieve the cost levels necessary for **financial viability**, it is essential to focus on improving the efficiency of off-site production, increasing standardisation and process efficiency to **reduce construction costs.**

Assuming the continuation of the learning curve previously traced for the aggregate type of houses and flats, starting from an initial cost of €1,832/m² and considering the reduction already achieved to €982/m², achieving the value of €500/m², necessary for full financial viability, would require a cumulative production of approximately **40,000 units** (cfr. Figure 40).

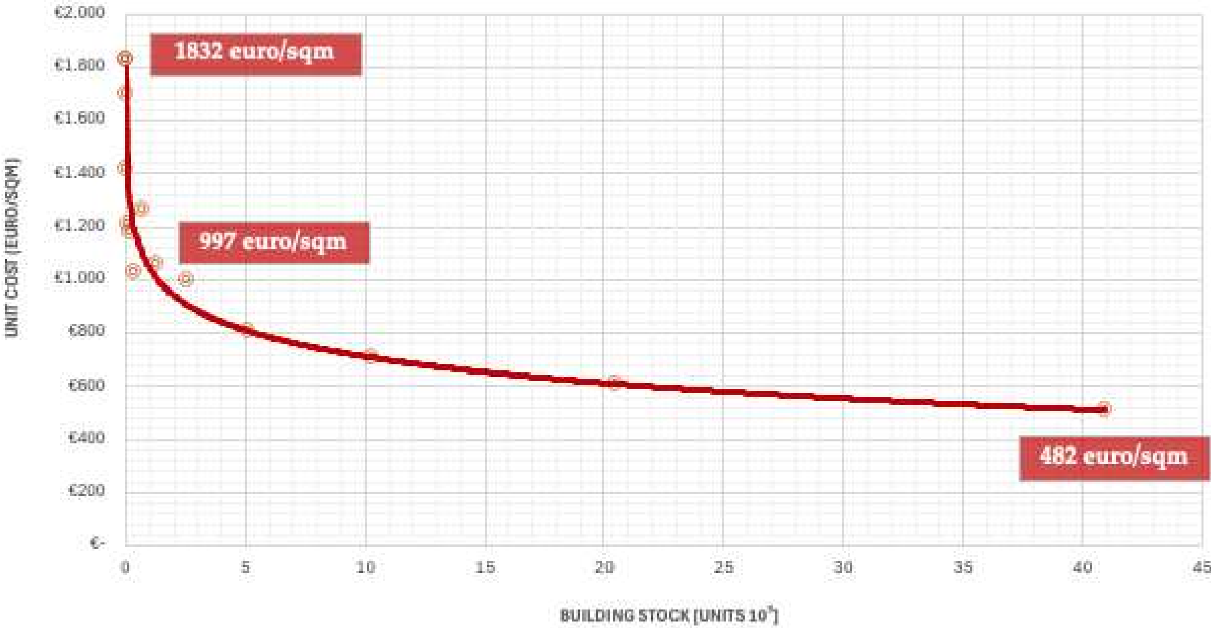


Figure 40: Learning curve: projection of the reduction in construction costs for the aggregate type as a function of the increase in the production of deep retrofit interventions

While the figure of 40,000 units may appear substantial, it is comparatively modest when viewed within the context of the national population. In Italy, 3,858,034 homes need energy efficiency improvements, representing 68% of the total residential stock. Moreover, when public housing in energy classes E, F and G is considered, the mandatory improvements to comply with EU regulations are considered, the total amounts to approximately 400,000 units, equal to 53.5% of public housing stock.

Consequently, reaching the threshold of 40,000 units represents **just 10% of the total number of units in inefficient public housing,** a realistic and achievable goal.

This evidence underscores the strategic nature of investments aimed at reducing construction costs. Interventions focused on this segment of the housing sector would facilitate an increase in off-site production, leveraging industrialised technology to further reduce unit costs. This approach has the potential to offer a tangible opportunity to enhance the energy efficiency of the national building stock and, in the long term, contribute to the achievement of European decarbonisation objectives.

Chapter 6

6. CONCLUSION

This research analyses the economic viability of deep energy retrofit in the residential sector, a crucial issue for the decarbonisation of the European building stock, which is characterised by high energy inefficiency. The primary objective is to assess whether deep energy refurbishment interventions generate a sufficient increase in market value to ensure financial viability and to identify the mechanisms necessary to achieve it.

The investigation begins with an analysis of the green premium in the Italian real estate market, conducted through hedonic regression models applied to eight cities of different sizes. The results show a statistically significant but territorially heterogeneous energy premium: 15.38% in major cities and 26.33% in mid-sized cities for the differential between properties in class A and G. The size and vitality of local markets thus influence the valuation of energy efficiency, with significant implications for social equity during the transition.

Having confirmed the existence of a real estate value proposition, the research identifies the MESA as the most suitable business model to capitalise on this value in the residential sector. MESA integrates services across the entire value chain, from design to implementation, through a single point of contact, ensuring payments based on the savings actually achieved.

The integration of the MESA model with off-site technologies, characterised by shorter construction times and uninterrupted occupancy, allows financial viability to be assessed through discounted cash flow analysis for three investor profiles. The results show negative NPV in all scenarios at current costs: 50% of the investment remains uncovered for owner-occupiers, 30–70% for developer-owners (depending on the urban context), and 12–50% for landlord-owners. Economic advantages are therefore systematically lower than the costs incurred.

The insufficiency of the value proposition leads to an investigation of the potential of off-site industrialised construction to reduce costs through cumulative learning processes. The analysis of 19 industrialised retrofit interventions in French social housing documents cumulative reductions of 47.8% for single-family homes and 27% for apartments, with average learning rates between 6.4% and 6.6%. The qualitative investigation also identifies four key mechanisms: accumulation of organisational competencies, process standardisation, serialisation of interventions, and logistical optimisation.

Learning curves allow the identification of critical thresholds for financial viability. Owner-occupiers achieve viability at costs below €500/m² in all contexts; owner-developer require €800–600/m² in major cities and €500–400/m² in mid-sized cities; owner-landlord require thresholds ranging from €1,100/m² in Milan to €500/m² in Udine.

Projections of the learning curve estimate that achieving the €500/m² threshold—necessary for universal financial viability—requires a cumulative production of around 40,000 units. This volume appears modest compared with national needs: 3,858,034 dwellings require energy efficiency interventions (68% of the stock), while 400,000 public housing units are inefficient (53.5% of the public stock). The 40,000 units represent 10% of inefficient public housing, constituting a realistic target. Public investment aimed at industrial scaling produces multiplier effects: interventions on public housing create the conditions for financially viable expansion into the private market.

The research highlights the structural inadequacy of uniform national programmes. The Superbonus 110% generates allocative inefficiencies and regressive redistributive effects: excessive advantages in major cities, with public funds transformed into unnecessary property rents, and insufficient support in mid-sized cities, reducing accessibility for households with lower economic capacity.

Evidence from learning curves suggests the need for strategic public intervention to strengthen the production ecosystem, through targeted R&D programmes, subsidies conditional on technological innovation for specialised firms, incentives for off-site skills training, and support for standardised design solutions. This approach, consistent with the *entrepreneurial state* paradigm outlined by Mazzucato, positions the public sector as a proactive actor in creating new technology markets rather than merely correcting market failures.

In a deep retrofit, public investment focused on supply acts as a catalyst for the transition to a mature industrial model, characterised by self-sustaining economies of scale. This approach progressively reduces the need for direct subsidies, transferring advantages to consumers through the market. Its implementation requires territorially differentiated programmes, calibrated to the specificities of local markets, conditionality mechanisms linking financing to innovation objectives, and multi-level coordination tools to maximise public-private synergies.

The identification of critical thresholds allows incentives to be calibrated to the actual gap, thereby optimising resource allocation and reducing deadweight losses. The systematic adoption of industrialised off-site processes is essential: once costs fall below €500/m², deep retrofit becomes financially self-sustaining for all investor profiles, eliminating the need for upfront public contributions.

While the French case provides a valuable reference point for analysing industrialised deep retrofit, its application to the Italian context presents several limitations that must be explicitly acknowledged. The Italian construction sector is characterised by a more fragmented production chain, less standardised procurement procedures, and generally lower levels of industrialisation compared with France. These structural differences may slow learning trajectories and reduce the pace at which the advantages associated with off-site processes can be realised.

Moreover, the Italian real estate market—more heterogeneous and less consolidated than its French counterpart—limits the direct transferability of cost curves derived from the Energiesprong France experience. For this reason, French cost benchmarks should be regarded as indicative rather than fully applicable estimates. Variations in public procurement frameworks, the achievable scale of interventions, and the ability of firms to integrate industrialised processes further imply that French figures constitute a plausible baseline but not a binding reference for the Italian market.

Looking ahead, it is essential to investigate the role of procurement procedures as instruments to stimulate innovation in deep retrofit, promoting criteria that encourage component standardisation, off-site solutions, and process efficiency. Comparative analysis of procurement models across Europe may help identify the most effective practices to reconcile environmental, economic, and social objectives.

It is likewise crucial to explore the role of the entrepreneur in industrialised retrofit, examining which organisational models and supply-chain strategies support sectoral scalability. Future research could analyse how firms coordinate competences, capital, and technological resources, and how different configurations—ranging from generalist contractors to specialised networks—affect the diffusion of industrialised retrofit solutions.

Another area of investigation concerns the drivers of cost reduction, distinguishing between building components (envelope, prefabricated façades, standardised modules), building services (HVAC, ventilation, heat pumps), and organisational-logistical aspects (construction time, supply, transport). Understanding which elements are most sensitive to learning economies allows for more efficient intervention design.

Finally, the interaction between retrofit and building use must be considered: deep interventions affect not only technical and financial aspects but also how dwellings are occupied, influencing thermal comfort, air quality, continuity of use during works, and occupant perception of value. Analysing these factors allows the economic, social, and relational value of deep retrofit to be assessed more accurately.

7. ANNEX

7.1. Energiesprong programme in France

The social housing sector in France comprises a housing stock of over five million units, the majority of which are characterised by poor energy efficiency and classified as class D or lower according to the EPC scale (303). The National Energy Renovation Plan of 26 April 2018 (304) identified the redevelopment of this housing stock as a priority, setting a target of 100,000 energy efficiency measures per year.

Nevertheless, the deep retrofit process is encountering significant challenges. In addition to enhancing energy performance, operators are tasked with the reconciliation of factors including the reduction of operating costs, the optimisation of living quality for tenants, and compliance with increasingly stringent environmental regulations. The measures implemented thus far have primarily concentrated on enhancing energy efficiency, yielding modest outcomes. In 60% of cases, there has been an improvement of only one energy class, while only 40% of buildings have attained a two-class improvement (305).

These limitations have fuelled interest in the Energiesprong model, which is regarded as an innovative and scalable solution to the challenges facing the sector. The process of implementation in France has followed a gradual trajectory, characterised by the progressive consolidation of the network of actors involved. The initial Charter of Commitment, signed in 2016, brought together 36 parties, comprising nine social landlords, 20 suppliers, and seven facilitators. The objective of this agreement was to renovate 3,600 homes by 2022. The second Charter, which was signed on 9 October 2018, involved 64 partners (14 of whom were social landlords). This increased the target to 6,650 homes by 2023 (306).

To date, 32 Energiesprong projects have been identified in France, which are distributed across six regions: The geographical distribution of cases is as follows: Hauts-de-France (28%), Auvergne-Rhône-Alpes (16%), Pays de la Loire (19%), Île-de-France (13%), Occitanie (9%), and Brittany (6%) (cfr. Figure 41).

The trial phase of the Energiesprong model in France commenced in 2018, with pilot projects situated in small to mid-sized municipalities: Hem (9,000 inhabitants), Longueau (5,500 inhabitants), and Wattrelos (41,000 inhabitants), all located in the Hauts-de-France region.

These areas have a significant proportion of social housing, accounting for around 33% of the local building stock, and a prevalence of single-family homes, which represent 66% of social housing in Hem. The properties involved were mainly two-storey terraced houses with gardens on both sides, initially classified in energy categories E, F or G.

Overall, the 31 interventions carried out include (cfr. Figures 28):

1,687 single-family social housing units;

2,578 apartments social housing units;

7 school buildings refurbished or nearing completion;

1 student collective housing intervention with 254 units.

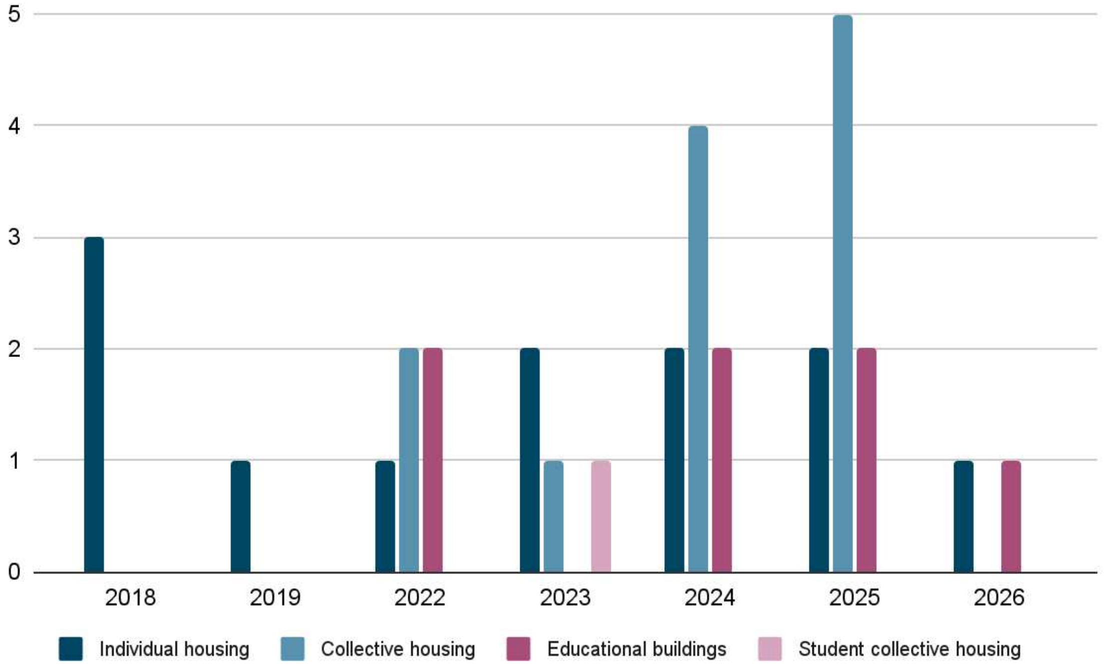


Figure 41: Deep retrofit projects using the Energiesprong model completed per year (2018–2026), broken down by type

The analysis of French social landlords shows that the Energiesprong model is being tested both through individual initiatives and through collaborations between multiple actors, facilitating the accumulation of experience and knowledge before potential wider-scale adoption. A prominent example of a collaborative approach is **MASH**, the purchasing consortium of Pays de la Loire, which brings together around 15 social landlords. Thanks to this strategy, MASH has brought 1,300 renovated dwellings to the market.

