LOCATEE

LOCAL AUTHORITIES TACKLING ENERGY POVERTY IN PRIVATE MULTI-APARTMENT BUILDINGS

Energy performance assessment of the multifamily building stock: The potential of renovation for energy demand reduction, decarbonisation and energy poverty mitigation

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About LOCATEE

LOCATEE aims to support local municipalities in addressing energy poverty through the renovation of private multi-apartment buildings for vulnerable residents. LOCATEE will achieve this goal by providing a toolkit for identifying energy-vulnerable households, matching tailored interventions to their needs, and integrating energy poverty alleviation activities into long-term strategies of municipalities such as Sustainable Energy and Climate Action Plans. LOCATEE will use administrative data to create household and building typologies to identify priority intervention locations. This process will help authorities and social partners address local energy poverty through coordinated solutions, including contact points and focus groups with housing entities, to facilitate knowledge exchange on renovation programs and targeted solutions.

The evidence-based and collaborative approach will be implemented in three pilot municipalities in Central, Southern and Southeastern Europe: Piraeus (Greece), Rumia (Poland), and Torres Vedras (Portugal) and, while ensuring the scaling up of the LOCATEE framework to more municipalities and regions across Europe.

WHO WE ARE

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8	Austrian Energy Agency	AEA	AT	AUSTRIAN ENERGY AGENCY
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Executive Summary

Building energy renovation and renewable energy integration are key measures for decarbonisation, addressing climate change, energy poverty mitigation, and the enhancement of well-being. However, relevant barriers still prevent its roll-out, especially in private multifamily buildings. This report addresses the informational barrier that hinders the design of more targeted energy renovation instruments at the local level across three pilots in Rumia (PL), Torres Vedras (PT), and Piraeus (GR) to support vulnerable households. The work presented herein presents building energy simulations using the DREEM model for representative dwelling typologies in each pilot city, examining the impact of building envelope insulation and heating system upgrade on energy demand, carbon emissions, and the potential PV production. It assesses improvements in the building's energy performance, carbon emissions reductions, and potential reductions in energy bills.

The results were examined across typologies within each pilot, compared across pilots, and assessed regarding their implications for energy poverty reduction. While results differ across the pilots, heat pump installation stands out as the most impactful and cost-effective measure, enabling the highest energy consumption and carbon emissions, and potential energy bill reductions across typologies in each pilot, especially in Torres Vedras and Piraeus (energy bill reductions of over 50%). Thermal insulation has limited cost-effectiveness for energy savings due to high investment costs, but it is most effective in older dwellings in Rumia and low-performing dwellings in Piraeus, with average potential energy bill reduction of 12.5% and 16.7%, respectively. Biomass and gas boiler upgrades can lead to meaningful energy consumption savings, energy bill reductions, and even carbon emissions reductions in certain typologies, particularly in less efficient dwellings with carbon-intensive, low-efficiency heating systems and higher energy consumption levels. Photovoltaic system installation has a favourable relative electricity consumption coverage and cost-effectiveness for electricity generation in each pilot (from 1.71€/EUR in Rumia to 2.16 €/EUR in Torres Vedras), despite relevant challenges regarding space and third-party approval.

This study identifies the most impactful and cost-effective measures, as well as the typologies with the highest potential for improvement. Despite the relevance of these results, further analysis and additional nuance beyond cost-effectiveness are required for each case and solution, as other aspects and externalities not considered in the study can affect the selection of the best options, such as low fuel costs, air quality issues, long-term indoor comfort, local availability, grid capacity, and unexpected greenhouse gas emissions. Nevertheless, this study can complement the energy poverty vulnerability mapping previously conducted for the LOCATEEE toolkit by enabling the matching of vulnerable households and buildings with the most cost-effective and impactful measures to reduce their vulnerability, which is particularly relevant in contexts of limited public funding. It can provide valuable inputs for municipalities to develop more multidimensional policy instruments, such as Sustainable Energy and Climate Action Plans and regional or local Energy Poverty Mitigation plans, integrating climate, energy, infrastructural, and social dimensions, towards a fairer distribution of support. It can also inform existing contact points and one-stop shops that provide vulnerable citizens with in-person help and advice, and support other local stakeholders working towards the same goals.

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Acronyms

DH – District heating

DREEM – Dynamic High-Resolution Demand-Side Management

EC – European Commission

EED - Energy Efficiency Directive

EU – European Union

EU-SILC - EU Statistics on Income and Living Conditions

EPAH – Energy Poverty Advisory Hub

EPC – Energy Performance Certificate

HVAC - Heating, Ventilation, and Air-Conditioning

MS – Member State

PV – Photovoltaic

RES – Renewable Energy Source

SECAP - Sustainable Energy and Climate Action Plan

TMY - Typical Meteorological Year

1 Introduction

Buildings are central to the European energy and climate transition, but they are also one of its greatest structural challenges. In the European Union, buildings account for around 40% of final energy consumption, and 50% of the EU's gas consumption is attributable to buildings. Approximately 85 % of the building stock was constructed before 2000, and a large majority performs poorly in energy terms (EC, 2026a). Improving the energy performance of existing buildings is therefore essential for reducing energy demand, improving affordability, and advancing towards a fully decarbonised building stock by 2050.

The condition of the residential building stock is also closely connected to energy poverty. At the EU level, energy poverty is understood as a household's lack of access to essential energy services required to secure basic standards of living and health, and it is shaped by a combination of low-income, high-energy expenditure, and poor energy performance of dwellings (EC, 2026b). In this context, the quality of construction, the thermal characteristics of the building envelope, the efficiency of heating, cooling, and domestic hot water systems all directly influence both household energy needs and the ability to maintain acceptable indoor conditions. Poor-energy performing dwellings therefore increase households' exposure not only to high energy bills but also to underheating in winter, overheating in summer, insufficient comfort, and greater vulnerability affecting occupants' health and well-being.

These dynamics are particularly relevant in multi-apartment buildings. This segment of the housing stock plays a major role in urban areas across Europe and is highly significant for local energy poverty mitigation, especially where older buildings, fragmented ownership structures, and collective technical systems are connected. In many cases, multi-apartment buildings combine substantial technical potential for energy demand reduction with considerable organisational complexity, as renovation decisions often require coordination among multiple owners, tenants, housing associations, building managers, and public authorities. Split incentives, limited access to finance, lack of information, and administrative burdens remain persistent barriers, even where the social, economic, and environmental arguments for renovation are strong.

Building renovation is therefore not only a technical intervention, but also a social and strategic instrument. Passive measures, such as wall, roof, and floor insulation, high-performance windows, shading, and airtightness improvements, can significantly reduce heat losses, limit unwanted heat gains, and improve thermal stability. Active measures, including efficient heating and cooling systems like heat pumps, improved domestic hot water systems, ventilation solutions, and renewable energy integration (e.g., solar PV systems), can further reduce consumption and emissions while improving service quality. When combined in a coherent, integrated renovation approach, these measures can lower energy demand while improving indoor thermal comfort, strengthening resilience to both cold periods and heatwaves, and supporting the electrification and decarbonisation of the residential sector.

The benefits of renovation extend well beyond energy savings alone (and energy bills). Better performing buildings can contribute to healthier living conditions, more stable indoor temperatures, and improved air quality when moisture, mould, and inadequate ventilation are properly addressed. This is especially important because dampness and mould are associated with increased respiratory symptoms, allergies, and asthma, and because poor indoor environmental quality remains a significant health risk across Europe (EEA, 2024). Renovation can therefore generate multiple co-benefits, including improved well-being and reduced exposure to harmful indoor conditions.

At the same time, the pace and depth of renovation in Europe remain insufficient. The annual energy renovation rate has remained low, at around 1%, which is far below the level needed to align the building sector with long-term climate neutrality objectives (EC, 2026a). In response, EU policy has increasingly positioned renovation as a cornerstone of the green transition and of mitigating energy poverty. The Renovation Wave aims to renovate 35 million buildings by 2030 and at least double the annual renovation rate, while explicitly linking building renovation to energy poverty alleviation, improved health and wellbeing, job creation, and stronger support for regional and local actors (EC, 2026c). In parallel, the revised Energy Efficiency Directive (EED) establishes the "energy efficiency first" principle as a legal foundation of EU energy policy, strengthens the focus on vulnerable households and social housing, and highlights the role of one-stop shops, technical assistance, financing instruments, and local heating and cooling planning (EC, 2026d).