In parallel, other landlords have pursued retrofit programmes individually. **Est Métropole Habitat** has completed approximately 998 units, while **Vilogia** has carried out 377 interventions, mainly concentrated in the Hauts-de-France region.

Some operators, such as ICF Habitat, have adopted a wait-and-see strategy, monitored the outcomes of initial trials while concurrently developed collective initiatives aimed at reducing costs and optimising intervention procedures. Other notably active actors include Garone, with 391 units, and Cristal Habitat, with 244 units, while several landlords have undertaken smaller-scale projects of fewer than 100 units each.

Below, the main actors are organised according to the number of units renovated, distinguished between single-family homes and collective apartments (cfr. Figures 42 and 43).

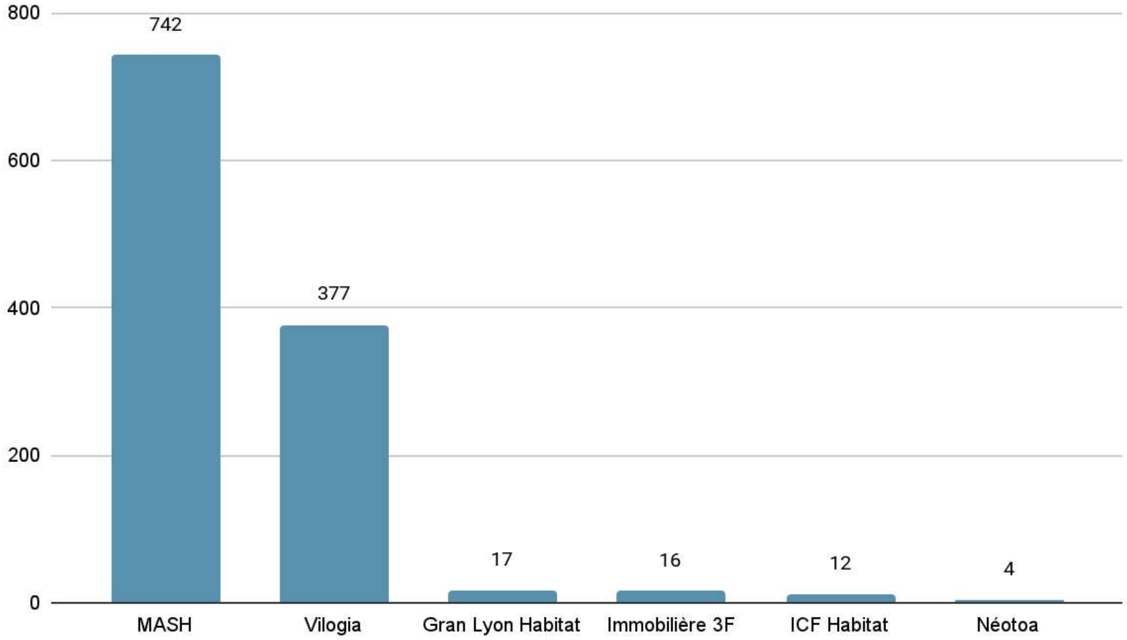


Figure 42: Number of single-family homes renovated under the Energiesprong approach, by property owner type

The construction sector exhibits a high degree of market concentration. Among the leading operators, **Vinci Construction** stands out as a market leader, managing a portfolio of over five active projects encompassing 1,641 residential units undergoing deep retrofit interventions.

Market entry strategies demonstrate marked diversification: some firms, such as **Rabot Dutilleul** and **Bouygues Bâtiment**, engaged immediately in pilot experiments, whereas others adopted a more cautious approach, waiting for operational evidence before scaling up investments.

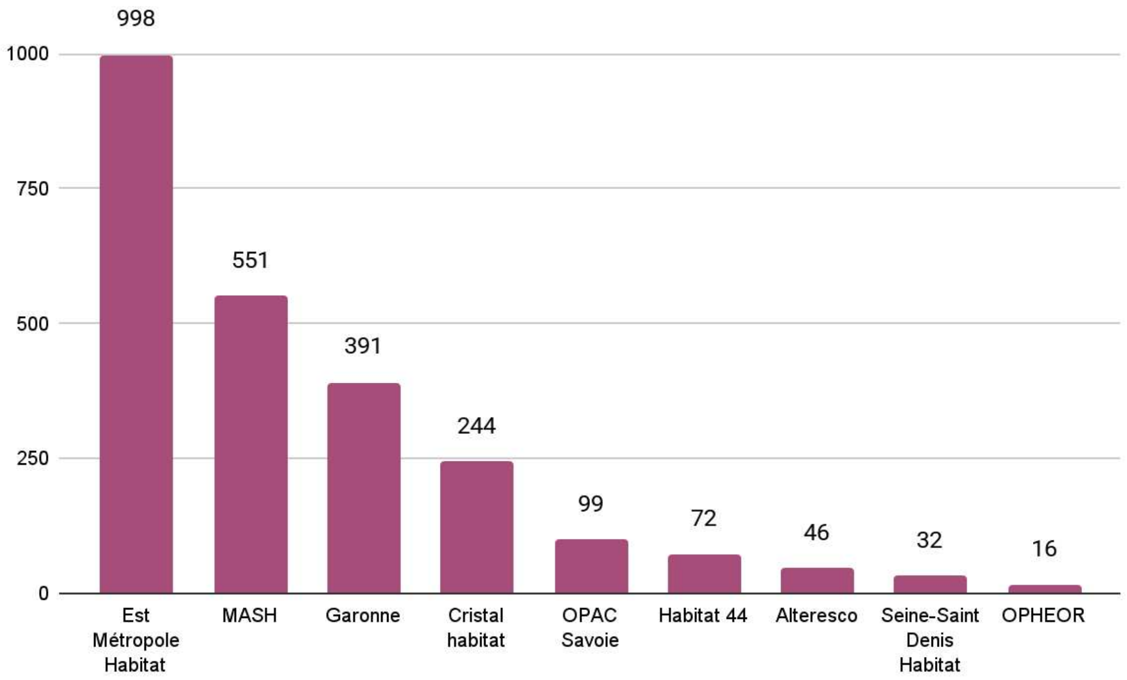


Figure 43: Number of collective apartments renovated under the Energiesprong approach, by property owner type

The adoption of the Energiesprong method in France constitutes a paradigmatic case of how technological innovation can rapidly evolve from experimental phases to industrial and geographically widespread implementation. This process has been facilitated by the establishment of a participatory governance model, integrating public authorities and governmental institutions, social housing operators, construction firms, and specialised territorial networks.

In France, the Energiesprong model is expanding gradually, both in scale and geographic reach. This development is supported by a collaborative ecosystem and dedicated financing instruments, including direct upfront contributions, low-interest loans, and municipal funding.

With the national "**France Relance**" plan of 2021, the government allocated **€6.7 billion** to enhance energy efficiency interventions. The French incentive system for building retrofits primarily comprises two instruments:

1. **MaPrimeRénov**: direct grants calculated according to the level of energy improvement achieved and the household's economic situation.
2. **Loc'Avantages**: fiscal incentives combined with ANAH financing for landlords meeting specific criteria regarding rental levels and tenant selection.

Additional support measures include:

3. exemptions from property tax for energy efficiency upgrades;
4. a reduced VAT rate of 5.5% for specific types of works;
5. mechanisms for sharing energy savings between landlords and tenants;
6. zero-interest eco-loans of up to €50,000 for energy efficiency projects.

Thanks to this integrated approach, France is promoting the uptake of deep retrofit solutions, lowering economic barriers and expanding the range of instruments available to both citizens and sector operators.

Concurrently, there is significant diversity in **operational models**, ranging from centralised procurement to regional partnership arrangements. This plurality reflects organisational flexibility and an ability to adapt to territorial specificities and the requirements of different stakeholders (202,305).

8. APPENDIX

8.1. Descriptive statistics and frequency analysis

Table A1: Descriptive analysis for the Milan dataset

Variable	n	Mean	S.D.	Min	Max
Zone (OMI)	858	2.26	0.82	1	3
Proximity to infrastructure	858	1.80	0.606	1	3
Typology	858	1.0	0.0	1	2
Number of bathrooms	858	1.54	0.680	0	4
Energy class	858	10.36	2.27	1	12
Maintenance status	858	1.61	0.77	1	4
Gross floor area	858	108.09	57.371	19	482
Value market	858	6324.94	2999.03	1307.69	21883.66

Table A2: Descriptive analysis for the Turin dataset

Variable	n	Mean	S.D.	Min	Max
Zone (OMI)	744	2.25	0.86	1	3
Proximity to infrastructure	744	2.21	0.71	1	3
Typology	744	0.00	0.73	0	2
Number of bathrooms	744	1.40	0.59	0	5
Energy class	744	9.98	1.97	1	12
Maintenance status	744	2.71	0.75	1	4
Gross floor area	744	101.99	53.80	20	430
Value market	744	2451.75	1006.92	707.69	8285.71

Table A3: Descriptive analysis for the Florence dataset

Variable	n	Mean	S.D.	Min	Max
Zone (OMI)	394	2.08	0.73	1	3
Proximity to infrastructure	394	1.92	0.82	1	3
Typology	394	1.00	0.0	1	1
Number of bathrooms	394	1.37	0.55	1	3
Energy class	394	11.02	1.89	2	12
Maintenance status	394	2.48	0.72	1	4
Gross floor area	394	88.56	32.75	30	230
Value market	394	3902.49	1216.81	2046.36	9833.33

Table A4: Descriptive analysis for the Trieste dataset

Variable	n	Mean	S.D.	Min	Max
Zone (OMI)	488	1.66	0.70	1	3
Proximity to infrastructure	488	4.00	0.00	3	3
Typology app.	488	0.93	0.24	0	1
Property class	487	2.51	0.67	1	4
Number of bathrooms	488	1.58	0.69	1	3
Energy class	488	2.43	0.80	1	3
Maintenance status	488	2.45	0.79	1	4
Gross floor area	488	122.97	149.06	25	300
Value market	488	2472.07	1126.53	483	9756

Table A5: Descriptive analysis for the Padua dataset

Variable	n	Mean	S.D.	Min	Max
Zone (OMI)	348	1.70	0.87	1	3
Proximity to infrastructure	348	1.97	0.83	1	3
Typology	348	0.92	0.21	0	1
Number of bathrooms	348	1.83	0.66	1	3
Energy class	348	10.25	2.34	1	12
Maintenance status	348	2.65	0.75	1	4
Gross floor area	348	143.33	67.74	26	450
Value market	348	2,031.82	804.21	781	6.252

Table A6: Descriptive analysis for the Mestre dataset

Variable	n	Mean	S.D.	Min	Max
Zone (OMI)	246	1.61	0.83	1	3
Proximity to infrastructure	246	1.82	0.83	1	3
Typology	246	0.98	0.22	0	1
Number of bathrooms	246	1.73	0.49	1	3
Energy class	246	11.32	2.57	1	12
Maintenance status	246	2.49	0.69	1	4
Gross floor area	246	95.39	27.43	27	203
Value market	246	1.676,02	583.59	945	5.637

Table A7: Descriptive analysis for the Bergamo dataset

Variable	n	Mean	S.D.	Min	Max
Zone (OMI)	285	1.81	0.91	1	3
Proximity to infrastructure	285	2.21	0.69	1	3
Typology	285	0.95	0.14	0	1
Number of bathrooms	285	1.39	0.61	1	3
Energy class	285	9.91	2.52	1	12
Maintenance status	285	2.52	0.70	1	4
Gross floor area	285	107.85	47.58	35	300
Value market	285	1,910	721,89	662	4,983

Table A8: Descriptive analysis for the Udine dataset

Variable	n	Mean	S.D.	Min	Max
Zone (OMI)	404	1.85	0.76	1	3
Proximity to infrastructure	0	-	-	-	-
Typology app.	404	0.94	0.23	0	1
Property class	404	2.58	0.62	1	4
Number of bathrooms	404	1.63	0.62	1	3
Energy class	404	9.29	2.75	1	12
Maintenance status	404	2.61	0.71	1	4
Gross floor area	404	128.73	66.71	23	490
Value market	404	1655.44	649.88	523	4063

Table A9: Frequency analysis for the Milan dataset

Variables	Categories	n	%
Zone	Central zone	205	23.9
	Semicentral zone	221	25.8
	Suburban zone	432	50.3
Proximity to infrastructure	Up to 200 m	261	30.4
	From 201 to 500 m	510	59.4
	Over 500 m	87	10.1
Typology	Villa	0	0.0
	Apartment	858	100.0
Property class	High-end	51	5.9
	Elite	463	54.0
	Standard	279	32.5
	Low-cost	19	2.2
	Not declared	46	5.4
Number of bathrooms	Zero bathroom	1	0.1
	One bathroom	480	55.9
	Two bathrooms	293	34.1
	Three bathrooms	82	9.6
	Four bathrooms	2	0.2
Energy class	A4	7	0.8
	A3	8	0.9
	A2	12	1.4
	A1	11	1.3
	A+	6	0.7
	A	23	2.7
	B	22	2.6
	C	20	2.3
	D	85	9.9
	E	126	14.7
	F	181	21.1
	G	357	41.6
Maintenance status	Newly built	47	5.5
	Refurbished	338	39.4
	Well-maintained	354	41.3
	Run-down	109	12.7
	Not declared	10	1.2