The revised Energy Performance of Buildings Directive further reinforces this direction by setting a pathway towards a zero-emission and fully decarbonised building stock by 2050. It introduces stronger requirements for renovating the worst-performing parts of the stock, requires Member States (MS) to establish national building renovation plans, supports the use of one-stop shops and financing mechanisms, and sets milestones, such as zero-emission standards for new buildings. These measures aim to reduce the average primary energy use of residential buildings by 16% by 2030 and by up to 22% by 2035 (EC, 2026a). Together with the EU objective of climate neutrality by 2050 and the intermediate target of reducing net greenhouse gas emissions by at least 55 % by 2030 compared to 1990, these measures place the building sector at the heart of Europe's climate and energy agenda.

Within this broader framework, the regional, city, and local scales are of particular importance. While EU directives and national strategies set the regulatory direction, renovation is ultimately implemented in concrete neighbourhoods, buildings, and households. Local and regional authorities are especially well placed to identify vulnerable areas, engage with building owners and residents, connect technical and social support, coordinate stakeholders, and integrate building renovation into wider climate and housing strategies. This is increasingly recognised in EU policy and governance frameworks, including the Covenant of Mayors, and in the revised EED, which promotes local heating and cooling plans and technical support mechanisms closer to implementation. Boosting renovation rates in private multi-apartment buildings, therefore, requires not only appropriate technologies and financing but also strong place-based governance, local knowledge, and coordination capacity.

Against this background, this report assesses the current energy performance of the multi-apartment building stock in the three LOCATEE pilot areas (Rumia, Piraeus, and Torres Vedras) and examines the potential of building renovation to reduce energy demand and support decarbonisation. Building on the broader objectives of LOCATEE, which aims to support local authorities in tackling energy poverty in private multi-apartment buildings, the report focuses on the technical characteristics of the stock, the implications of renovation and energy efficiency improvement, and the relevance of these findings for local energy poverty mitigation strategies. In doing so, it seeks to contribute to an improved understanding of how building-focused action, particularly at the local level, can help address the interconnected challenges of inefficient housing, social vulnerability, and the climate transition.

This report is organised into six sections. Besides the introduction, section 2 provides a characterisation of the current state and policy context of the building stock in the national and local pilots. Section 3 describes the methods employed to define dwelling typologies and simulate energy performance using the DREEM model. It also outlines the different scenarios and describes the tested renovation measures, as well as the methods for assessing carbon emissions reduction, photovoltaic (PV) electricity production, the cost-effectiveness of the measures, and the potential energy bill reduction for the different renovation scenarios. Section 4 presents the results of the model simulations for the baseline and renovation scenarios, per dwelling typology, for each pilot. Section 5 analyses the results through three different lenses – cross-typology analysis within each pilot region, cross-pilot comparison, and implications of the study for energy poverty mitigation. Finally, Section 6 concludes the study, framing the study and its outputs within national and local policy goals

2 Overview of Energy Poverty Measurement in the EU

This chapter presents a characterisation of the national and pilot-area building stock, highlighting the main characteristics of dwelling typologies, the mix of building envelope solutions, energy sources, and space-heating and cooling systems. It also delves into renovation actions at these geographic scales, as well as the existing policy mechanisms to promote energy renovation and efficiency in the residential sector.

2.1 National Overview

This section presents an overview of the current state of the national building stock in Poland, Portugal, and Greece, bridging historic evolution and current realities, and setting the scene for a more contextualised characterisation of the current situation of the dwelling stock in each of the three pilot areas, in its technical, social, and political dimensions.

2.1.1 Poland

The origins of contemporary housing in Poland date back to 1918, when the Polish state was re-established after more than a century during which Polish territories did not exist as a separate political entity. Within the newly defined administrative borders, the condition of the housing stock was marked by substantial internal variation, reflecting both long-term economic and socio-cultural processes across the Polish lands and the direct consequences of the First World War, including extensive damage to residential buildings. During this period, housing development broadly kept pace with population growth, but the quality of a large share of newly completed dwellings remained low. At the same time, the pace of residential construction was insufficient to meet overall housing needs (Nowak, 2021).

The Second World War fundamentally reshaped the trajectory of housing policy and housing development in Poland. In addition to causing major demographic losses, the war resulted in the destruction of an estimated 22–24% of the housing stock that had existed in 1939 within the country's current borders. It also brought profound political and territorial changes, including the imposition of a socialist system and a westward shift of Poland's administrative borders (Nowak, 2021).

Under state socialism, the functioning of a free housing market was effectively eliminated, with negative consequences for long-term housing development. In the first post-war years, the expansion of the housing stock was centrally planned in terms of the number, location, and type of dwellings, while responsibility for housing provision rested primarily with state-owned enterprises. Individual housebuilding was strongly restricted, although it remained possible, particularly in rural areas. Cooperative housing construction was also largely suspended, accounting for less than 1% of all dwellings completed in the first half of the 1950s. As a result, housing development became highly dependent on state financial outlays and broader economic priorities. Since economic policy at the time favoured productive investment, especially in industry, housing was assigned a secondary role. Consequently, the pace of housing development remained insufficient to meet social needs (Kucharska-Stasiak, 2008).

In the second half of the 1950s, an effort was made to accelerate housing provision by mobilising households' own financial resources. The construction of owner-occupied houses was permitted, and residents were also allowed to co-finance housing development through housing cooperatives. This contributed to a rise in the total number of dwellings completed, which peaked in the late 1970s. From the mid-1960s until the early 1990s, housing cooperatives accounted for the majority of new housing completions, while the share of dwellings delivered by state-owned enterprises remained slightly higher than that of individually built single-family houses until the end of the 1970s (Kubów, 2012; Nowak, 2021).

The systemic transition after 1989 marked a shift towards a market-based housing model in which purchasing or building an owner-occupied dwelling became the principal route to meeting housing needs. Housing policy in the post-socialist period focused primarily on supporting market-based residential construction, which accounted for up to 95% of all new dwellings delivered in Poland over the following 25 years (Markowski *et al.*, 2018). At the same time, responsibility for addressing the housing needs of low-income households was transferred to municipalities. In the early 1990s, municipalities took over a substantial share of the housing stock previously owned by state enterprises. As they were not prepared to bear the high maintenance costs of these inherited stocks, which consisted largely of pre-war dwellings, they increasingly pursued housing policies centred on privatisation. This led to a rapid decline in the stock of municipal housing available to households in difficult financial circumstances (Kucharska-Stasiak, 2008). In this respect, the privatisation of housing stock and the decentralisation of housing policy in Poland reflected broader trends observed across Central and Eastern Europe. At present, Poland has close to 15 million dwellings, of which 59% are located in multifamily buildings, while 41% are single-family houses with one or two dwellings (GUS, 2025). More than 82% of dwellings are owner-occupied, reflecting the historically entrenched homeownership model. Municipalities own around 5% of the housing stock, while housing cooperatives account for a further 12%. The current structure of the housing stock also reflects long-term historical patterns of housing development. Of the more than 7.5 million residential buildings in Poland, only 8% are multifamily buildings (KAPE, 2024). As shown in **Figure 1**, the largest share of the stock consists of buildings constructed before 1970 (60%), which reflects the scale of housing provision under the centrally planned system, as well as buildings completed after 2011 (22.8%), associated with market liberalisation and the expansion of private investment.

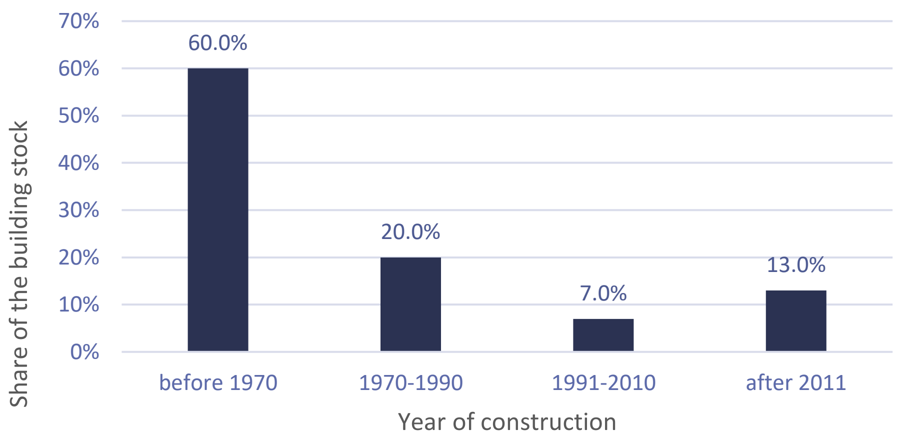


Figure 1. Share of building stock per construction year in Poland

Source: Own elaboration based on the draft National Building Renovation Plan (KAPE, 2024)

The majority of multifamily buildings in Poland were constructed before 1990, with significant implications for their current energy performance and renovation needs. While a substantial part of the housing stock owned by housing cooperatives has undergone thermal modernisation, in the remaining segments of the stock, older buildings generally remain less energy efficient.