Table A10: Frequency analysis for the Turin dataset

Variables	**Categories**	**n**	**%**
Zone	Central zone	206	27.7
	Semicentral zone	150	20.2
	Suburban zone	388	52.2
Proximity to infrastructure	Up to 200 m	129	17.3
	From 201 to 500 m	329	44.2
	Over 500 m	286	38.4
Typology	Villa	1	0.1
	Apartment	741	99.6
Property class	High-end	24	3.2
	Elite	315	42.3
	Standard	311	41.7
	Low-cost	41	5.5
	Not declared	53	7.1
Number of bathrooms	Zero bathroom	1	0.1
	One bathroom	480	64.5
	Two bathrooms	229	30.8
	Three bathrooms	31	4.2
	Four bathrooms	3	0.4
	Five bathrooms	1	0.1
Energy class	A4	5	0.7
	A3	1	0.1
	A2	1	0.1
	A1	12	1.6
	A+	3	0.4
	A	19	2.6
	B	25	3.4
	C	51	6.9
	D	123	16.5
	E	170	22.8
	F	138	18.5
	G	196	26.3
Maintenance status	Newly built	30	4.0
	Refurbished	245	32.9
	Well-maintained	355	47.7
	Run-down	101	13.6
	Not declared	13	1.7

Table A11: Frequency analysis for the Florence dataset

Variables	Categories	n	%
Zone	Central zone	89	22.6
	Semicentral zone	179	45.4
	Suburban zone	126	32.0
Proximity to infrastructure	Up to 200 m	151	38.3
	From 201 to 500 m	125	21.7
	Over 500 m	118	29.9
Typology	Villa	0	0.0
	Apartment	394	100.0
Property class	High-end	8	2.0
	Elite	116	29.4
	Standard	211	53.6
	Low-cost	42	10.7
	Not declared	17	4.3
Number of bathrooms	Zero bathroom	0	0.0
	One bathroom	264	67.0
	Two bathrooms	115	29.2
	Three bathrooms	15	3.8
	Four bathrooms	0	0.0
	Five bathrooms	0	0.0
Energy class	A4	0	0.0
	A3	1	0.3
	A2	1	0.3
	A1	7	1.8
	A+	5	1.3
	A	4	1.0
	B	12	3.0
	C	3	0.8
	D	13	3.3
	E	30	7.6
	F	68	1.3
	G	250	65.3
Maintenance status	Newly built	20	5.1
	Refurbished	193	49.0
	Well-maintained	146	47.1
	Run-down	32	8.1
	Not declared	3	0.8

Table A12: Frequency analysis for the Trieste dataset

Variables	**Categories**	**n**	**%**
Zone	Central zone	231	47.3
	Semicentral zone	189	38.7
	Suburban zone	68	13.9
Proximity to infrastructure	Up to 200 m	0	0.0
	From 201 to 500 m	0	0.0
	Over 500 m	488	100.0
Typology	Villa	31	64
	Apartment	457	936
Property class	High-end	30	6.1
	Elite	195	40.0
	Standard	240	49.2
	Low-cost	21	4.3
	Not declared	2	0.4
Number of bathrooms	Zero bathroom	0	0.0
	One bathroom	261	53.5
	Two bathrooms	170	34.8
	Three bathrooms	57	11.7
	Four bathrooms	0	0.0
	Five bathrooms	0	0.0
Energy class	A4	22	4.5
	A3	7	1.4
	A2	9	1.8
	A1	18	3.7
	A+	8	1.6
	A	8	1.6
	B	24	4.9
	C	29	5.9
	D	54	11.1
	E	99	20.3
	F	116	23.8
	G	94	19.3
Maintenance status	Newly built	57	11.7
	Refurbished	187	38.3
	Well-maintained	209	42.8
	Run-down	35	7.2
	Not declared	0	0.0

Table A13: Frequency analysis for the Padua dataset

Variables	**Categories**	**n**	**%**
Zone	Central zone	204	58.6
	Semicentral zone	40	11.5
	Suburban zone	104	29.09
Proximity to infrastructure	Up to 200 m	125	35.9
	From 201 to 500 m	95	27.3
	Over 500 m	128	36.8
Typology	Villa	20	5.7
	Apartment	328	94.3
Property class	High-end	-	-
	Elite	-	-
	Standard	-	-
	Low-cost	-	-
	Not declared	-	-
Number of bathrooms	Zero bathroom	0	0.0
	One bathroom	3	0.9
	Two bathrooms	31	8.9
	Three bathrooms	63	18.1
	Four bathrooms	106	30.5
	Five bathrooms	145	41.7
Energy class	A4	10	2.9
	A3	1	0.3
	A2	2	0.6
	A1	6	1.7
	A+	0	0.0
	A	6	1.7
	B	6	1.7
	C	9	2.6
	D	34	9.8
	E	66	19.0
	F	90	25.9
	G	118	33.9
Maintenance status	Newly built	24	6.9
	Refurbished	97	27.9
	Well-maintained	176	50.6
	Run-down	36	10.3
	Not declared	15	4.3

Table A14: Frequency analysis for the Mestre dataset

Variables	**Categories**	**n**	**%**
Zone	Central zone	152	61.8
	Semicentral zone	44	17.9
	Suburban zone	50	20.3
Proximity to infrastructure	Up to 200 m	100	40.7
	From 201 to 500 m	80	32.5
	Over 500 m	66	26.8
Typology	Villa	2	0.8
	Apartment	244	99.2
Property class	High-end	-	-
	Elite	-	-
	Standard	-	-
	Low-cost	-	-
	Not declared	-	-
Number of bathrooms	Zero bathroom	2	0.8
	One bathroom	157	63.8
	Two bathrooms	85	34.6
	Three bathrooms	2	0.8
	Four bathrooms	0	0.0
	Five bathrooms	0	0.0
Energy class	A4	11	4.5
	A3	1	0.4
	A2	1	0.4
	A1	2	0.8
	A+	3	1.6
	A	2	0.8
	B	4	1.6
	C	7	2.8
	D	18	7.3
	E	31	12.6
	F	70	28.5
	G	95	38.6
Maintenance status	Newly built	20	8.1
	Refurbished	86	35.0
	Well-maintained	125	50.8
	Run-down	7	2.8
	Not declared	8	3.3

Table A15: Frequency analysis for the Bergamo dataset

Variables	Categories	n	%
Zone	Central zone	148	51.9
	Semicentral zone	38	13.3
	Suburban zone	99	34.7
Proximity to infrastructure	Up to 200 m	58	20.4
	From 201 to 500 m	120	42.1
	Over 500 m	107	37.5
Typology	Villa	8	2.8
	Apartment	277	97.2
Property class	High-end	-	-
	Elite	-	-
	Standard	-	-
	Low-cost	-	-
	Not declared	-	-
Number of bathrooms	Zero bathroom	0	0.0
	One bathroom	172	60.4
	Two bathrooms	102	35.8
	Three bathrooms	11	3.9
	Four bathrooms	0	0.0
	Five bathrooms	0	0.0
Energy class	A4	3	1.1
	A3	3	1.1
	A2	1	0.4
	A1	7	2.5
	A+	4	1.4
	A	8	2.8
	B	20	7.0
	C	23	8.1
	D	26	9.1
	E	52	18.2
	F	43	15.1
	G	95	33.3
Maintenance status	Newly built	38	13.3
	Refurbished	114	40.0
	Well-maintained	113	39.6
	Run-down	18	6.3
	Not declared	2	0.7

Table A16: Frequency analysis for the Udine dataset

Variables	Categories	n	%
Zone	Central zone	151	37.4
	Semicentral zone	160	39.6
	Suburban zone	93	23.0
Proximity to infrastructure	Up to 200 m	0	0.0
	From 201 to 500 m	0	0.0
	Over 500 m	0	0.0
Typology	Villa	24	5.9
	Apartment	380	94.1
Property class	High-end	15	3.7
	Elite	152	37.6
	Standard	222	55.0
	Low-cost	15	3.7
	Not declared	0	0.0
Number of bathrooms	Zero bathroom	0	0.0
	One bathroom	179	44.3
	Two bathrooms	193	47.8
	Three bathrooms	32	7.9
	Four bathrooms	0	0.0
	Five bathrooms	0	0.0
Energy class	A4	21	5.2
	A3	2	0.5
	A2	5	1.2
	A1	4	1.0
	A+	8	2.0
	A	4	1.0
	B	26	6.4
	C	31	7.7
	D	52	12.9
	E	91	22.5
	F	91	22.5
	G	69	17.1
Maintenance status	Newly built	31	7.7
	Refurbished	116	28.7
	Well-maintained	234	57.9
	Run-down	23	5.7
	Not declared	0	0.0

8.2. Case study Energiesprong France

ID-1

City and Region: Hem, Hauts-de-France

Delivery Date and Duration of Works: 2018, 4 months

Building Type: Individual social housing

Client (MOA): Vilogia

Project Size: 10 houses; 840 m² SHAB

Project Cost: €1.25 million

Energy Performance: from 315 kWhep/m2.an to 77 kWhep/m2.an; PV production: 5,1 MWh

Project Consortium: Architect: Red Cat Architecture; General Contractor: Rabot Dutilleul Construction; Engineering Offices: Symoe and Nortec; Operations Company: Pouchain

ID-2

City and Region: Longueau, Hauts-de-France

Delivery Date and Duration of Works: 2018, 9 months

Building Type: Individual social housing

Client (MOA): ICF Habitat

Project Size: 12 houses; 984 m² SHAB

Project Cost: €1.84 million

Energy Performance: from 289 kWhep/m2.an to -64 kWhep/m2.an; annual PV production: 8.7 MWh

Project Consortium: Lead Contractor: Bouygues Bâtiment Grand Ouest; Architect: Ranson Bernier Architecture Studio; AMO (Assistance to Owner): Pouget Consultants; Technical Equipment and Maintenance Contractor: Dalkia; Multidisciplinary Engineering (TCE): Alterea

ID-3

City and Region: Châteaugiron, Brittany

Delivery Date and Duration of Works: 2019, 3 months

Building Type: Individual social housing

Client (MOA): Néotoa

Project Size: 4 houses; 244 m² SHAB

Project Cost: 460,000

Energy Performance: Energy consumption reduced from 43,764,00 kWhep/m2.an to 18,000 kWhep/m2.an; annual PV production: 6.8 MWh

Project Consortium: Architecture: Quinze Architecture; Energy Engineering: Élogia; Thermal Engineering: Hinoki; Contractors: Sylvestre Énergies, Euro Énergie

ID-4

City and Region: Vaulx-en-Velin, Auvergne–Rhône-Alpes

Delivery Date and Duration of Works: 2022, 19 months

Building Type: Collective social housing

Client (MOA): Est Métropole Habitat

Project Size: 998 apartments; 65,587 m^2 SHAB

Project Cost: €24 million

Energy Performance: Energy consumption reduced from 215 kWhep/m2.an to 90 kWhep/m2.an

Project Consortium: AMO: VOXOA; Design Team / Lead Architects: C&Associés, ITAQUES, Atelier 127, WRA; Main Contractor: Citinea (Arbinos, Vinci Construction France subsidiary)

ID-5

City and Region: Hem, Hauts-de-France

Delivery Date and Duration of Works: 2018, 4 months

Building Type: Individual social housing

Client (MOA): Vilogia

Project Size: 160 houses; 13,000 m^2 SHAB

Project Cost: €17.2 million

Energy Performance: Energy consumption reduced from 25 MWh to 5 MWh; PV production over 2 years: 5 MWh

Project Consortium: Architect: Red Cat Architecture; General Contractor: Rabot Dutilleul Construction; Engineering Offices: Symoe, Nortec; Operations Company: Pouchain

ID-6

City and Region: Saint-Jean-de-Védas, Occitanie

Delivery Date and Duration of Works: 2022, 7 months

Building Type: Educational building

Client (MOA): City of Saint-Jean-de-Védas

Project Size: 1 building; 1,500 m^2 SHAB

Project Cost: €1.6 million

Energy Performance: Energy consumption reduced from 165,655 kWh to 45,477 kWh

Project Consortium: Sogea–Vinci Construction, Alabision Ingénierie, Auditori Home, MBI, PFS

ID-7

City and Region: Hangers, Pays de la Loire

Delivery Date: 2022

Building Type: Individual social housing

Client (MOA): Podeliha

Project Size: 32 houses; 2,800 m² SHAB

Project Cost: €3.6 million

Energy Performance: from D to A by scale EPC

Project Consortium: Lead Contractor: Bouygues Bâtiment Grand Ouest; Architect: Johanne San; Engineering Offices: Flides, Pouget Consultants; Energy Awareness & Support: Alisée

ID-8

City and Region: Raismes, Hauts-de-France

Delivery Date and Duration of Works: 2023, 10 mon.

Building Type: Individual social housing

Client (MOA): City of Raismes

Project Size: 1 building; 1,962 m² SHAB

Project Cost: €6.9 million

Energy Performance: from F to energy efficienc

Project Consortium: Nortec SAS, Concept Développement, HDF Construction, Les Murs ont des Plumes, MRB

ID-9

City and Region: Toulouse, Occitaniee

Delivery Date: 2023

Building Type: Student collective housing

Client (MOA): Garonne Développement – Les Chalets

Project Size: 254 apartments; 6,000 m² SHAB

Project Cost: €9.6 million

Energy Performance: from F to energy efficienc

Project Consortium: Biotope (Engineering Office), Bourdarios (General Contractor), Agtherm (Heating Systems Contractor)

ID-10

City and Region: Montmélian, Auvergne–Rhône-Alpes

Delivery Date: 2023

Building Type: Collective social housing

Client (MOA): OPAC Savoie

Project Size: 99 apartments; 6,200 m² SHAB

Project Cost: €11.5 million

Energy Performance: Energy consumption reduced from 236 kWh to 52 kWh

Project Consortium: AMO 35 Concept; Lead Contractor: Campenon Bernard Dauphiné Savoie; Clement & Associés; Impulse; Supplier: Panobloc (prefabricated façade panels)

ID-11

City and Region: Saint Denis, Île-de-France

Delivery Date: 2024

Building Type: Educational building

Client (MOA): Université Paris 8

Project Size: 1 building; 4,850 m²

Project Cost: €4.9 million

Energy Performance: Energy consumption reduced from 806 kWh to 16 kWh

Project Consortium: Alteresco (AMO); Altyn; Méandre; Lecity; Prochalor; Floret Scheide Architectes

ID-12

City and Region: Le Mans, Pays de la Loire

Delivery Date and Duration of Works: 2024, 18 mon.

Building Type:

Client (MOA): MASH Sarthe Habitat

Project Size: 251 apartments; 15,520 m²

Project Cost: €21 million

Energy Performance: from E to B by scale EPC

Project Consortium: Altyn (Lead Contractor/AMO); Alterea; Floret Scheide Architectes; Façadebois (wood façades); Ossabois (prefabricated façades)

ID-13

City and Region: Maine-et-Loire and Sarthe

Delivery Date: 2024

Building Type: Individual social housing

Client (MOA): MASH Maine-et-Loire Habitat

Project Size: 296 houses

Project Cost: approx. €32 million

Energy Performance: from E/F/G to A/B by scale EPC

Project Consortium: Sogea; Bouygues Construction; Pouget Consultants; Johanne San (Architect)

ID-14

City and Region: Chambéry, Auvergne–Rhône-Alpes

Delivery Date and Duration of Works: 2024, 18 mon.

Building Type: Collective social housing

Client (MOA): Cristal Habitat

Project Size: 244 apartments; 25,200 m² SHAB

Project Cost: €32 million

Energy Performance: Energy consumption reduced from 257 kWhep/m2.an to 87 kWhep/m2.an

Project Consortium: Grouping of Citinea (Villeurbanne), Campenon Bernard Dauphiné Savoie (Annecy), Nepsen Ginger Deleo; Architects: Typo (Chambéry), Atelier des Vergers (Saint-Étienne); Prefabricated timber façades manufactured in Jura by Charm Ossature

ID-15

City and Region: Halluin, Hauts-de-France

Delivery Date and Duration of Works: 2024, 12 mon.

Building Type: Collective social housing

Client (MOA): 3F Notre Logis

Project Size: 80 apartments, of which 40 retrofit

Project Cost: €9.79 million (including €6 million for Energiesprong retrofitting)

Energy Performance: from F to A by scale EPC

Project Consortium: RedCat Architecture; Nortec; Symoe; Bélencontre; Contractors: Tomasini Construction, Dumont Énergie, Emenda

ID-16

City and Region: Brétigny-sur-Orge, Île-de-France

Delivery Date: 2023

Building Type: Individual social housing

Client (MOA): Immobilière 3F

Project Size: 16 houses; 1,250 m² SHAB

Project Cost: €1.7 million

Energy Performance: from energy inefficient to energy efficient

Project Consortium: AMO Alterea

ID-17

City and Region: Saint-Haon-le-Châtel & Villerest, Auvergne–Rhône-Alpes

Delivery Date and Duration of Works: 2024, 12 mon.

Building Type: Collective social housing

Client (MOA): OPHEOR

Project Size: 16 houses ; 1,250 m² SHAB

Project Cost: €1.12 million

Energy Performance: from F to A by scale EPC

Project Consortium: AMO Alterea

ID-18

City and Region: Lille, Hauts-de-France

Delivery Date and Duration of Works: 2023–25, 18 m.

Building Type: Educational buildings

Client (MOA): City of Lille

Project Size: 2 school buildings; 9,000 m²

Project Cost: €14 million

Energy Performance: from energy inefficient to energy efficient

Project Consortium: Energelio; Equans; Dujardin Vincent; SAS Maning; Energiesprong France; FACE B; Build Up

ID-19

City and Region: Pays de la Loire

Delivery Date and Duration of Works: 2025, 24 mon.

Building Type: Individual social housing

Client (MOA): MASH – Maine-et-Loire Habitat, Prodeliha, Mancelle d'Habitation

Project Size: 446 houses

Project Cost: €40 million

Energy Performance: from energy inefficient to energy efficient

Project Consortium: E-lof; Project Management: Cabinet d'Architecture Triede; Engineering: NRGYS; Grouping Agir Synerprod (Lead), Triede NRGYS Green Yellow

ID-20

City and Region: Pays de la Loire

Delivery Date: 2025

Building Type: Collective social housing

Client (MOA): MASH – Nantes Métropole Habitat, Habitat 44, Sarthe Habitat, Atlantique Habitation CDC

Project Size: 551 apartments

Project Cost: Not disclosed

Energy Performance: from energy inefficient to energy efficient

Project Consortium: Alterea; Lead Contractor: ALTYN

ID-21

City and Region: Hem, Roubaix, and Croix, Hauts-de-France

Delivery Date and Duration of Works: 2025, 9 months

Building Type: Individual social housing

Client (MOA): Vilogia, represented by GIE Septalia

Project Size: 207 houses; 16,150 m^2 SHAB

Project Cost: €28.8 million

Energy Performance: from E to B by scale EPC

Project Consortium: Project Management: Atelier MA; General Contractor Lead: Bouygues Bâtiment Nord-Est; Nortec; Symoe; AMO Design Phase: Alterea; Commissioner: VOE

ID-22

City and Region: Palaiseau, Île-de-France

Delivery Date: 2025

Building Type: Educational buildings

Client (MOA): City of Palaiseau

Project Size: 6 buildings

Project Cost: €7 million

Energy Performance: from energy inefficient to energy efficient

Project Consortium: Bouygues Bâtiment Île-de-France; ENIA Architects

ID-23

City and Region: Ramonville, Occitanie

Delivery Date: 2025

Building Type: Collective social housing

Client (MOA): Garonne

Project Size: 137 apartments, 7 buildings; 11,760 m²

Project Cost: Not known

Energy Performance: from E/D to A by scale EPC

ID-24
City and Region: Île-de-France
Delivery Date: 2025
Building Type: Collective social housing
Client (MOA): Seine-Saint-Denis Habitat
Project Size: 32 apartments
Energy Performance: from energy inefficient to energy efficient
Project Consortium: AMO Setec; Emenda; Komorebi

ID-25
City and Region: Auvergne-Rhône-Alpes
Delivery Date: 2026
Building Type: Individual social housing
Client (MOA): Grand Lyon Habitat
Project Size: 17 houses; 1,700 m² SHAB
Energy Performance: from G to A by scale EPC
Project Consortium: Not known

ID-26

City and Region: Marcq-en-Barœul, Hauts-de-France

Delivery Date: 2026

Building Type: Educational building

Client (MOA): City of Marcq-en-Barœul

Project Size: 1 building; 11,500 m² SHAB

Project Cost: Not known

Energy Performance: from energy inefficient to energy efficient

ID-27

City and Region: Lille, Hauts-de-France

Delivery Date: 2025

Building Type: Educational building

Client (MOA): City of Lille

Project Size: 1 building; 1,850 m² SHAB

Project Cost: €1,950,000

Energy Performance: from energy inefficient to energy efficient

ID-28

City and Region: Lompret, Hauts-de-France

Delivery Date: 2022-2024

Building Type: Educational building

Client (MOA): Municipality of Lompret

Project Size: 1 building; 1,123 m² SHAB

Project Cost: €3,250,000

Energy Performance: from energy inefficient to energy efficient

Project Consortium: ALT174; design and engineering by Sébastien Cellier, Projex Ingénierie

ID-29

City and Region: Bretegnolles, Centre-Val de Loire

Delivery Date and Duration of Works: 2025, 14 month

Building Type: Collective social housing

Client (MOA): Habitat 44

Project Size: 72 dwellings; 5,547 m² SHAB

Project Cost: €8,303,400

Energy Performance: from energy-inefficient to energy-efficient

Project Consortium: Project Management: Atelier MA; General Contractor Lead: Bouygues Bâtiment Nord-Est; Nortec; Symoe; AMO Design Phase: Alterea; Commissioner: VOE

ID-30

City and Region: Nantes, Pays de la Loire

Delivery Date: 2025

Building Type: Collective social housing

Client (MOA): Not specified

Project Size: 88 dwellings; 6,779 m² SHAB

Project Cost: €6,366,000

Energy Performance: from energy inefficient to energy efficient

ID-31

City and Region: Pluvigner, Bretagne

Delivery Date: 2025

Building Type: Collective social housing

Client (MOA): Not specified

Project Size: 44 dwellings; 3,390 m² SHAB

Project Cost: €1,900,000

Energy Performance: from energy-inefficient to energy-efficient

ID-32

City and Region: Saint-Herblain, Pays de la Loire

Delivery Date: 2024

Building Type: Collective social housing

Client (MOA): Alteresco, in partnership with four social housing providers: Atlantique

Project Size: 46 dwellings; 3,310 m² SHAB

Project Cost: €5,770,133

Energy Performance: from energy-inefficient to energy-efficient

Project Consortium: Architects Floret-Scheide

8.3. Off-site energy renovation housing questionnaire

The survey was distributed to 71 individuals, primarily MOEs involved in Energiesprong projects conducted in France. The questionnaire was created and administered via Google Forms and was accompanied by an introductory e-mail presenting the research, explaining the questionnaire structure, and outlining the objectives of the study.

It was organized into 6 sections comprising a total of 34 questions. For participants with experience in multiple projects, the questionnaire automatically generated additional sections (from Section 8 onwards), allowing the documentation of up to 14 projects in total.

The purpose of the survey was to collect detailed information on the characteristics of projects implemented with the Energiesprong approach, with a particular focus on cost-related aspects. Respondents were invited to report on projects that were either completed or still in progress, beginning with the most important or representative one.

Section 1: Respondent information

1. Name of your company: [.....]
2. Type of company:
    - ○ Housing provider
    - ○ Architect
    - ○ Solution provider
3. Do you wish your name or your company's name to be mentioned in the doctoral thesis and in other scientific publications related to this study?
    - ○ Yes
    - ○ No

Section 2: Role and project information

Please describe the energy renovation projects carried out with Energiesprong. If you have carried out multiple projects, please fill out one questionnaire per project. Start with the most important project.

4. Project name: [.....]
5. Project location: [.....]
6. Project start year: [.....]
7. Project completion year: [.....]
8. What was your company's role in the selected Energiesprong project?
   - ○ General contractor (MOE globale)
   - ○ Technical project management (installations, structures, etc.)
   - ○ Construction management
   - ○ Site coordination
   - ○ Architect
   - ○ Lead contractor
   - ○ Engineering consultancy
   - ○ Operations company
   - ○ Client (Maître d'Ouvrage)
   - ○ AMO (Assistant to project owner)
   - ○ Multi-disciplinary design office
   - ○ Heating company

Section 3: Scale and type of intervention

9. What type of building was involved?
   - ○ Single-family homes
   - ○ Multi-family housing
   - ○ Student residence
10. Number of buildings concerned (indicate per type): [.....]
11. Total intervention surface area (m^2): [.....]
12. Number of dwellings (per type): [.....]
13. Average surface per dwelling (m^2): [.....]
14. Project timeline (from design to delivery):
    - ○ Design: _____ months
    - ○ Construction: _____ months

○ Assembly per dwelling: _____ days/dwelling

15. Did the project experience delays compared to the planned schedule? If yes, what were the causes?indicate:
    ○ Duration of delay: _____ months
16. What degree of industrialization was applied?
    ○ None
    ○ Partial (e.g., façades)
    ○ Full (façades, roof, installations, etc.)
17. Was the end user (tenant or owner) involved? If yes – at which stages?
    ○ Envelope and system choices
    ○ System choices only
    ○ Interior layout
    ○ Furniture / usage solutions
    ○ Household appliances (washing machine, fridge, electric hob, etc.)

Section 4: Overall intervention costs

18. Total intervention cost (including design, construction, overheads):
    ○ €/total: __________
    ○ €/m²: __________
    ○ €/per dwelling: __________
19. Construction cost only (*hard costs*):
    ○ €/m²: __________
    ○ €/per dwelling: __________
    ○ Electrical grid adaptation: __________
20. Share of costs by category (% of total construction cost):
    ○ Prefabricated insulated façades: _____ %
    ○ Insulated roof + PV: _____ %
    ○ Technical systems (ventilation, heating, DHW): _____ %
    ○ Interior finishes / comfort: _____ %
    ○ Structural adaptations / site works: _____ %

- Connections / infrastructures: _____ %

21. Share of indirect costs (*soft costs*) (% of total construction cost):
    - Design: _____ %
    - Construction management: _____ %
    - Safety (SPS): _____ %
    - Permits and procedures: _____ %
    - Technical fees: _____ %
    - Financial costs: _____ %
    - Contingencies: _____ %
22. Did costs increase compared to initial forecasts?
    - If yes, what factors caused the increase?
    - If yes, by how much (in % compared to planned cost of each component)? (e.g., +10% compared to forecast material costs)

Section 5: Observed reductions (past projects)

23. In which categories have you observed reductions compared to earlier Energiesprong projects (if you participated in multiple projects)?
    - Design – Reduction: _____ %
    - Construction management – Reduction: _____ %
    - Civil works – Reduction: _____ %
    - Façades – Reduction: _____ %
    - Roof / Renewables – Reduction: _____ %
    - Installations – Reduction: _____ %
    - Specific components – Reduction: _____ %
    - Insulation materials – Reduction: _____ %
    - Logistics / timelines – Reduction: _____ %
    - Other: ______________ – Reduction: _____ %
24. What were the main causes of observed reductions?
    - Team experience
    - Component standardization

- ○ Serial production / economies of scale
- ○ Reduction in system costs
- ○ Reduction in material costs
- ○ Reduction in equipment costs
- ○ Joint procurement by several clients
- ○ Industrial collaboration

25. Do you foresee further cost reductions in the future?
    - ○ Yes
    - ○ No
26. In your experience, which components are most suitable for standardization in future projects?
    - ○ Façades
    - ○ Roofs / Renewables
    - ○ Control / automation solutions
    - ○ BIM coordination
    - ○ Installations
    - ○ Specific components
    - ○ Design
    - ○ Assembly time
    - ○ Design–construction integration
27. Estimated reductions. For each relevant element, indicate the name and the expected percentage reduction.