The draft National Plan for Building Renovation identifies significant deficiencies in the thermal quality of the residential stock. One in five dwellings in Poland is in a building without external wall insulation, while slightly more than 40% are in buildings with insulation thicknesses of 5-12 cm. Only about one-quarter of dwellings are in buildings with insulation exceeding 12 cm. In addition, one in three dwellings is in a building where the ceiling above the top floor or the attic is not insulated (KAPE, 2024).

The extent of renovation also varies considerably across ownership categories. In multifamily buildings owned by housing cooperatives, district heating is by far the dominant heat source, accounting for more than 90% of heating systems, while a further 5% rely on gas boilers. Other fuels play only a marginal role. The situation is markedly different in the municipal housing stock. Although more than 40% of municipal dwellings are connected to district heating, 27% still rely on traditional tiled stoves for space heating. When extrapolated to the national level, this suggests that more than 100,000 municipal dwellings across Poland continue to be heated in this way (KAPE, 2024).

Substantial differences can also be observed in the thermal condition and technical standard of buildings across ownership types. A clear majority of cooperative dwellings (77%) are located in buildings with external partitions insulated to a thickness of more than 5 cm. The corresponding share for municipal dwellings is less than 40%, while 59% of municipal dwellings are located in uninsulated buildings. This gap, however, should be interpreted in light of the different age profiles of the two segments. Cooperative housing largely consists of apartment blocks constructed in the 1970s and 1980s, whereas municipal housing typically comprises much older buildings, often of historic character or subject to heritage protection, which significantly limits the scope for thermal modernisation. One in five cooperative dwellings requires heating system upgrades, and in one in three cases, heat consumption is not billed based on individual metering. The situation is even more challenging in the municipal segment: 37% of dwellings require heating system modernisation, while more than 60% lack meters or heat cost allocators, a figure that should be interpreted in the context of the widespread use of individual heat sources in municipal housing. The condition of window joinery also remains a recurrent problem in municipal dwellings, affecting up to 27% of units (KAPE, 2024).

Building renovation and improvements in energy efficiency remain pressing challenges and require continued support through dedicated financial instruments. Among housing cooperatives, one in three reported having used loans combined with a thermo-modernisation or renovation bonus to finance renovation works undertaken to date. A further 15% relied on non-repayable grants from EU or domestic sources, while 13% used loans or credit instruments supported by EU or national funds. Nearly all cooperatives also used their own resources. Only 7% declared that no thermo-modernisation works had been carried out (KAPE, 2024).

2.1.2 Portugal

The history of the Portuguese residential building stock is directly connected to the development of the economic, technological, and social contexts. Until the 19th century, low-density single-story rural houses were the predominant typology in the country. These were mostly built from traditional materials such as stone, wood, earth, lime, and plaster (Andrade *et al.*, 2019). The 20th century brought the modernisation of construction processes and the introduction of modern materials – such as iron, glass, cement, and concrete - enabling the exploration of new aesthetic expressions and spatialities

(Andrade, 2019). A period of slow industrialisation from the end of the 19th to the beginning of the 20th century coincides with a more systematic construction of the multifamily building typologies. In the first decades of the 20th century, industrialisation and relative economic growth in the main urban centres, together with considerable levels of poverty and hardship in the rural areas, led to a significant exodus of the rural population to these centres (Paulo, 2021). The rise in population density in coastal urban areas and the development of the rental housing market further advanced the construction of multi-apartment buildings. The inability of free markets to ensure access to adequate housing for low-income individuals led to greater public regulation-based housing promotion in the country, in opposition to the classical perspective (Silva, 1994). Between 1930 and 1970, there was a period of growth of concrete multifamily buildings, for social housing and the rental market. However, it was not enough to prevent a significant imbalance between supply and demand, resulting in a considerable percentage of the urban population occupying clandestine informal housing with poor quality and security standards (Silva, 1994). The political revolution in 1974 brought strong social mobilisation for promoting the right to housing and comprehensive housing policies, boosting the regeneration of urban spaces, the construction of public housing, and rent protection measures. The construction of private multi-apartment buildings rose at the end of the 1980s, with political stabilisation, gradual market liberalisation, credit availability, and economic growth (Costa, 2012), halted by more recent periods of economic crisis.

Nowadays, an estimated 41.7% of first-residence dwellings in Portugal are integrated into multifamily buildings, while 58.3% are single- or two-story houses, indicating the rising share of apartments in the dwelling stock (INE, 2021a). For this estimate, buildings with three stories or more were identified as multifamily buildings. Around 70% of dwellings in Portugal are owner-occupied (INE, 2021a), reflecting the historical consolidation of the home-property model, although this percentage may be slightly lower in multifamily dwellings. The historical trends in multifamily building construction are well illustrated in the share of dwellings in this building typology per year of construction (**Figure 2**). The highest shares of dwellings can be found in multifamily buildings from the periods of 1961-1990 (42.4%), related to strong policy action, public mobilisation, and higher demand; and 1990-2005 (36.2%), related to market liberalisation and increased investment.

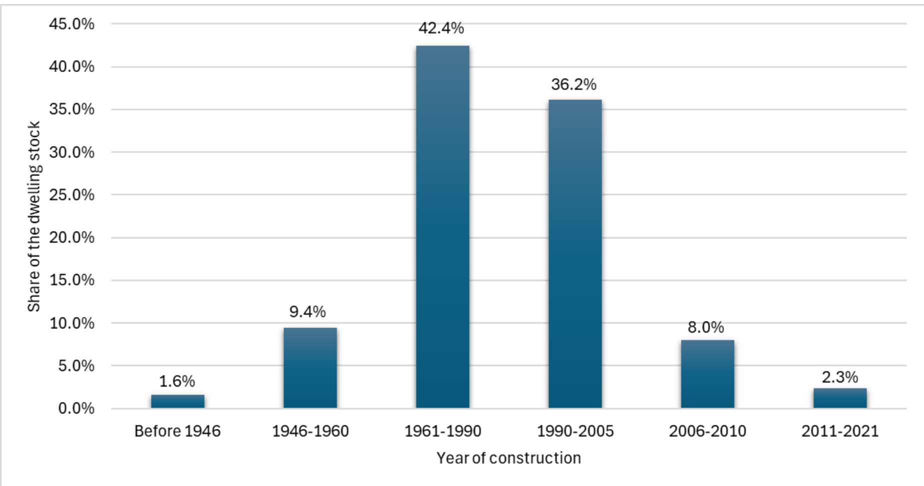


Figure 2. Share of main residence dwellings in multifamily buildings per year of construction in Portugal

Source: own elaboration based on INE (2021).

Building age is an important proxy for energy efficiency. Over 73% of main residence dwellings in multifamily buildings were built before 1990, the year the first energy-performance regulation for residential buildings was adopted. The age of construction is associated with lower energy efficiency in the absence of renovation measures. Representing the whole dwelling stock (apartments and houses), for a total of 2.08 million energy performance certificates, the share of dwellings with a C or lower EPC class is 67% (ADENE, 2026a). It is important to mention that the requirement for new and renovated buildings is class B-. Estimating the shares of EPC per class for multifamily building dwellings, with a smaller sample of 0.98 million EPCs from the period 2014-2020, the share of dwellings in the same range increases to 85% (**Figure 3**), highlighting the poorer energy efficiency conditions of private apartments (ADENE, 2026b).

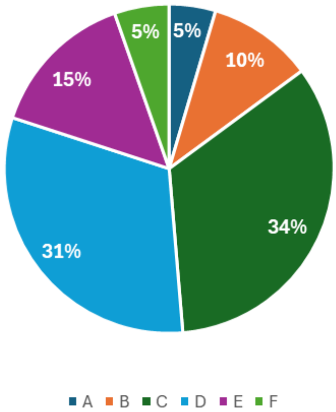


Figure 3. Share of EPCs per class for multifamily building dwellings in Portugal

Source: own elaboration based on ADENE (2026b).

According to the energy efficiency module of the EU SILC (Survey on Income and Living Conditions) of 2023, around 40.9% of the population reported having only single glazing in their windows, a less energy-efficient option. Having at least one window with double or triple glazing is associated with a reduced inability (8.2 p.p.) to keep the home adequately warm. Portugal also reports one of Europe's highest thermal transmission coefficients for walls, windows, and roofs (Zebra2020, 2016). Regarding energy use, 83.4% of the population reported using a heating system. This value decreases to 61.7% in the population estimated to be at risk of poverty. These numbers highlight the connection between income poverty and lack of access to proper energy services and energy efficiency (INE, 2023). According to the survey on domestic energy consumption (DGEG/ADENE, 2021), the individual electric heater is the most common system for space heating (81.6%), followed by the fireplace with heat recovery (24.2%). Conversely, only 32.7% of dwellings used a space cooling system, mostly ventilators (58.8%) and A/C units (45.5%).