    Element: __________ – Expected reduction: _____ %
28. Necessary conditions for achieving these reductions:
    - ○ Greater serial production
    - ○ Off-site production
    - ○ Multiple markets / framework contracts
    - ○ Public policy support
    - ○ Industrial partnerships

Section 6: Market analysis

29. Market / rental value before renovation:
    - ○ €/m² (sale): __________
    - ○ €/m²/month (rent): __________
    - ○ Increase in value after intervention (%): __________ %
30. Factors explaining the value increase (distribution in %, total = 100%):
    - ○ Overall appreciation of the property: _____ %
    - ○ Perceived energy savings: _____ %
    - ○ Other): __________________________ : _____ %
31. Average annual energy expenditure per dwelling BEFORE renovation:
    - ○ Electricity bill: __________ €/year
    - ○ Gas bill: __________ €/year
    - ○ Other: __________ €/year
32. Average annual energy expenditure per dwelling AFTER renovation:
    - ○ Electricity bill: __________ €/year
    - ○ Gas bill: __________ €/year
33. Have you received public subsidies?
    - ○ Reduced interest rate
    - ○ Equipment financing
    - ○ Public subsidies
    - ○ European funds
    - ○ National calls for projects
    - ○ Other: __________
34. Private or bank financing?
    - ○ Yes – Percentage: _____ %
    - ○ Use: _______________

REFERENCES

1. Calvin K, Dasgupta D, Krinner G, Mukherji A, Thorne PW, Trisos C, et al. IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. First. Geneva: Intergovernmental Panel on Climate Change (IPCC); 2023 lug. Disponibile su: https://www.ipcc.ch/report/ar6/syr/
2. United Nations. The 17 Goals Sustainable Development. 2024. Disponibile su: https://sdgs.un.org/goals
3. IEA. World Energy Outlook 2024. Paris; 2024 ott. Disponibile su: https://www.iea.org/reports/world-energy-outlook-2024
4. GlobalABC. Globalabc Annual Narrative Report. 2022. Disponibile su: https://globalabc.org/index.php/resources/publications/2021-globalabc-annual-narrative-report
5. European Commission. REfurbishment decision making platform through advanced technologies for near Zero energy BUILDing renovation. 2024. Disponibile su: https://cordis.europa.eu/project/id/768623/reporting
6. UNEP - United Nations Environment Programme. Global Status Report for Buildings and Construction: Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector. Nairobi; 2021. Disponibile su: https://globalabc.org/
7. Commissione europea. Direttiva del Parlamento Europeo e del Consiglio 2002/91/CE del 16 dicembre 2002 sul rendimento energetico nell'edilizia. 2002/91/CE dicembre, 2002.
8. Parlamento Europeo, Consiglio dell'Unione europea. Direttiva 2010/31/UE sulla prestazione energetica nell'edilizia. Gazzetta ufficiale dell'Unione europea maggio, 2010.
9. European Parliament, Council of the European Union. Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency. 2018/844 2018. Disponibile su: http://data.europa.eu/eli/dir/2018/844/oj
10. European Commission. Proposal for a Directive of the European Parliament and of the Council on the energy performance of building (recast). 2021/0426(COD), COM(2021)802 dic, 2021. Disponibile su: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52021PC0802
11. Urban Land Institute (ULI). Emerging Trends in Real Estate in the eye of the storm. 2023. Disponibile su: https://knowledge.uli.org/en/reports/emerging-trends/2023/emerging-trends-in-real-estate-europe
12. Boland B, Levy C, Palter R, Stephens D. Climate risk and the opportunity for real estate. McKinsey & Company. 2022;1–8.
13. Aydin E, Brounen D, Kok N. The capitalization of energy efficiency: Evidence from the housing market. Journal of Urban Economics. maggio 2020;117:103243.
14. Eichholtz P, Kok N, Quigley JM. The Economics of Green Building. The Review of Economics and Statistics. 2013;95(1):50–63.
15. Fuerst F, McAllister P, Nanda A, Wyatt P. Energy performance ratings and house prices in Wales: An empirical study. Energy Policy. maggio 2016;92:20–33.
16. Ngwakwe CC. Environmental and economic benefits of compliance to green building. IJGE. 2019;13(3/4):288.
17. Ries R, Bilec MM, Gokhan NM, Needy KL. The Economic Benefits of Green Buildings: A Comprehensive Case Study. The Engineering Economist. 2006;51(3):259–95.

18. Dell'Anna F, Bottero M. Green premium in buildings: Evidence from the real estate market of Singapore. Journal of Cleaner Production. 2021;286:125327.
19. Leskinen N, Vimpari J, Junnila S. A Review of the Impact of Green Building Certification on the Cash Flows and Values of Commercial Properties. Sustainability. gennaio 2020;12(7):2729.
20. Eichholtz P, Kok N, Quigley JM. Doing Well by Doing Good? Green Office Buildings. The American Economic Review. 2010;100(5):2492–509.
21. Addae-Dapaah K, Wilkinson J. Green Premium: What is the Implied Prognosis for Sustainability? Journal of Sustainable Real Estate. 2020;12(1):16–33.
22. Neumann U, Taruttis L. Sorting in an urban housing market—is there a response to demographic change? Rev Reg Res. 2022;42(2):111–39.
23. Baden-Fuller C, Haefliger S. Business Models and Technological Innovation. Long Range Planning. 2013;46(6):419–26.
24. Bidmon CM, Knab SF. The three roles of business models in societal transitions: New linkages between business model and transition research. Journal of Cleaner Production. 2018;178:903–16.
25. Boons F, Lüdeke-Freund F. Business models for sustainable innovation: state-of-the-art and steps towards a research agenda. Journal of Cleaner Production. 2013;45:9–19.
26. European Commission. Communication from the commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the regions. A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives. COM/2020/662 2020.
27. Cluett R, Amann J. Multiple Benefits of Multifamily Energy Efficiency for Cost-Effectiveness Screening. American Council for an Energy-Efficient Economy; 2015.
28. Lafond F, Bailey AG, Bakker JD, Rebois D, Zadourian R, McSharry P, et al. How well do experience curves predict technological progress? A method for making distributional forecasts. Technological Forecasting and Social Change. 2018;128:104–17.
29. Moschetti R, Brattebø H. Sustainable Business Models for Deep Energy Retrofitting of Buildings: State-of-the-art and Methodological Approach. Energy Procedia. 2016;96:435–45.
30. EnergieSprong. Transition Zero. 2015. Disponibile su: https://cdn.prod.website-files.com/59944999990f53000134107e/5bc8766a33d973180b34d58c_ESUK-Transition_Zero_document.pdf
31. Energiesprong. Homepage Energiesprong. 2025. Disponibile su: https://energiesprong.org/
32. Morano P, Tajani F, Di Liddo F, Amoruso P. A Feasibility Analysis of Energy Retrofit Initiatives Aimed at the Existing Property Assets Decarbonisation. Sustainability. 2024;16(8):3204.
33. Streicher KN, Mennel S, Chambers J, Parra D, Patel MK. Cost-effectiveness of large-scale deep energy retrofit packages for residential buildings under different economic assessment approaches. Energy and Buildings. 2020;215:109870.
34. Bragolusi P, D'Alpaos C. The valuation of buildings energy retrofitting: A multiple-criteria approach to reconcile cost-benefit trade-offs and energy savings. Applied Energy. 2022;310:118431.
35. Kerr N, Gouldson A, Barrett J. The rationale for energy efficiency policy: Assessing the recognition of the multiple benefits of energy efficiency retrofit policy. Energy Policy. 1 luglio 2017;106:212–21.
36. Rosenow J, Eyre N. A post mortem of the Green Deal: Austerity, energy efficiency, and failure in British energy policy. Energy Research & Social Science. 1 novembre 2016;21:141–4.
37. De La Tour A, Glachant M, Ménière Y. Predicting the costs of photovoltaic solar modules in 2020 using experience curve models. Energy. 1 dicembre 2013;62:341–8.
38. Delpont S. Industrialisation de la rénovation énergétique. Annales des Mines - Réalités industrielles. 6 maggio 2022;2022:35–8.

39. EnergieSprong France. Observatoire Coûts, Qualité et Impact des rénovations EnergieSprong. 2021. (Baromètre de l'Observatoire).
40. Cajias M, Piazolo D. Green performs better: Energy efficiency and financial return on buildings. Journal of Corporate Real Estate. 2013;15(1):53–72.
41. Cerin P, Hassel LG, Semenova N. Energy Performance and Housing Prices. Sustainable Development. 2014;22(6):404–19.
42. Copiello S, Donati E. Is investing in energy efficiency worth it? Evidence for substantial price premiums but limited profitability in the housing sector. Energy and Buildings. novembre 2021;251:111371.
43. Zhang L, Wu J, Liu H. Turning green into gold: A review on the economics of green buildings. Journal of Cleaner Production. 20 gennaio 2018;172:2234–45.
44. Fizaine F, Voye P, Baumont C. Does the Literature Support a High Willingness to Pay for Green Label Buildings? An Answer with Treatment of Publication Bias. In: Revue d'économie politique. Dalloz; 2018. p. 1013–46. Disponibile su: https://shs.cairn.info/revue-d-economie-politique-2018-5-page-1013
45. Krawchenko TA, Gordon M. How Do We Manage a Just Transition? A Comparative Review of National and Regional Just Transition Initiatives. Sustainability. gennaio 2021;13(11):6070.
46. Wang X, Lo K. Just transition: A conceptual review. Energy Research & Social Science. 1 dicembre 2021;82:102291.
47. Geels FW, Schot J. Typology of sociotechnical transition pathways. Research policy. 2007;36(3):399–417.
48. Kieft AC, Harmsen R, van Laerhoven FSJ, Hekkert MP. Innovatie in de woningbouw. Een innovatiesysteemanalyse. 2013;
49. Brown D. Business models for residential retrofit in the UK: a critical assessment of five key archetypes. Energy Efficiency. 1 agosto 2018;11(6):1497–517.
50. Mao C, Shen Q, Pan W, Ye K. Major barriers to off-site construction: The developer's perspective in China. Journal of management in engineering. 2015;31(3):04014043.
51. Pan W, Sidwell R. Demystifying the cost barriers to offsite construction in the UK. Construction management and economics. 2011;29(11):1081–99.
52. Junginger M, de Visser E, Hjort-Gregersen K, Koornneef J, Raven R, Faaij A, et al. Technological learning in bioenergy systems. Energy policy. 2006;34(18):4024–41.
53. Del Giudice V, Massimo DE, Salvo F, De Paola P, De Ruggiero M, Musolino M. Market Price Premium for Green Buildings: A Review of Empirical Evidence. Case Study. In: Bevilacqua C, Calabrò F, Della Spina L, curatori. New Metropolitan Perspectives. Cham: Springer International Publishing; 2021. p. 1237–47. (Smart Innovation, Systems and Technologies).
54. Frank RH, Cartwright E. Microeconomics and behavior. Vol. 8. McGraw-Hill New York; 2010.
55. Rodríguez-Pose A, Bartalucci F. The green transition and its potential territorial discontents. Cambridge Journal of Regions, Economy and Society. 18 novembre 2023;
56. Porter ME. Competitive advantage. New York. 1985;13.
57. Brookes L. Energy efficiency fallacies revisited. Energy policy. 2000;28(6–7):355–66.
58. Howden-Chapman P, Viggers H, Chapman R, O'Sullivan K, Barnard LT, Lloyd B. Tackling cold housing and fuel poverty in New Zealand: A review of policies, research, and health impacts. Energy policy. 2012;49:134–42.
59. Addae-Dapaah K, Chieh SJ. Green mark certification: does the market understand? Journal of Sustainable Real Estate. 2011;3(1):162–91.
60. Coyne B, Denny E. Mind the Energy Performance Gap: testing the accuracy of building Energy Performance Certificates in Ireland. Energy Efficiency. agosto 2021;14(6):57.

61. Department of Building Economics, University of Moratuwa, Rajithan M, Soorige D, Department of Building Economics, University of Moratuwa, Amarasinghe SDIA, Department of Building Economics, University of Moratuwa. ANALYSING THE GAP BETWEEN PREDICTED AND ACTUAL OPERATIONAL ENERGY CONSUMPTION IN BUILDINGS: A REVIEW. In: Proceedings of the 9th World Construction Symposium 2021 on Reshaping construction: Strategic, Structural and Cultural Transformations towards the «Next Normal». The Ceylon Institute of Builders - Sri Lanka; 2021. p. 63–74. Disponibile su: http://dl.lib.uom.lk/handle/123/16551
62. Konar S, Cohen MA. Does the Market Value Environmental Performance? Review of Economics and Statistics. maggio 2001;83(2):281–9.
63. Copiello S. Building energy efficiency: A research branch made of paradoxes. Renewable and Sustainable Energy Reviews. 1 marzo 2017;69:1064–76.
64. Ou Y, Bailey N, McArthur DP, Zhao Q. The price premium of residential energy performance certificates: A scoping review of the European literature. Energy and Buildings. 1 aprile 2025;332:115377.
65. Fregonara E, Rubino I. Buildings' energy performance, green attributes and real estate prices: Methodological perspectives from the European literature. Aestimum. 2021;79:43–73.
66. Cespedes-Lopez MF, Mora-Garcia RT, Perez-Sanchez VR, Perez-Sanchez JC. Meta-analysis of price premiums in housing with energy performance certificates (EPC). Sustainability. 2019;11(22):6303.
67. Tricco AC, Lillie E, Zarin W, O'Brien KK, Colquhoun H, Levac D, et al. PRISMA extension for scoping reviews (PRISMA-ScR): checklist and explanation. Annals of internal medicine. 2018;169(7):467–73.
68. Simonotti M. La segmentazione del mercato immobiliare per la stima degli immobili urbani. Aestimum. 1998; Disponibile su: https://oaj.fupress.net/index.php/ceset/article/view/6359
69. Brounen D, Kok N. On the economics of energy labels in the housing market. Journal of Environmental Economics and Management. settembre 2011;62(2):166–79.
70. Fuerst F, McAllister P, Nanda A, Wyatt P. Does energy efficiency matter to home-buyers? An investigation of EPC ratings and transaction prices in England. Energy Economics. marzo 2015;48:145–56.
71. Fuerst F, Oikarinen E, Harjunen O. Green signalling effects in the market for energy-efficient residential buildings. Applied Energy. ottobre 2016;180:560–71.
72. Cajias M, Fuerst F, Bienert S. Tearing down the information barrier: the price impacts of energy efficiency ratings for buildings in the German rental market. Energy Research & Social Science. 2019;47:177–91.
73. Fuerst F, Oikarinen E, Shimizu C, Szumilo N. Measuring "green value": An international perspective. Green Value Associates: London, UK. 2014;
74. Fuerst F, Haddad MFC, Adan H. Is there an economic case for energy-efficient dwellings in the UK private rental market? Journal of Cleaner Production. 2020;245:118642.
75. Feige A, Mcallister P, Wallbaum H. Rental price and sustainability ratings: which sustainability criteria are really paying back? Construction Management and Economics. 2013;31(4):322–34.
76. Copiello S, Gabrielli L, Micelli E. Building Industry and Energy Efficiency: A Review of Three Major Issues at Stake. In: Computational Science and its Applications – ICCSA 2021. 2021. p. 226–40. (Lecture Notes in Computer Science; vol. 12954).
77. Copiello S, Coletto S. The price premium in green buildings: A spatial autoregressive model and a multi-criteria optimization approach. Buildings. 2023;13(2):276.
78. Copiello S, Bonifaci P. Price premium for buildings energy efficiency: empirical findings from a hedonic model. Valori e valutazioni. 2015;14:5–15.

79. Fregonara E, Rolando D, Semeraro P, Vella M. The impact of Energy Performance Certificate level on house listing prices. First evidence from Italian real estate. Aestimum. 6 febbraio 2015;143-163 Pages.
80. Barreca A, Fregonara E, Rolando D. EPC Labels and Building Features: Spatial Implications over Housing Prices. Sustainability 2021, 13, 2838. s Note: MDPI stays neutral with regard to jurisdictional claims in published; 2021.
81. Fregonara E, Rolando D, Semeraro P. Energy performance certificates in the Turin real estate market. Journal of European Real Estate Research. 1 gennaio 2017;10(2):149–69.
82. Morano P, Tajani F, Di Liddo F, Guarnaccia C. The value of the energy retrofit in the Italian housing market: two case-studies compared. WSEAS Transactions on Business and Economics. 2018;15(1):249–58.
83. Morano P, Rosato P, Tajani F, Di Liddo F. An Analysis of the Energy Efficiency Impacts on the Residential Property Prices in the City of Bari (Italy). In 2020. p. 73–88.
84. Manganelli B, Morano P, Tajani F, Salvo F. Affordability Assessment of Energy-Efficient Building Construction in Italy. Sustainability. 2019;11(1):249.
85. Amecke H. The impact of energy performance certificates: A survey of German home owners. Energy policy. 2012;46:4–14.
86. Hyland M, Lyons RC, Lyons S. The value of domestic building energy efficiency — evidence from Ireland. Energy Economics. novembre 2013;40:943–52.
87. Kholodilin KA, Mense A, Michelsen C. The market value of energy efficiency in buildings and the mode of tenure. Urban Studies. 2017;54(14):3218–38.
88. Davis PT, McCord JA, McCord M, Haran M. Modelling the effect of energy performance certificate rating on property value in the Belfast housing market. International Journal of Housing Markets and Analysis. 2015;8(3):292–317.
89. De Ayala A, Galarraga I, Spadaro JV. The price of energy efficiency in the Spanish housing market. Energy Policy. luglio 2016;94:16–24.
90. Chegut A, Eichholtz P, Holtermans R, Palacios J. Energy efficiency information and valuation practices in rental housing. The Journal of Real Estate Finance and Economics. 2020;60(1):181–204.
91. Jensen OM, Hansen AR, Kragh J. Market response to the public display of energy performance rating at property sales. Energy Policy. giugno 2016;93:229–35.
92. Wahlström MH. Doing good but not that well? A dilemma for energy conserving homeowners. Energy Economics. novembre 2016;60:197–205.
93. Taltavull P, Anghel I, CIora C. Impact of energy performance on transaction prices: Evidence from the apartment market in Bucharest. Journal of European Real Estate Research. 2017;10(1):57–72.
94. de La Paz PT, Perez-Sanchez VR, Mora-Garcia RT, Perez-Sanchez JC. Green premium evidence from climatic areas: A case in Southern Europe, Alicante (Spain). Sustainability (Switzerland). 2019;11(3):1–29.
95. Marmolejo-Duarte C, Chen A. The Uneven Price Impact of Energy Efficiency Ratings on Housing Segments and Implications for Public Policy and Private Markets. Sustainability. 12 gennaio 2019;11(2):372.
96. Dell'Anna F. Spatial econometric analysis of multi-family housing prices in Turin: the heterogeneity of preferences for energy efficiency. In: International Conference on Computational Science and Its Applications. Springer; 2022. p. 211–27.
97. McCord M, Lo D, Davis PT, Hemphill L, McCord J, Haran M. A spatial analysis of EPCs in The Belfast Metropolitan Area housing market. Journal of Property Research. 2020;37(1):25–61.

98. Evangelista R, Ramalho EA, e Silva JA. On the use of hedonic regression models to measure the effect of energy efficiency on residential property transaction prices: Evidence for Portugal and selected data issues. Energy Economics. 2020;86:104699.
99. Bisello A, Antoniucci V, Marella G. Measuring the price premium of energy efficiency: A two-step analysis in the Italian housing market. Energy and Buildings. 1 febbraio 2020;208:109670.
100. Massimo D, Paola P, Musolino M, Malerba A, Del Giudice FP. Green and Gold Buildings? Detecting Real Estate Market Premium for Green Buildings through Evolutionary Polynomial Regression. Buildings. 7 maggio 2022;12:621.
101. Ruggeri A, Gabrielli L, Scarpa M, Marella G. What Is the Impact of the Energy Class on Market Value Assessments of Residential Buildings? An Analysis throughout Northern Italy Based on Extensive Data Mining and Artificial Intelligence. Buildings. 30 novembre 2023;13:2994.
102. Broekel T, Alfken C. Gone with the wind? The impact of wind turbines on tourism demand. Energy Policy. 1 novembre 2015;86:506–19.
103. Dijkstra L, Poelman H, Rodríguez-Pose A. The geography of EU discontent. Regional Studies. 2 giugno 2020;54(6):737–53.
104. Arndt C, Halikiopoulou D, Vrakopoulos C. The centre-periphery divide and attitudes towards climate change measures among Western Europeans. Environmental Politics. 16 aprile 2023;32(3):381–406.
105. Williams S, Doyon A. Justice in energy transitions. Environmental Innovation and Societal Transitions. 1 giugno 2019;31.
106. Banca d'Italia, Eurosistema, Istat. La ricchezza dei settori istituzionali in Italia 2005-2021. 2023. Disponibile su: https://www.bancaditalia.it
107. Galgoczi B. Phasing out Coal – A Just Transition Approach. SSRN Journal. 2019. Disponibile su: https://www.ssrn.com/abstract=3402876
108. Wikipedia. 2025. Zona climatica. Disponibile su: https://it.wikipedia.org/w/index.php?title=Zona_climatica&oldid=144515932
109. Presidente della Repubblica Italiana. d.P.R. n. 412 - Regolamento recante norme per la progettazione, l'installazione, l'esercizio e la manutenzione degli impianti termici degli edifici ai fini del contenimento dei consumi di energia. ago, 1993. Disponibile su: https://www.bosettiegatti.eu/info/norme/statali/1993_0412.htm
110. Micelli E, Righetto E. How do metropolitan cities evolve after the 2008/2012 crisis and the Covid-19 pandemic? An analysis from real estate market values: Come evolvono le città metropolitane dopo crisi e pandemia Covid-19? Un'analisi a partire dai valori del mercato immobiliare. Valori e Valutazioni. febbraio 2023;31:49–67.
111. Micelli E, Righetto E. The Great Concentration. Demography, Economy, Real Estate Values and the Development of Italian Metropolitan Cities. In: Giuffrida S, Trovato MR, Rosato P, Fattinnanzi E, Oppio A, Chiodo S, curatori. Science of Valuations: Natural Structures, Technological Infrastructures, Cultural Superstructures. Cham: Springer Nature Switzerland; 2024. p. 133–48. Disponibile su: DOI: 10.1007/978-3-031-53709-7_10
112. Glaeser EL. Are cities dying? Journal of economic perspectives. 1998;12(2):139–60.
113. Hall S, Burdett R, Burdett R. The SAGE Handbook of the 21st Century City. Sage; 2017. 731 p.
114. Balland PA, Jara-Figueroa C, Petralia SG, Steijn MPA, Rigby DL, Hidalgo CA. Complex economic activities concentrate in large cities. Nat Hum Behav. marzo 2020;4(3):248–54.
115. Glaeser E. Triumph of the city: How our greatest invention makes us richer, smarter, greener, healthier, and happier. New York: Penguin; 2013.

116. Bruzzone F, Cavallaro F, Nocera S. The effects of high-speed rail on accessibility and equity: Evidence from the Turin-Lyon case-study. Socio-Economic Planning Sciences. 1 febbraio 2023;85:101379.

117. Guerrieri G. Il mercato della casa. Domanda, offerta, tassazione e spesa pubblica. Roma: Carocci; 2022. 384 p.

118. ENEA. Certificazione Energetica degli Edifci Italiani. 2024. Disponibile su: https://pnpe2.enea.it/statistiche

119. Immobiliare.it. Dati dei prezzi degli immobili in Italia. 2025. Disponibile su: https://www.immobiliare.it

120. Agenzia delle Entrate. Osservatorio del Mercato Immobiliare, Banca dati delle quotazioni immobiliari. 2025. Disponibile su: http://www.agenziaentrate.gov.it

121. Parlamento Europeo, Consiglio dell'Unione europea. Regulation 2017/1369 of the European Parliament and of the Council of 4 July 2017 setting a framework for energy labelling and repealing Directive 2010/30/EU. 1369 2017. Disponibile su: http://www.bloomsburycollections.com/book/fundamental-texts-on-european-private-law-1

122. Rosen S. Hedonic Prices and Implicit Markets: Product Differentiation in Pure Competition. Journal of Political Economy. 1974;82(1):34–55.

123. Lancaster KJ. A New Approach to Consumer Theory. Journal of Political Economy. aprile 1966;74(2):132–57.

124. Dastrup SR, Zivin JG, Costa DL, Kahn ME. Understanding the Solar Home price premium: Electricity generation and "Green" social status. European Economic Review. 2012;56(5):961–73.

125. Freeman III AM. Hedonic prices, property values and measuring environmental benefits: a survey of the issues. In: Measurement in public choice. Springer; 1981. p. 13–32.

126. Malpezzi S. Hedonic Pricing Models: A Selective and Applied Review. In: Housing Economics and Public Policy: Essays in Honor of Duncan Maclennan. Oxford; 2002. p. 67–89. (Blackwell Science).

127. Bottero M, Bravi M, Dell'Anna F, Mondini G. Valutazione dell'efficienza energetica degli edifici con il metodo dei prezzi edonici: gli effetti spaziali sono rilevanti? Valori e valutazioni. 2018;(21):27–39.

128. Palmquist RB. Chapter 16 Property Value Models. In: Mler KG, Vincent JR, curatori. Handbook of Environmental Economics. Elsevier; 2005. p. 763–819. (Valuing Environmental Changes; vol. 2). Disponibile su: https://www.sciencedirect.com/science/article/pii/S1574009905020164

129. Camagni R. Principi di economia urbana e territoriale. Roma: Carocci; 2012.

130. Marcoulides KM, Raykov T. Evaluation of Variance Inflation Factors in Regression Models Using Latent Variable Modeling Methods. Educational and Psychological Measurement. 1 ottobre 2019;79(5):874–82.

131. Aroul RR, Rodriguez M. The increasing value of green for residential real estate. Journal of Sustainable Real Estate. 2017;9(1):112–30.

132. Ottensmann J, Payton S, Man J. Urban Location and Housing Prices within a Hedonic Model. Journal of Regional Analysis and Policy. 1 gennaio 2008;38.

133. Copiello S. Spatial dependence of housing values in Northeastern Italy. Cities. 2020;96:102444.

134. LeSage JP. The theory and practice of spatial econometrics. University of Toledo Toledo, Ohio. 1999;28(11):1–39.

135. Taruttis L, Weber C. Estimating the impact of energy efficiency on housing prices in Germany: Does regional disparity matter? Energy Economics. 1 gennaio 2022;105:105750.

136. JLL. Environmentally sustainable real estate attracts higher prices. 2023. Disponibile su: https://www.jll.com/en-uk/newsroom/environmentally-sustainable-real-estate-attracts-higher-prices.html

137. Rodríguez-Pose A, Bartalucci F. The green transition and its potential territorial discontents. Cambridge Journal of Regions, Economy and Society. 18 novembre 2023;
138. Marais V. The employment crisis, just transition and the universal basic income grant. In: Satgar V, curatore. The Climate Crisis: South African and Global Democratic Eco-Socialist Alternatives. Wits University Press; 2018. Disponibile su: https://www.jstor.org/stable/10.18772/22018020541
139. Azis SS, Sipan I, Sapri M, Abdul Jalil R, Mohammad IS. The effect of green envelope components on green building value. Property Management. 1 gennaio 2017;35(2):181–201.
140. Chegut A, Eichholtz P, Kok N. Supply, Demand and the Value of Green Buildings. Urban Studies. 1 gennaio 2014;51(1):22–43.
141. Bottero M, D'Alpaos C, Dell'Anna F. Boosting Investments in Buildings Energy Retrofit: The Role of Incentives. In 2019. p. 593–600.
142. Rosenow J, Eyre N. Re-energising the UK's approach to domestic energy efficiency. Eceee. 2015;281–9.
143. Mangialardo A, Micelli E. Innovation of Off-Site Constructions: Benefits for Developers and the Community in an Italian Case Study. In: Green Energy and Technology. 2020. p. 217–28.
144. Lohse R, Mørck OC, Zhivov A. Deep Energy Retrofit—Case Studies: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings; Energy in Buildings and Communities Programme; Annex 61, Subtask A. Springer Nature; 2023.
145. Nesticò A, De Mare G, Aurigemma I. Off-Site Construction. The Economic Analyses for the Energy Requalification of the Existing Buildings. In: Mondini G, Oppio A, Stanghellini S, Bottero M, Abastante F, curatori. Values and Functions for Future Cities. Cham: Springer International Publishing; 2020. p. 447–62. Disponibile su: https://doi.org/10.1007/978-3-030-23786-8_25
146. Change C on C. Reducing UK emissions: 2019 progress report to parliament. 2019 Progress Report to UK Parliament. 2019;
147. Lowe R. Technical options and strategies for decarbonizing UK housing. Building Research & Information. 2007;35(4):412–25.
148. Change CC. Net Zero The UK's contribution to stopping global warming. 2019;
149. Jin R, Gao S, Cheshmehzangi A, Aboagye-Nimo E. A holistic review of off-site construction literature published between 2008 and 2018. Journal of Cleaner Production. 20 novembre 2018;202:1202–19.
150. Zhang Z, Zou Y, Guo BHW, Dimyadi J, Davies R, Jiang L. Knowledge management for off-site construction. Automation in Construction. 1 ottobre 2024;166:105632.
151. Gupta R, Gregg M, Passmore S, Stevens G. Intent and outcomes from the Retrofit for the Future programme: Key lessons. Build Res Inf. 2015;43(4):435–51.
152. Filippidou F, Nieboer N, Visscher H. Energy efficiency measures implemented in the Dutch non-profit housing sector. Energy Build. 2016;132:107–16.
153. Gutland M, Munro K, Cant K, Kotha R, Evins R. Una *meta* -analisi del processo di progettazione schematica dei progetti di ristrutturazione profonda. Energy and Buildings. 1 dicembre 2024;324:114868.
154. Hasik V, Escott E, Bates R, Carlisle S, Faircloth B, Bilec MM. Comparative whole-building life cycle assessment of renovation and new construction. Building and Environment. 2019;161:106218.
155. Saffari M, Beagon P. Home energy retrofit: Reviewing its depth, scale of delivery, and sustainability. Energy and Buildings. 2022;269:112253.
156. Howden-Chapman P, Matheson A, Crane J, Viggers H, Cunningham M, Blakely T, et al. Effect of insulating existing houses on health inequality: cluster randomised study in the community. Bmj. 2007;334(7591):460.