For dwellings in multifamily buildings, the mix of energy systems and construction characteristics can be identified using the EPC sample. However, it is important to note that this sample may overestimate the prevalence of more efficient solutions, as dwellings with an EPC in Portugal are more likely to have higher EE than the average dwelling. In this typology, 36.1% of households use a boiler (mostly gas), 35% use a split or multi-split heat pump, and 21.6% use biomass heat recovery. Individual heaters are still possibly the most used heating solution, but this type of system is not identified in the EPCs. The same applies to ventilators for space cooling: the most commonly used equipment, according to the

EPC data, is split A/C units (56.5%) and multi-split units (38.8%). While electricity is the only energy source used for space cooling, biomass is the main energy source for space heating (81.2%), followed by electricity (7.6%). Regarding building elements, the opaque envelope is mainly characterised by horizontal roofs without thermal insulation (68.7%), pavement without thermal insulation (59.0%), and single- or double-plastered walls (after 1960) (59.2%). As for the windows, there are two main solutions: Metal frames without thermal breaks with single glazing (39.5%) and with double glazing (35.8%). The building solutions stock shows considerable potential for transformation towards a more energy-efficient and thermally resilient building stock.

Building renovation and energy efficiency improvement remain significant and timely challenges, especially in multifamily buildings and for households in energy poverty, due to barriers such as high upfront costs, lack of information on the most suitable EE measures, and split incentives between tenants and landlords (Bertoldi *et al.*, 2021; Pillai *et al.*, 2021). In 2023, the renovation rates for light, medium and deep renovation of residential buildings are estimated at respectively 0.41%, 0.57% and 0.70%, according to the data presented in the draft version of the National Plan for Building Renovation (Government of Portugal, 2026), below the annual target of 2% defined in the Renovation Wave framework (European Commission, 2020). There are two ongoing national measures addressing energy poverty via building renovation and energy efficiency promotion from two different approaches, one through direct funding and the other through information and personal support:

- **"E-Lar" (e-home)** [since 2025] – a subsidy scheme supporting home electrification and efficiency by replacing gas appliances with efficient electric ones. It has a fund of €91 million. This support allows for a maximum co-funding rate of 100%, up to the limits defined for the equipment type. Provides higher subsidies for energy-poor households.
- **"Espaços Energia"** (energy spaces) [since 2025] - National one-stop shop network providing free local support on energy efficiency, renewables, mobility, and financing, to promote a more conscious and sustainable use of energy.

Neither instrument directly supports building-envelope renovation, a significant flaw in central public policy aimed at promoting EE and mitigating energy poverty. "Espaços Energia" establishes an important liaison with municipal governments, as the identified citizens and collected data can be used to improve local efforts to mitigate energy poverty.

2.1.3 Greece

The history of the Greek residential building stock is closely associated with the country's urbanisation trajectory, the family-centred provision of housing, and the gradual consolidation of multi-apartment buildings as the dominant urban residential form (Karamiditriou *et al.*, 2021; Tsellos, 2025). Before the large-scale urban transformations of the 1950s, a considerable part of the housing stock consisted of low-rise (i.e., 2-3 floors) dwellings, often incrementally developed, many of which were self-built and could later be expanded through additions or extra floors (Tsellos, 2025). After the Second World War, rapid internal migration towards the main urban centres, especially Athens and Piraeus, combined with strong housing demand, limited state provision of social housing, and the absence of broad mortgage finance until much later, created the conditions for a highly fragmented but dynamic model of urban residential development (Arapoglou *et al.*, 2021; Tsellos, 2025). In this context, the "land-for-apartment" exchange system known in Greek as "Antiparochi" became the central mechanism of post-war housing production and drove the mass diffusion of multi-apartment buildings, which reshaped Greek cities, particularly during the 1950s, 1960s and 1970s (Tsellos, 2025).

Nowadays, Greece remains one of the most apartment-dominated housing systems in Europe (Eurostat, 2024). According to the Hellenic Statistical Authority (2023), 64.7% of households in Greece live in apartments or flats, while detached houses account for 26.6% of dwellings and semi-detached or terraced houses for 8.7%. Moreover, 70.4% of households own their dwelling outright (i.e., without an outstanding mortgage), while a further 6.1% are homeowners with a mortgage, confirming that owner-occupation remains the dominant tenure structure in the country.

Figure 4 presents the distribution of multi-apartment buildings in Greece by construction period. The distribution reflects the historical phases of urban expansion in the country. The largest share of multi-apartment buildings was constructed between 1961 and 1980, representing the peak of post-war urban development associated with rapid urbanisation and the widespread use of the "land-for-apartment" exchange system. Construction activity remained high during the 1981-2000 period, although at slightly lower levels, indicating the continued expansion of apartment-based urban housing. Earlier periods, such as 1920-1940 and 1941-1960, account for a considerably smaller share of the stock, reflecting the more limited scale of urban residential development before the post-war building boom. More recent decades, particularly 2011-2020, show a sharp decline in construction activity, which can be partly attributed to the prolonged economic crisis and contraction of the Greek construction sector.

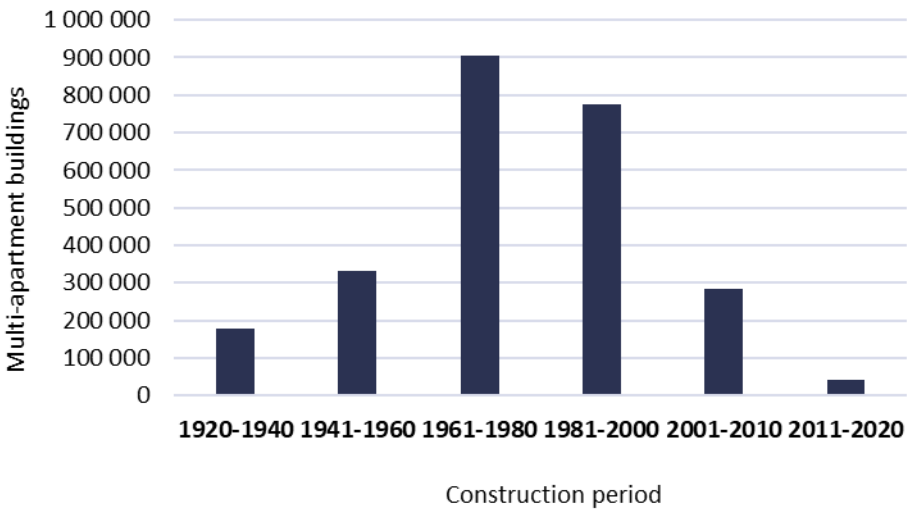


Figure 4. Distribution of the number of existing multi-apartment buildings in Greece based on their construction period.

Source: Triantafyllopoulos N. (2024).

The age profile of the Greek building stock has important implications for energy performance and climate policy. A substantial share of multi-apartment buildings was constructed before the introduction of the first thermal insulation regulation in 1981 (Thermal Insulation Regulation) (Technical Chamber of Greece, 2017), meaning that a large part of the urban dwelling stock was developed without modern insulation standards. This historical characteristic contributes to the relatively low energy performance observed in many residential buildings. Official statistics from the Greek Ministry of the Environment and Energy (2025a) regarding the building energy performance certification system further illustrate the scale of the challenge. **Figure 5** presents the distribution of the EPCs that have been issued for dwellings of multi-apartment buildings in Greece. Of the 2,635,938 Energy Performance Certificates (EPCs) issued until 2025, 2,101,455 (79.72%) correspond to dwellings in multi-apartment buildings, confirming the central role of this building typology within the certification system. Within this sample, 1,292,474 certificates (61.50%) fall within the low energy performance classes E, F and G, while only 154,300 (7.34%) correspond to EPC classes A and B.