157. Baborska-Narożny M, Stevenson F, Grudzińska M. Overheating in retrofitted flats: occupant practices, learning and interventions. Building Research & Information. 2017;45(1–2):40–59.

158. Tink V, Porritt S, Allinson D, Loveday D. Measuring and mitigating overheating risk in solid wall dwellings retrofitted with internal wall insulation. Building and Environment. 2018;141:247–61.

159. Doll SC, Davison EL, Painting BR. Weatherization impacts and baseline indoor environmental quality in low income single-family homes. Building and Environment. 2016;107:181–90.

160. McKinsey. McKinsey technology trends outlook 2025: The top trends in tech. McKinsey & Company; 2025. Disponibile su: https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/the-top-trends-in-tech#/

161. Goolsbee A, Syverson C. The Strange and Awful Path of Productivity in the U.S. Construction Sector. National Bureau of Economic Research; 2023.. Disponibile su: https://www.nber.org/papers/w30845

162. Oesterreich TD, Teuteberg F. Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry. Computers in Industry. 1 dicembre 2016;83:121–39.

163. Sveikauskas L, Rowe S, Mildenberger J, Price J, Young A. Productivity Growth in Construction. Journal of Construction Engineering and Management. 1 ottobre 2016;142(10):04016045.

164. Rathnayake A, Middleton C. Systematic Review of the Literature on Construction Productivity. Journal of Construction Engineering and Management. 1 giugno 2023;149(6):03123005.

165. Wuni IY, Shen GQ. Barriers to the adoption of modular integrated construction: Systematic review and meta-analysis, integrated conceptual framework, and strategies. Journal of Cleaner Production. 10 marzo 2020;249:119347.

166. Saull A, Baum A, Braesemann F. Can digital technologies speed up real estate transactions? Journal of Property Investment & Finance. 20 maggio 2020;38(4):349–61.

167. Mangialardo A, Micelli E. Off-site Retrofit to Regenerate Multi-family Homes: Evidence from Some European Experiences. In: New Metropolitan Perspectives: Local Knowledge and Innovation Dynamics Towards Territory Attractiveness Through the Implementation of Horizon/E2020/Agenda2030–Volume 2. Springer International Publishing; 2019. p. 629–36.

168. Tatum CB, Vanegas JA, Williams JM. Constructability improvement using prefabrication, preassembly, and modularization. Bureau of Engineering Research, University of Texas at Austin Austin, TX; 1987.

169. Gibb A, Isack F. Re-engineering through pre-assembly: client expectations and drivers. Building research & information. 2003;31(2):146–60.

170. Björnfot A, Sardén Y. Prefabrication: a lean strategy for value generation in construction. In: Annual Conference of the International Group for Lean Construction: 25/07/2006-27/07/2006. Catholic University of Chile, School of Engineering; 2006. p. 265–77.

171. Emmitt S, Gorse CA. Barry's Advanced Construction of Construction of Buildings (2nd ed.). Chichester, U. K.: Wiley-Blackwell; 2010 [citato 22 settembre 2025]. Disponibile su: http://eu.wiley.com

172. Blismas N, Wakefield R. Drivers, constraints and the future of offsite manufacture in Australia. Construction innovation. 2009;9(1):72–83.

173. Senaratne S, Ekanayake S. Evaluation of application of lean principles to precast concrete bridge beam production process. Journal of Architectural Engineering. 2012;18(2):94–106.

174. Brown D, Hall S, Martiskainen M, Davis ME. Conceptualising domestic energy service business models: A typology and policy recommendations. Energy Policy. 1 febbraio 2022;161:112704.

175. Teece DJ. Business Models, Business Strategy and Innovation. Long Range Planning. 1 aprile 2010;43(2):172–94.

176. Boons F, Montalvo C, Quist J, Wagner M. Sustainable innovation, business models and economic performance: an overview. Journal of Cleaner Production. 2013;45:1–8.

177. Roome N, Louche C. Journeying toward business models for sustainability: A conceptual model found inside the black box of organisational transformation. Organization & Environment. 2016;29(1):11–35.

178. Wainstein ME, Bumpus AG. Business models as drivers of the low carbon power system transition: a multi-level perspective. Journal of Cleaner Production. 10 luglio 2016;126:572–85.

179. Osterwalder A, Pigneur Y, Tucci CL. Clarifying Business Models: Origins, Present, and Future of the Concept. Communications of the Association for Information Systems. 5 luglio 2005;16(1). Disponibile su: https://aisel.aisnet.org/cais/vol16/iss1/1

180. Brege S, Stehn L, Nord T. Business models in industrialized building of multi-storey houses. Construction Management and Economics. 1 febbraio 2014;32(1–2):208–26.

181. Johnson MW, Christensen CM, Kagermann H. Reinventing your business model. Harvard business review. 2008;86(12):50–9.

182. Suikki RM, Goman AMJ, Haapasalo HJO. A framework for creating business models – a challenge in convergence of high clock speed industry. International Journal of Business Environment. gennaio 2006;1(2):211–33.

183. Mlecnik E. Opportunities for supplier-led systemic innovation in highly energy-efficient housing. Journal of Cleaner Production. 1 ottobre 2013;56:103–11.

184. Foxon TJ, Bale CSE, Busch J, Bush R, Hall S, Roelich K. Low carbon infrastructure investment: extending business models for sustainability. Infrastructure Complexity. 12 giugno 2015;2(1):4.

185. Gauthier C, Gilomen B. Business Models for Sustainability: Energy Efficiency in Urban Districts. Organization & Environment. 1 marzo 2016;29(1):124–44.

186. Hall S, Roelich K. Business model innovation in electricity supply markets: The role of complex value in the United Kingdom. Energy Policy. 1 maggio 2016;92:286–98.

187. Hannon MJ, Bolton R. UK Local Authority engagement with the Energy Service Company (ESCo) model: Key characteristics, benefits, limitations and considerations. Energy Policy. 1 marzo 2015;78:198–212.

188. Mahapatra K, Gustavsson L, Haavik T, Aabrekk S, Svendsen S, Vanhoutteghem L, et al. Business models for full service energy renovation of single-family houses in Nordic countries. Applied Energy. 1 dicembre 2013;112:1558–65.

189. Winther T, Gurigard K. Energy performance contracting (EPC): a suitable mechanism for achieving energy savings in housing cooperatives? Results from a Norwegian pilot project. Energy Efficiency. 1 giugno 2017;10(3):577–96.

190. Shang T, Zhang K, Liu P, Chen Z. A review of energy performance contracting business models: Status and recommendation. Sustainable Cities and Society. 1 ottobre 2017;34:203–10.

191. Bertoldi P, Boza-Kiss B, Della Valle N, Economidou M. The role of one-stop shops in energy renovation - a comparative analysis of OSSs cases in Europe. Energy and Buildings. 1 novembre 2021;250:111273.

192. Bertoldi P, Economidou M, Palermo V, Boza-Kiss B, Todeschi V. How to finance energy renovation of residential buildings: Review of current and emerging financing instruments in the EU. Wiley Interdisciplinary Reviews: Energy and Environment. 2021;10(1):e384.

193. Vine E. An international survey of the energy service company (ESCO) industry. Energy Policy. 1 marzo 2005;33(5):691–704.

194. Bertoldi P, Boza-Kiss B. Analysis of barriers and drivers for the development of the ESCO markets in Europe. Energy Policy. 1 agosto 2017;107:345–55.

195. Brown D, Kivimaa P, Sorrell S. An energy leap? Business model innovation and intermediation in the 'Energiesprong' retrofit initiative. Energy Research & Social Science. 1 dicembre 2019;58:101253.

196. Copiello S, Donati E, Bonifaci P. Energy efficiency practices: A case study analysis of innovative business models in buildings. Energy and Buildings. 15 giugno 2024;313:114223.

197. Kim C, O'Connor R, Bodden K, Hochman S, Liang W, Pauker S, et al. Innovations and opportunities in energy efficiency finance. Wilson Sonsini Goodrich and Rosati, New York, USA Retrofitting buildings in the UK. 2012;129.

198. Bianco V, Sonvilla PM, Gonzalez Reed P, Villoslada Prado A. Business models for supporting energy renovation in residential buildings. The case of the on-bill programs. Energy Reports. 1 novembre 2022;8:2496–507.

199. Dall'O' G. Energy Retrofit Strategies in the Building Sector. In: Dall'O' G, curatore. Green Planning for Cities and Communities: Novel Incisive Approaches to Sustainability. Cham: Springer International Publishing; 2020 [citato 22 settembre 2025]. p. 203–28. Disponibile su: https://doi.org/10.1007/978-3-030-41072-8_9

200. Gauzin-Müller D, Gaillard C, Delpont S. Rénovation globale et performante d'aujourd'hui: L'approche zéro énergie d'EnergieSprong. Plaissan: MUSEO; 2025. 160 p.

201. Friedler C, Kumar C. Reinventing retrofit: how to scale up home energy efficiency in the UK » Green Alliance. Alliance G, curatore. 2019. Disponibile su: https://green-alliance.org.uk/publication/reinventing-retrofit-how-to-scale-up-home-energy-efficiency-in-the-uk/

202. Pellegrino M, Wernert C, Chartier A. Rénovation énergétique Hors site de l'habitat : enjeux, premières réalisation et débats en France et aux Pays-Bas. Paris: Ponts Chaussees; 2025. 288 p.

203. Fawcett T, Topouzi M. The time dimension in deep renovation: evidence and analysis from across the EU. In Belambra Presqu'ile de Giens, France; 2019. p. 1253–8. Disponibile su: https://ora.ox.ac.uk/objects/uuid:292ca2d4-d6f8-43d8-89c3-c91188886ba7/files/sws859g71d

204. Van Hal A, Coen M, Stutvoet E. Energy performance fee to cover investments in the energy efficiency of affordable housing. In 2018. p. 243–58.

205. Micelli E, Mangialardo A. Recycling the City New Perspective on the Real-Estate Market and Construction Industry. In: Bisello A, Vettorato D, Stephens R, Elisei P, curatori. Smart and Sustainable Planning for Cities and Regions: Results of SSPCR 2015. Cham: Springer International Publishing; 2017. p. 115–25. (Green Energy and Technology). Disponibile su: https://doi.org/10.1007/978-3-319-44899-2_8

206. Sovacool BK, Turnheim B, Martiskainen M, Brown D, Kivimaa P. Guides or gatekeepers? Incumbent-oriented transition intermediaries in a low-carbon era. Energy Research & Social Science. 1 agosto 2020;66:101490.

207. Pellegrino M, Wernert C, Chartier A. Social Housing Net-Zero Energy Renovations With Energy Performance Contract: Incorporating Occupants' Behaviour. Urban Planning. 2022;7(2):5–19.

208. Dalla Zuanna GD, Weber G. Cose da non credere: Il senso comune alla prova dei numeri. Bari: Laterza; 2012. 75 p.

209. Fylan F, Glew D, Smith M, Johnston D, Brooke-Peat M, Miles-Shenton D, et al. Reflections on retrofits: Overcoming barriers to energy efficiency among the fuel poor in the United Kingdom. Energy Research & Social Science. 1 novembre 2016;21:190–8.

210. Michelsen C, Rosenschon S, Schulz C. Small might be beautiful, but bigger performs better: Scale economies in "green" refurbishments of apartment housing. Energy Economics. 1 luglio 2015;50:240–50.