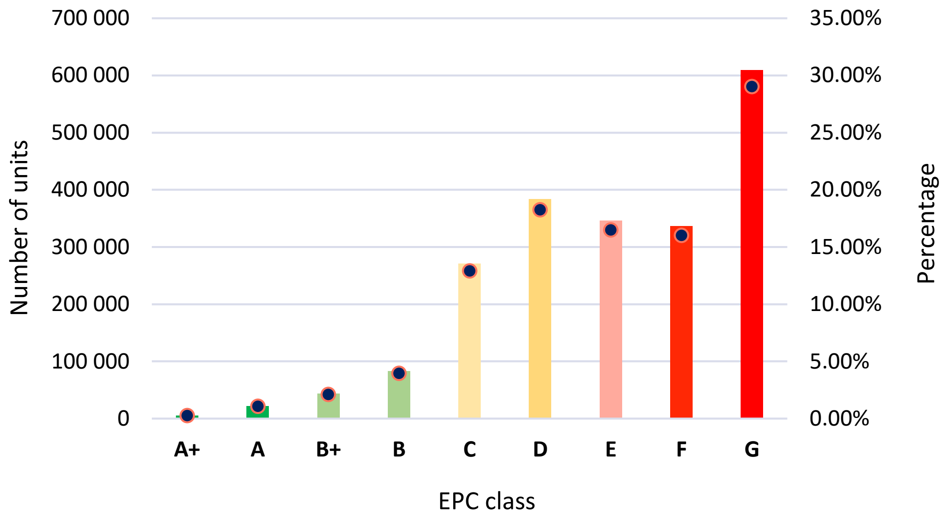


Figure 5. Distribution (numbers and percentages) of the EPCs that have been issued for dwellings belonging to multi-apartment buildings in Greece.

Source: own elaboration based on the Greek Ministry of the Environment and Energy (2025a)

Beyond the energy performance classification of buildings, examining the heating systems used in dwellings provides additional insight into the operational characteristics of the residential stock. According to the Hellenic Statistical Authority (2025), 56.2% of households had central heating, while the main heating systems included oil boilers (36.6%), natural gas boilers (18.4%), air-conditioning units (15.7%), and electric heating appliances (9.3%) (**Figure 6**). These figures illustrate the continued reliance on conventional heating systems, particularly oil-based boilers, across a significant share of the residential building stock.

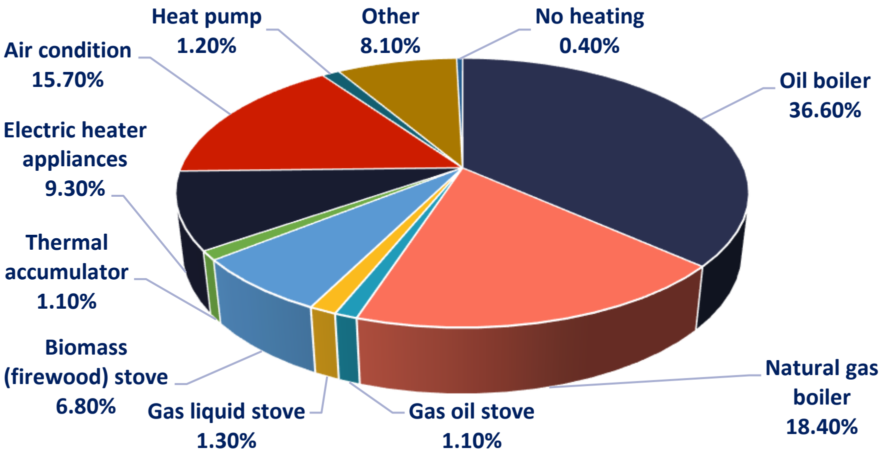


Figure 6. Percentage distribution of households by main heating system in Greece.

Source: own elaboration based on Hellenic Statistical Authority (2025).

In this context, Eurostat and Energy Poverty Advisory Hub (EPAH) indicators highlight the significant scale of energy poverty in Greece (EC, 2026e). In 2024, 19.0% of the population reported being unable to keep their home adequately warm, while the country recorded the highest housing cost overburden rate in the EU (28.9%). According to EPAH data, 26.9% of the population were at risk of poverty or social exclusion, illustrating the broader socioeconomic conditions that exacerbate energy vulnerability. In addition, 32% of households reported arrears on utility bills, indicating widespread financial pressure related to energy costs. Thermal comfort indicators also reveal notable challenges: only 72% of the population reported that their dwelling was comfortably warm in winter, indicating that more than one-quarter of households experience inadequate thermal comfort during the heating season. In the context of multi-apartment buildings, these pressures can be further intensified by the ageing characteristics of a large share of the apartment stock, fragmented ownership structures, and the coexistence of households with different financial capacities within the same building, which can complicate collective renovation decisions and delay energy efficiency improvements.

Against this background, the renovation of dwellings in Greek multi-apartment buildings emerges as a key priority for improving energy efficiency and addressing energy poverty. However, renovation in this building typology is not only a technical issue but also a complex governance and social policy challenge. Several barriers hinder building-level renovation, including the need for collective decision-making among co-owners, unequal financial capacities to contribute to renovation costs, administrative and organisational complexity, and limited access to information on available support schemes (Manias *et al*., 2025).

This necessity is also reflected in Greece's updated National Energy and Climate Plan (2025) (Greek Ministry of the Environment and Energy, 2025b) and the Long-term Renovation Strategy (LTRS) (Greek Ministry of the Environment and Energy, 2021), which is currently under revision. These strategic frameworks set ambitious targets for improving the energy performance of the building stock and accelerating renovation rates in the residential sector. However, achieving these targets requires the effective implementation of policy instruments capable of addressing the structural barriers associated with the renovation of multi-apartment buildings. A central instrument in this policy mix is the "Exoikonomo" programme ("Saving Energy" in Greek), which has been implemented through successive cycles over the past decade and continues with the "Exoikonomo 2025" scheme (Greek

Ministry of Economy and Finance, 2025). The programme supports the energy upgrading of residential buildings through measures such as thermal insulation, window replacement, heating and cooling system upgrades, solar water heaters and smart energy management systems, with subsidy rates ranging from 50% to 100% depending on household characteristics. Complementary initiatives include the "Renovate and Rent" programme (Hellenic Republic, 2026), which provides financial support for the refurbishment of vacant dwellings to increase their availability in the rental market, as well as schemes supporting the installation of rooftop photovoltaic systems in households. In addition, the Greek Ministry of the Environment and Energy has announced a forthcoming package of energy efficiency programmes aligned with the implementation of the revised Energy Performance of Buildings Directive (EPBD), expected to support the renovation of approximately 60,000 residential buildings and the replacement of around 380,000 heating systems in the coming years. Together, these initiatives form the core of the current policy framework supporting residential renovation and energy efficiency improvements in Greece.

2.2 Current situation in the pilot areas

This section presents the characterisation of current situation of multifamily building dwelling stock in the three pilot areas - the City of Rumia (Poland), the City of Torres Vedras (Portugal), and the Municipality of Piraeus (Greece) (**Figure 7**), focusing on constructive elements, periods of construction, energy efficiency indicators, ownership and political efforts and actors involved in this transformation.

Figure 7. The LOCATEE pilot cities (own elaboration)

2.2.1 Rumia

Rumia is a young, rapidly developing city of approximately 53,000 inhabitants, located in Northern Poland, in close proximity to Gdynia and forming part of the Gdańsk-Gdynia-Sopot metropolitan area. Notably, Rumia is the largest city in Poland without county (powiat) status. Population growth has been sustained and is closely linked to the city's spatial planning strategy, which has facilitated residential development in recent decades, particularly through single-family and multi-family buildings targeted at households relocating from the metropolitan area's core cities.

Compared to other Polish cities of similar size, Rumia has a higher share of single-family buildings. Approximately three-quarters of the building stock was constructed after 1989, reflecting the post-transition expansion of housing. This newer stock contrasts markedly with older residential areas: the Szmelta estate, built in the 1930s and representing municipal housing, the relatively limited stock of older homeowner association buildings, and the multi-family, cooperative housing estates of the 1970s and 1980s — concentrated primarily in the Janowo district. The latter constitutes the largest housing cooperative in the city (SM Janowo), home to approximately 10% of Rumia's population.

The number of multifamily buildings and dwellings in the city continues to increase. In 2024, most multifamily buildings are owned by individuals (69%), with homeowner associations accounting for 18% and housing cooperatives for 11% (**Figure 8**). It should be noted that a significant share of privately owned multifamily buildings, as classified in the national building database, are, in practice, small-scale structures comprising only a few units and closely resemble oversized single-family homes. Their presence reflects a tradition of constructing larger, multi-generational homes.

Based on available EPC data, the energy performance of multifamily buildings in Rumia is relatively close to that of other municipalities in Polish metropolitan areas. The mean primary energy indicator stands at 111.2 kWh/m²/year. Buildings with the lowest energy performance tend to be older, especially small homeowner associations converted from former municipal housing stock, as well as buildings currently managed by the municipality. Moreover, we hypothesise that for the majority of buildings with poor energy performance – particularly smaller ones owned by private individuals – energy performance certificates have not been prepared, as such properties are less frequently subject to market transactions or rental. Conversely, newer buildings are generally subject to more stringent technical conditions and exhibit relatively good energy performance; these structures typically rely on district heating, natural gas, or heat pumps.

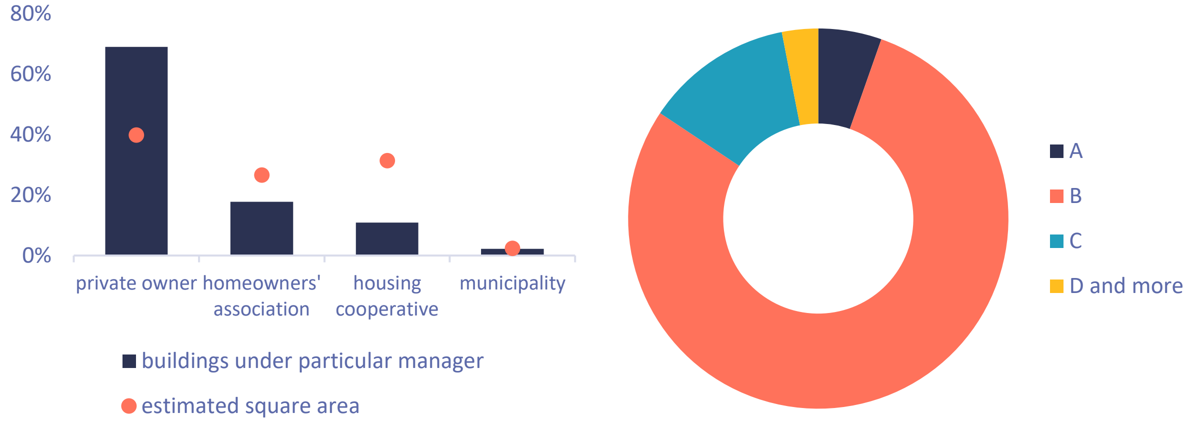


Figure 8. Owners of multi-family buildings, as well as the energy classes. Note: energy classes are assigned in line with the project (National Energy Conservation Agency) and also cover only 1/3 of the multi-family housing stock in Rumia.

Source: own elaboration based on Statistics Poland, Database of Topographic Objects, and EPC database, 2024 (GUGiK, 2024).

Natural gas, district heating, and solid-fuel combustion are the primary heating sources for multifamily buildings in the city. Our estimates based on the CEEB database (Central Register of Emissivity of Buildings) (**Figure 9**) indicate that approximately 70% of dwellings have access to natural gas, while 32% are connected to the district heating network – a relatively low penetration rate by national standards for similar cities. About 21% of dwellings still have solid-fuel-burning appliances; however, many are not in use or not used as a main source. Electric heating is used in approximately 7% of cases. Fuel stacking – the parallel use of multiple heating sources, for example, supplementary fireplace heating in oversized single-family-like buildings – is a relatively common practice.

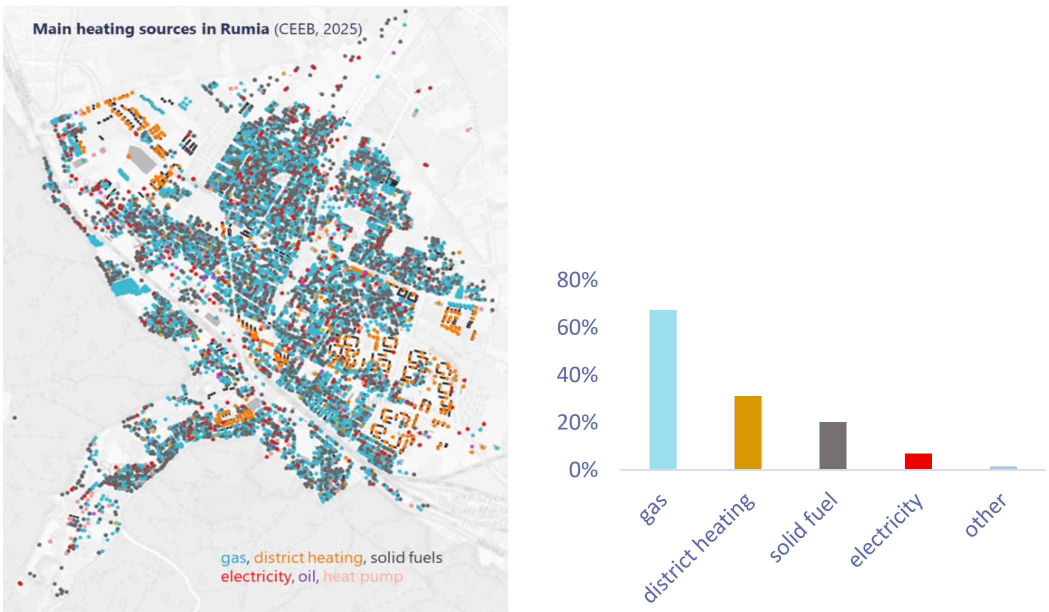


Figure 9. Map of heating sources in residential buildings in Rumia (left) and Access to multi-apartment buildings to the heating sources (right). Note: The results do not sum to 100% due to the simultaneous presence of multiple heating sources.

Source (right): own elaboration based on Central Register of Emissivity of Buildings, 2024.
Source (left): own elaboration based on Central Register of Emissivity of Buildings, 2024.

In general, housing cooperative buildings and municipal stock predominantly rely on district heating, while homeowner associations and privately owned buildings use natural gas or solid fuels. Despite intensive municipal efforts, low-stack emissions remain a challenge in Rumia during heating season, owing to its location and the continued use of individual solid-fuel boilers in single-family buildings and private transport. Data on space-cooling equipment ownership in multifamily buildings in Rumia is limited. Survey data from the largest housing cooperative (SM Janowo) indicates that approximately one in five households already possesses some form of cooling device, highlighting emerging cooling demand in the building stock (Frankowski *et al*., 2025).

The renovation status of Rumia's multifamily building stock is uneven. Housing cooperatives and municipal buildings have benefited to some extent from national funding mechanisms — notably the Ekofundusz and KAWKA programmes — enabling partial thermal modernisation. SM Janowo, the city's largest cooperative, has also pursued more advanced innovations, including building management systems, photovoltaic installations, and well-developed heat management solutions. In contrast, small, privately owned multifamily buildings – frequently constructed before 1989 with low-quality materials – pose greater challenges. Additionally, ageing housing estates from the 1980s and 1990s are showing signs of physical deterioration. Moreover, analysis from the LOCATEE tool identified indicators of energy poverty and financial constraints among these buildings.

Given the structure of its housing stock, the socioeconomic profile of its residents, and its coastal location, Rumia exhibits lower exposure to energy poverty than other Polish municipalities and the national average. Modelling carried out within the project estimates that approximately 20% of buildings face a medium or high risk of energy poverty, with only 4% (45 buildings out of 1072 multi-apartment ones) classified as high risk. A dedicated survey conducted at SM Janowo — Rumia's largest cooperative — provides further granularity. Only 7% of households reported problems with window condensation, excess moisture, or mould. Excess energy expenditure was identified in 6% of cases. Overheating in summer was reported twice as frequently (4%) as severe cold in winter (2%), which is consistent with growing cooling demand in the building stock (Frankowski *et al*., 2025). These figures suggest that, while energy poverty remains a relevant concern, it is less widespread than in other Polish urban contexts with a declining population, a far-from-vibrant local labour market, and a higher share of old housing stock.

The City of Rumia pursues an active climate and energy policy. Primary responsibility for developing and implementing local climate and energy documents rests with the Air and Climate Protection Department at Rumia City Hall, established in 2020–2021. The department employs four staff members, covering competencies in climate and air protection policy, coordination of strategic documents, management of heat source replacement subsidies, and oversight of compliance with national and local regulations. Notably, the department also administers housing benefits - an arrangement uncommon among Polish municipalities – potentially providing the city with an instrument for addressing energy poverty in an integrated manner.

Regarding instruments specifically targeted at multifamily buildings, the city acted as an animator for the national “Warm apartment” programme. The municipality also monitors and disseminates information to building managers regarding available financing schemes from the Regional Fund for Environmental Protection and Water Management (WFOŚiGW), Bank Gospodarstwa Krajowego (BGK), and the Pomeranian Development Fund (PFR), operating through a local advisory point. Moreover, the city offered small subsidies for heating-source replacement – a measure that has largely been implemented in multifamily buildings. It also maintains limited influence over local district heating operators and lacks dedicated own-source financing instruments, though it awards housing allowances, a national instrument dedicated to eligible households. More broadly, Polish municipalities — beyond heating source replacement — less frequently provide direct financial support for building renovation but retain significant capacity to coordinate and stimulate such activities through strategic documents and educational initiatives. In this regard, Rumia stands among the more active local authorities, as evidenced by its participation in the Zielony Lider initiative, its high results in replacing old stoves in single-family buildings under the Clean Air Programme, and the organisation of regional training events for other municipalities.