211. Stevens B. Single-Site Economies in the Construction of Multi-Family Housing. Land Economics. 1975;51(1):50–7.

212. Downs A. Characteristics of Various Economic Studies. Appraisal Journal. 1966;34(3).
213. Dilmore G. The new approach to real estate appraising. Prentice Hall; 1971.
214. Ratcliff RU. Valuation for real estate decisions. Democrat Press; 1972.
215. Marshall P. Equated yield analysis. Estates Gazette. 1976;239:493–7.
216. Insee. Indice du coût de la construction des immeubles à usage d'habitation (ICC) | Insee. 2025. Disponibile su: https://www.insee.fr/fr/statistiques/serie/000008630
217. Less BD, Casquero-Modrego N, Walker IS. Home Energy Upgrades as a Pathway to Home Decarbonization in the US: A Literature Review. Energies. gennaio 2022;15(15):5590.
218. Morri G, Benedetto P, Mazzocco A, Caselli S. Valutazione immobiliare. Metodologie e casi. Milano: EGEA; 2017. 322 p.
219. Orefice M, Orefice L. Estimo civile. Roma: De Agostini; 2014.
220. Tsikaloudaki K, Laskos K, Bikas D. On the Establishment of Climatic Zones in Europe with Regard to the Energy Performance of Buildings. Energies. gennaio 2012;5(1):32–44.
221. Eurostat. Our lives in the city. 2018. Disponibile su: https://ec.europa.eu/eurostat/web/products-eurostat-news/-/EDN-20180207-1
222. Mangialardo A, Micelli E. Who Drives the Growth? Empirical Evidences from Real-Estate Market Values of 12 Italian Metropolitan Cities. In: Bevilacqua C, Calabrò F, Della Spina L, curatori. New Metropolitan Perspectives. Cham: Springer International Publishing; 2021. p. 1023–31. (Smart Innovation, Systems and Technologies).
223. Kain JF, Quigley JM. Measuring the value of house quality. Journal of the American Statistical Association. 1970;65(330):532–48.
224. Yayar R, DemiR D. Hedonic estimation of housing market prices in Turkey. ERÜ İİBF DERGİSİ. 2014;(43):67.
225. Simonotti M. Metodi di stima immobiliare. Applicazione degli standard internazionali. Dario Flaccovio; 2006.
226. ARERA. Andamento del prezzo del gas naturale per un consumatore domestico tipo in regime di tutela. 2024. Disponibile su: https://www.arera.it
227. Quale Energia.it. INFODATA ENERGIA | QualEnergia.it. 2024. Disponibile su: https://www.qualenergia.it/pro/documenti/quota-rinnovabili-4-9-21-31-pun-5-9-21-e-mwh-11309-petrolio-wti-b-6929-co2-3-9-21-e-ton-6133/
228. D'Agostino. Estimo immobiliare urbano ed Elementi di Economia. Società Editrice Esculapio; 2020.
229. Agenzia del Territorio. Manuale operativo delle stime immobiliari. Franco Angeli; 2012.
230. Copiello S. A Discounted Cash Flow variant to detect the optimal amount of additional burdens in Public-Private Partnership transactions. MethodsX. 1 gennaio 2016;3:195–204.
231. Ling DC. Implementing discounted cash flow valuation models: what is the correct discount rate? Appraisal Journal. 1992;60(2).
232. Patterson A. High Stakes, Higher Rates: An Overview and Step-by-Step Approach to Calculating the Cost of Capital in Emerging Market firms. In: Derindere Köseoğlu S, Patterson A, curatori. Valuation in Emerging Markets: Challenges, Approaches and Strategies. Cham: Springer Nature Switzerland; 2025. p. 173–98. Disponibile su: https://doi.org/10.1007/978-3-031-93526-8_8
233. Mian MA, Vélez-Pareja I. Applicability of the Classic WACC Concept in Practice. Latin American Business Review. 17 aprile 2008;8(2):19–40.
234. Assofin. Osservatorio sul credito immobiliare. 2024. Disponibile su: https://www.assofin.it/
235. McIntosh RJ. Discounted cash flows: their current use. Valuer and Land Economist. 1993;32(6).

236. Dewick P, Miozzo M. Sustainable technologies and the innovation–regulation paradox. Futures. 1 novembre 2002;34(9):823–40.

237. Khalfan MM, Maqsood T. Current State of Off-Site Manufacturing in Australian and Chinese Residential Construction. Journal of Construction Engineering. 2014;2014(1):164863.

238. Júnior GGS, Satyro WC, Bonilla SH, Contador JC, Barbosa AP, de Paula Monken SF, et al. Construction 4.0: Industry 4.0 enabling technologies applied to improve workplace safety in construction. Research, society and development. 2021;10(12):e280101220280–e280101220280.

239. Berndt ER. The practice of econometrics: classic and contemporary. 702: Addison Wesley; 1996.

240. Choi D, Kim YJ. Local and global experience curves for lumpy and granular energy technologies. Energy Policy. 1 marzo 2023;174:113426.

241. Micelli E, Giliberto G, Righetto E. Is the Energy Transition of Housing Financially Viable? Unlocking the Potential of Deep Retrofits with New Business Models. Buildings. 3 aprile 2025;15:26.

242. Anzanello MJ, Fogliatto FS. Learning curve models and applications: Literature review and research directions. International Journal of Industrial Ergonomics. 1 settembre 2011;41(5):573–83.

243. Rahman M, Kirby D. Learning-Curve Applications for Emerging Products and Services.

244. Li V, Siniosoglou I, Sarigiannidis P, Argyriou V. Enhancing Manufacturing Training Through VR Simulations. In: 2025 IEEE International Conference on Engineering, Technology, and Innovation (ICE/ITMC). IEEE; 2025. p. 1–9.

245. Ebbinghaus H. Über das gedächtnis: untersuchungen zur experimentellen psychologie. Duncker & Humblot; 1885.

246. Wright TP. Factors affecting the cost of airplanes. Journal of the aeronautical sciences. 1936;3(4):122–8.

247. Ayres RU. Technological forecasting and long-range planning. 1969;

248. Sahal D. A theory of progress functions. AIIE Trans. 1979;11(1):23–9.

249. Anderson JR. Acquisition of cognitive skill. Psychological review. 1982;89(4):369.

250. Adler PS, Clark KB. Behind the learning curve: A sketch of the learning process. Management science. 1991;37(3):267–81.

251. Dar-El EM, Rubinovitz J. Using learning theory in assembly lines for new products. International Journal of Production Economics. 1991;25(1–3):103–9.

252. Pananiswami S, Bishop RC. Behavioral implications of the learning curve for production capacity analysis. International Journal of Production Economics. 1991;24(1–2):157–63.

253. Teplitz CJ. The learning curve deskbook: A reference guide to theory, calculations, and applications. 1991;

254. Nembhard DA, Uzumeri MV. An individual-based description of learning within an organization. IEEE transactions on engineering management. 2000;47(3):370–8.

255. Lapré MA, Mukherjee AS, Van Wassenhove LN. Behind the learning curve: Linking learning activities to waste reduction. Management Science. 2000;46(5):597–611.

256. Nembhard DA, Uzumeri MV. Experiential learning and forgetting for manual and cognitive tasks. International journal of industrial ergonomics. 2000;25(4):315–26.

257. Nembhard DA, Osothsilp N. Task complexity effects on between-individual learning/forgetting variability. International journal of industrial ergonomics. 2002;29(5):297–306.

258. Vits J, Gelders L. Performance improvement theory. International journal of production economics. 2002;77(3):285–98.

259. Hamade RF, Artail HA, Jaber MY. Evaluating the learning process of mechanical CAD students. Computers & Education. 2007;49(3):640–61.

260. Wickens CD, Gordon SE, Liu Y, Lee J. An introduction to human factors engineering. Vol. 2. Pearson Prentice Hall Upper Saddle River, NJ; 2004.

261. Martino JP. Technological forecasting for decisionmaking. 1972;

262. Alberth S. Forecasting technology costs via the experience curve—myth or magic? Technological Forecasting and Social Change. 2008;75(7):952–83.

263. Nagy B, Farmer JD, Bui QM, Trancik JE. Statistical Basis for Predicting Technological Progress. PLOS ONE. 28 febbraio 2013;8(2). Disponibile su: https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0052669

264. Smunt TL, Watts CA. Improving operations planning with learning curves: Overcoming the pitfalls of «messy» shop floor data. J Oper Manage. 2003;21(1):93–107.

265. Chen CK, Lo CC, Liao YX. Optimal lot size with learning consideration on an imperfect production system with allowable shortages. International Journal of Production Economics. 2008;113(1):459–69.

266. Jaber MY, El Saadany AM. An economic production and remanufacturing model with learning effects. International Journal of Production Economics. 2011;131(1):115–27.

267. Azadegan A, Dooley KJ. Supplier innovativeness, organizational learning styles and manufacturer performance: An empirical assessment. Journal of operations management. 2010;28(6):488–505.

268. Grosse EH, Glock CH. The effect of worker learning on manual order picking processes. International Journal of Production Economics. 2015;170:882–90.

269. Abernathy WJ, Wayne K. Limits of the learning curve. Harvard business review. 1974;52(5):109–19.

270. Plaza M, Rohlf K. Learning and performance in ERP implementation projects: A learning-curve model for analyzing and managing consulting costs. International Journal of Production Economics. 2008;115(1):72–85.

271. Nadeau MC, Kar A, Roth R, Kirchain R. A dynamic process-based cost modeling approach to understand learning effects in manufacturing. International Journal of Production Economics. 2010;128(1):223–34.

272. Feldman LS, Cao J, Andalib A, Fraser S, Fried GM. A method to characterize the learning curve for performance of a fundamental laparoscopic simulator task: Defining "learning plateau" and "learning rate". Surgery. 1 agosto 2009;146(2):381–6.

273. Glock CH, Grosse EH, Jaber MY, Smunt TL. Applications of learning curves in production and operations management: A systematic literature review. Computers & Industrial Engineering. 1 maggio 2019;131:422–41.

274. Glover JH. Manufacturing progress functions II. Selection of trainees and control of their progress. The International Journal of Production Research. 1966;5(1):43–59.

275. Baloff N. The learning curve--some controversial issues. The Journal of Industrial Economics. 1966;275–82.

276. Steedman I. Some improvement curve theory. The International Journal of Production Research. 1970;8(3):189–206.

277. Jakob M. Marginal costs and co-benefits of energy efficiency investments. The case of the Swiss residential sector. Energy Policy. 2006;34(2 SPEC. ISS.):172–87.

278. Yeh S, Rubin ES. A review of uncertainties in technology experience curves. Energy Economics. 2012;34(3):762–71.

279. Argote L, Epple D. Learning Curves in Manufacturing. Science. 23 febbraio 1990;247(4945):920–4.

280. Arrow KJ. The economic implications of learning by doing. The review of economic studies. 1962;29(3):155–73.

281. Thompson P. Chapter 10 - Learning by Doing. In: Hall BH, Rosenberg N, curatori. Handbook of the Economics of Innovation. North-Holland; 2010. p. 429–76. Disponibile su: https://www.sciencedirect.com/science/article/pii/S0169721810010105
282. Hirschmann WB. Profit from the Learning Curve. Harvard Business Review. 1964;42(1):125–39.
283. Carlson JGH. Cubic learning curves-precision tool for labor estimating. Manufacturing engineering & management. 1973;71(5):22–5.
284. Badiru AB. Computational survey of univariate and multivariate learning curve models. IEEE transactions on Engineering Management. 2002;39(2):176–88.
285. De Jong JR. The effects of increasing skill on cycle time and its consequences for time standards. Ergonomics. 1957;1(1):51–60.
286. Claeson Colpier U. Using the experience curve to analyze the cost development of the combined cycle gas turbine. Energy Conversion, Chalmers University of Technology; 1999.
287. Ibenholt K. Explaining learning curves for wind power. Energy Policy. 1 ottobre 2002;30(13):1181–9.
288. Ostwald PF, Reisdorf JB. Measurement of technology progress and capital cost for nuclear, coal-fired, and gas-fired power plants using the learning curve. Engineering and Process Economics. 1979;4(4):435–54.
289. Jaber MY, Guiffrida AL. Learning curves for imperfect production processes with reworks and process restoration interruptions. European journal of operational research. 2008;189(1):93–104.
290. Wong LF. A generalized learning curve adapted for purchasing and cost reduction negotiations. Advances in Operations Research. 2013;2013(1):584762.
291. Schauf M, Schwenen S. Mills of progress grind slowly? Estimating learning rates for onshore wind energy. Energy Economics. 2021;104:105642.
292. Weiss M, Junginger M, Patel MK, Blok K. A review of experience curve analyses for energy demand technologies. Technological forecasting and social change. 2010;77(3):411–28.
293. Wei M, Smith SJ, Sohn MD. Experience curve development and cost reduction disaggregation for fuel cell markets in Japan and the US. Applied Energy. 2017;191:346–57.
294. Trappey AJ, Trappey CV, Tan H, Liu PH, Li SJ, Lin LC. The determinants of photovoltaic system costs: an evaluation using a hierarchical learning curve model. Journal of Cleaner Production. 2016;112:1709–16.
295. Garzón Sampedro MR, Sanchez Gonzalez C. Spanish photovoltaic learning curve. International Journal of Low-Carbon Technologies. 2016;11(2):177–83.
296. Gan PY, Li Z. Quantitative study on long term global solar photovoltaic market. Renewable and Sustainable Energy Reviews. 2015;46:88–99.
297. McDonald A, Schrattenholzer L. Learning rates for energy technologies. Energy policy. 2001;29(4):255–61.
298. Burroni L, Gherardini A, Scalise G. Policy Failure in the Triangle of Growth: Labour Market, Human Capital, and Innovation in Spain and Italy. South European Society and Politics. 5 marzo 2019;24:1–24.
299. Collegio degli ingegneri e architetti di Milano. Prezzi tipologie edilizie. Roma: DEI - Tipografia del Genio Civile; 2024. 548 p.
300. Blue R, McIlroy J, Agar B. Beyond energy efficiency: Deep retrofits save more than just money. Beyond energy efficiency. Calgary: Pembina Institute; 2024. Disponibile su: https://www.pembina.org/reports/beyond-energy-efficiency.pdf
301. Lassandro P, Devitofrancesco A, Bellazzi A, Cascardi A, De Aloysio G, Laghi L, et al. Facing the Constraints to the Deep Energy Renovation Process of Residential Built Stock in European Markets. Sustainability. gennaio 2024;16(1):294.

302. Rismanchi B. District energy network (DEN), current global status and future development. Renewable and Sustainable Energy Reviews. 1 agosto 2017;75:571–9.

303. Valranges D. La rénovation énergétique : une priorité nationale. Actualités Habitat. 2018;

304. Commissariat général au développement durable, ministère de la Transition écologique et solidaire. Le parc locatif social au 1er janvier 2018. 2018.

305. Pellegrino M. Les acteurs du bâtiment face au défi de la massification de la rénovation énergétique très performante: Le cas de la démarche Energiesprong aux Pays-Bas et en France [Building sector stakeholders facing the challenge of scalingup high-performance energy renovation: The case of the Energiesprong approach in the Netherlands and France]. Revue Internationale d'Urbanisme. 2019;(8).

306. EnergieSprong. Charte d'engagement energiesprong france relative au projet de massification de la rénovation énergétique à énergie zéro en logement social. 2017.

307. Michelangeli, A. Il metodo dei prezzi edonici per la costruzione di indici dei prezzi per il mercato immobiliare. In Principi Metodologici per la Costruzione di Indici dei Prezzi del Mercato Immobiliare; Del Giudice, V., D'Amato, M., Eds.; Maggioli: Rimini, Italy, 2008.

308. Curto, R.; Fregonara, E.; Semeraro, P. Asking prices vs market prices: An empirical analysis. Territ. Ital. 2012, 12, 53–72.

309. asking priLoberto, M.; Mistretta, A.; Spuri, M. The Capitalization of Energy Labels into House Prices. Evidence from Italy. SSRN J. 2024.