Beyond the city council, a range of institutional and civil society actors support the energy renovation and efficiency of multifamily buildings. Housing cooperatives — particularly SM Janowo – are significant actors due to their technical capacity and ongoing investment in energy management. Homeowner associations, though smaller and more fragmented, represent an important segment of the stock that is less institutionally supported. Engaging building owners in Rumia requires a tailored communication strategy. The diversity of ownership forms – Individual owners, small associations, cooperatives, and municipal holdings – demands differentiated approaches. In terms of the other stakeholders, the important role is mostly with local councillors and, to a limited extent, with NGOs.

2.2.2 Torres Vedras

In Torres Vedras, a steady rise in population has been observed in the municipality since 1864 (INE, 2021b), with population numbers doubling in the last one hundred years, directly impacting the configuration of the multifamily building stock. Compared to the national dwelling stock, the dwelling stock in Torres Vedras follows a similar distribution (**Figure 10**), with the highest shares of dwellings found in buildings from the periods 1961-1990 and 1990-2005 (INE, 2021a). The percentage of more recent buildings (after 2005) is slightly higher than the national figures (respectively 11.8% and 10.4%). This is consistent with the population growth, which peaked in the periods of 1970-1980 and 2001-2011. The rising population can be linked to a higher demand for housing and a growth of the multi-apartment building stock in the municipality, particularly in more urban civil parishes like União das Freguesias de Torres Vedras (São Pedro, Santiago, Santa Maria do Castelo e São Miguel) and Matacães, where the city of Torres Vedras is located. Conversely, the civil parishes of União das freguesias de Carvoeira e Carmões (18%) and União das freguesias de Dois Portos e Runa (17%) have the older dwelling stock (before 1946) in this specific typology.

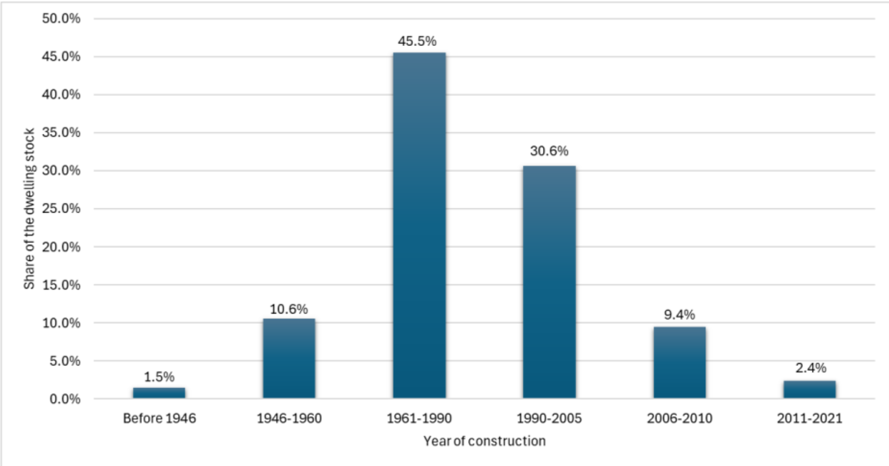
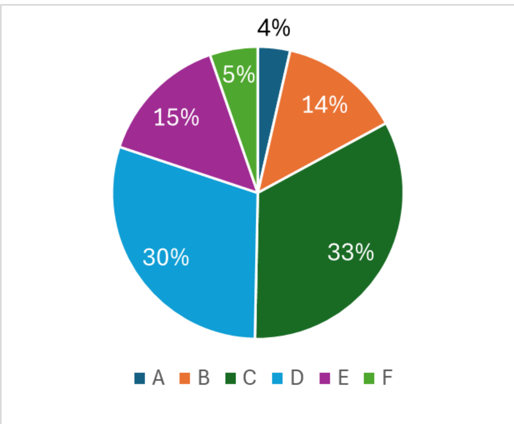


Figure 10. Share of dwellings per multifamily building period of construction in Torres Vedras

Source: own elaboration based on INE (2021)

Home ownership is also the common scenario in Torres Vedras, with 73% of dwellings occupied by the property owner (INE, 2021a). Peripheric civil parishes like Ventosa and São Pedro da Caldeira, predominantly rural, have higher shares of home ownership (83.3% and 82.0%), while more urban civil parishes like União das Freguesias de Torres Vedras and Matacães have lower rates (64.8%), possibly due to a more relevant rental property market.

Considering that the first building energy performance regulation dates back to 1990, the building quality and energy efficiency standards are not consistent across older typologies. As shown in **Figure 11**, the EPC class distribution of multifamily dwellings in the municipality indicates that most dwellings have a substandard EPC class (under current regulatory standards) of C (33%) or D (30%), consistent with the national trend. In a more in-depth look at dwellings by period of construction, an association is found between older dwellings and higher percentages of lower EPC classes, which is consistent with the adoption and impact of different energy performance regulations on multifamily building EE levels. However, regulations do not entirely prevent low EPC classes in some dwellings from more recent construction periods.



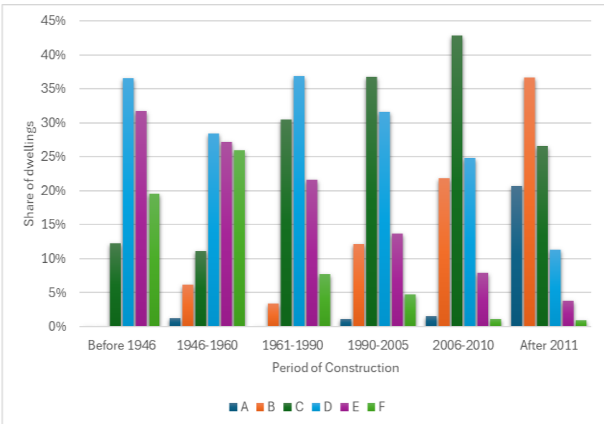
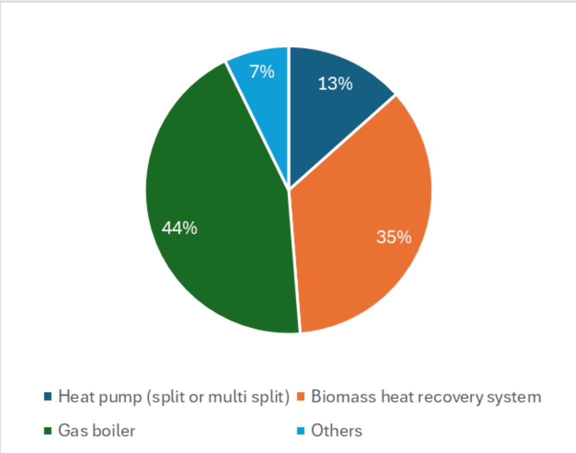


Figure 11. Share of EPCs for dwellings in multifamily buildings per class (left) and dwellings' period of construction (right) in Torres Vedras

Source: Own elaboration based on ADENE (2026b)

Regarding the stock of space-heating and cooling equipment, gas boilers are the primary system used for space heating, followed by biomass heat recovery systems (**Figure 12**). The predominance of this type of equipment presents a compound opportunity to increase energy efficiency, lower energy bills, promote decarbonisation, and potentially improve indoor and outdoor air quality. In approximately 13% of dwellings, a heat pump is already being used for space heating, a more efficient solution. Space cooling equipment ownership is considerably lower than space heating equipment, and households use almost exclusively a heat pump or A/C unit, either split (56.5%) or multi-split (41.4%). It is important to note that EPCs, as previously mentioned, do not acknowledge ownership of portable individual systems such as electric heaters and ventilators, which are inexpensive but considerably less efficient options that potentially coexist with and compete with these fixed systems.



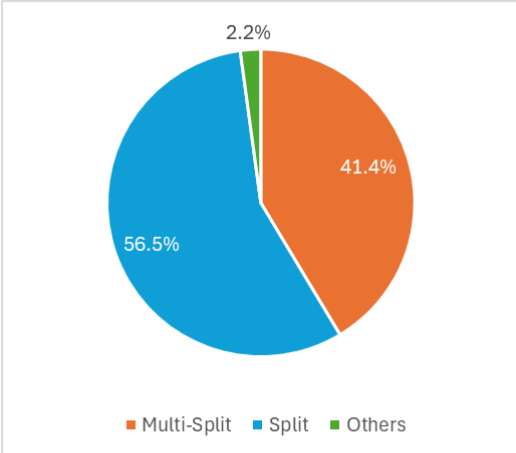


Figure 12. Share of space heating systems of dwellings in multifamily buildings in Torres Vedras

Source: Own elaboration based on ADENE (2026b)

Building envelope characteristics also differ from those of the national building stock. In general, more efficient window solutions are more common than the national average. Around 53.1% of dwellings (**Figure 13**) have double glazing, either with metal or plastic frames. Wooden window frames are also relatively common (15.1%), a feature associated with improved thermal and acoustic performance. Regarding the opaque envelope, most dwellings are part of a building with a horizontal roof without thermal insulation (62.1%). A poorly insulated roof is often the source of considerable heat loss. Similar to the national building stock, the main wall solution is single- or double-plastered walls (after 1960) (55.3%). Single (17.8%) and double walls (15.3%) without thermal insulation are the following most common solutions. Pavement with thermal insulation is the most prevalent pavement solution, found in 81.8% of dwellings, highlighting potential further gains in energy efficiency if this building element is targeted.

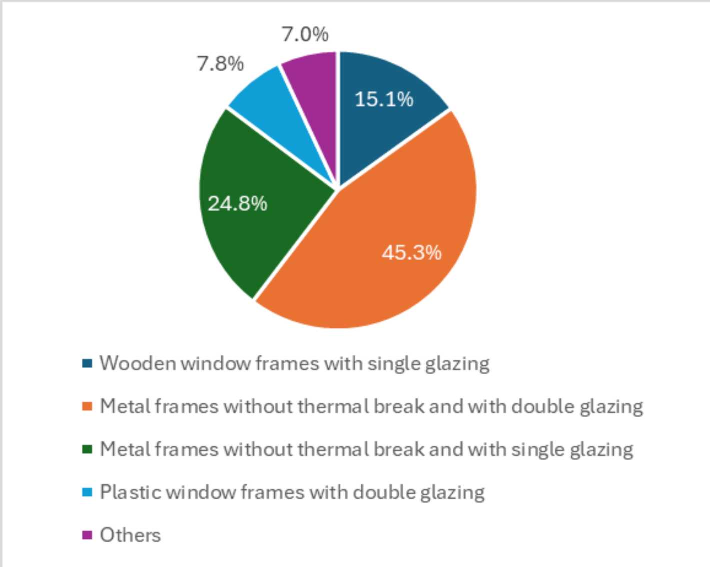


Figure 13. Share of dwellings in multifamily buildings per window solution in Torres Vedras

Source: Own elaboration based on ADENE (2026b)

To tap into existing potential, the city council is a key actor in promoting energy renovation and efficiency in private multifamily buildings. Its planned actions and instruments are integrated into broader policy plans and strategies that aim to drive the comprehensive transformation of different sectors towards sustainability. The Municipal Climate Action Plan is an example that integrates energy efficiency improvements, technical support for vulnerable households, and incentives for the adoption of renewable energy, aligning with the municipality's commitment to climate mitigation, adaptation and social equity. Focusing directly on housing accessibility, the Local Housing Strategy of the Municipality of Torres Vedras aims to address structural housing needs. According to the addendum to the co-financing agreement, the total investment is 60 million euros for approximately 444 housing solutions. A few instruments are also enacted to support the renovation of private multifamily buildings:

- **1st Right Program** [1.º Direito] – National program that funds rehabilitation and construction solutions, with positive impacts on thermal performance and overall living conditions, of vulnerable households, applicable to private and public buildings.
- **Co-financing Program for Conservation, Repair or Improvement of Degraded Housing** [Programa para a Comparticipação em Obras de Conservação, Reparação ou Beneficiação de Habitações Degradadas (PCOCRBHD)] – Provides financial support for rehabilitation works in degraded dwellings occupied by residents in socio-economic vulnerability, addressing dampness, insulation deficits, structural degradation and other issues directly relevant to household energy performance.
- **Instrumento Financeiro para a Reabilitação e Revitalização Urbanas** (IFFRU) [Financial Instrument for Urban Rehabilitation and Revitalization] - It offers loans on more favourable terms than the market for the complete renovation of buildings used for housing or other activities, including appropriate integrated energy efficiency solutions within the scope of the renovation (CM-TVedras, 2026).

- **Urban taxes exemption** – attributed to dwellings in the Areas of Urban Rehabilitation for works including building renovation and rehabilitation (CM-TVedras, 2026).

In collaboration with the central administration, the municipality, through the Planning and Territorial Management Division – Housing and Urban Regeneration Unit provides direct and technical support to citizens and investors, namely consultancy and information about rehabilitation interventions, eligibility in Urban Rehabilitation Areas (ARUs), tax benefits, exemptions and conducting inspections to verify the rise in level in the state of conservation after de interventions. In the municipality of Torres Vedras, the UHRU manages 7 Urban Rehabilitation Areas (ARU) currently in effect, with the ARU territory covering approximately 55% of the existing built-up area.

The municipality also operates the Espaço Energia, an Energy One-Stop-Shop (OSS) integrated within the national network of OSS – Rede Espaço Energia, technically supported by the national energy agency (ADENE) and funded by the Recovery and Resilience Plan. The OSS supports citizens on energy bills, renovation options, financing schemes, and renewable solutions, promoting community-level engagement to address energy poverty.

Other stakeholders also play a relevant part in supporting energy renovation and efficiency of multifamily buildings. Central administration institutions such as IHRU (Instituto for Housing and Urban Rehabilitation) also play a significant role, as they own dwellings in mixed-property buildings in the municipality. As Maria da Graça Igreja, director of the IHRU’s Observatory of Housing, Renting and Urban Regeneration, noted, by upholding high energy performance standards in their public dwellings and promoting renovation, they push private households in the same buildings to do the same. Also, the municipality identifies dwellings in need of support under the 1st Right Program, which is managed by IHRU. The city council also collaborates with associations like Just a Change, in the identification of vulnerable households in need of home rehabilitation and renovation, which is conducted by the association. Engaging with building owners is also a key component of a comprehensive strategy for building renovation. These stakeholders are diverse and often unresponsive, requiring a dedicated, tailored communication and engagement strategy that clearly highlights the potential benefits and support opportunities. For individual owners, building management companies, UHRU technicians, and the Municipal Social Service are important intermediaries in this process due to their role and proximity to property owners from the beginning to the end of the intervention.

2.2.3 Piraeus

The Municipality of Piraeus is understood as a mature, highly urbanised and historically compact port city whose multi-apartment building stock reflects long-standing metropolitan densification rather than contemporary outward growth. Piraeus is often described as demographically stagnant within the Athens metropolitan area since the 1950s, with only limited long-term population change compared with surrounding suburban municipalities (Maloutas, 2017). More specifically, Piraeus’ permanent population declined from 181,933 residents in 2001 to 163,688 in 2011. Today (2026), the municipality has 168,151 residents (ELSTAT, 2023), ranking among the five most populous municipalities in the country and among the most densely populated (Climate Piraeus, 2026).

Urban building stock data for Piraeus indicate an ageing and vertically dense built environment. More specifically, 61.3% of buildings have three or more floors, confirming the structural importance of multi-apartment buildings in the municipality’s housing system. The same data indicate that 81.7% of buildings are constructed from reinforced concrete, while 9.8% are assessed as being in poor condition and only 59.5% in good condition. From a climate-resilience perspective, the central area of Piraeus remains densely residential and functionally mixed, but with very limited green space (Municipality of Piraeus, 2021; Climate Piraeus, 2026). In particular, the 1st Municipal Community provides only 0.45 m² of urban green space per resident, while the 2nd Municipal Community provides 1.85 m² per resident. In practice, this combination of ageing reinforced-concrete apartment buildings, high urban density and scarce greenery increases the relevance of building-envelope retrofits and measures addressing summer overheating, which are closely related to issues of thermal comfort and energy poverty in dense urban environments.

The ageing profile of buildings in Piraeus is reflected in the distribution of dwellings by construction period. More specifically, 63.72% of dwellings were constructed before 1981, while 35.14% of them were built between 1981 and 2010. By contrast, only 1.14% of dwellings date from 2011 onwards (Greek Ministry of the Environment and Energy, 2025c). These figures indicate that most of the municipality's housing stock was developed either before the introduction of modern building energy standards or during transitional regulatory periods when thermal insulation and energy performance requirements remained below current expectations. The latter suggests that energy inefficiency is not limited to isolated cases but represents a structural characteristic of the city's residential stock.

This structural profile is also reflected in the distribution of EPC classes among dwellings in the municipality. In a total of 48,405 dwellings, only 2,038 (4.21%) fall within the higher-performing EPC classes A+, A, B+ and B. By contrast, 18,300 dwellings (37.81%) are classified in the intermediate range of classes C, D and E, while 28,067 dwellings (57.98%) belong to the lowest-performing classes F and G (**Figure 14**). This distribution indicates that the majority of dwellings in Piraeus are concentrated at the lower end of the EPC spectrum, pointing to the poor thermal and energy performance of a substantial share of the local residential stock, which is consistent with the predominance of pre-1981 buildings.

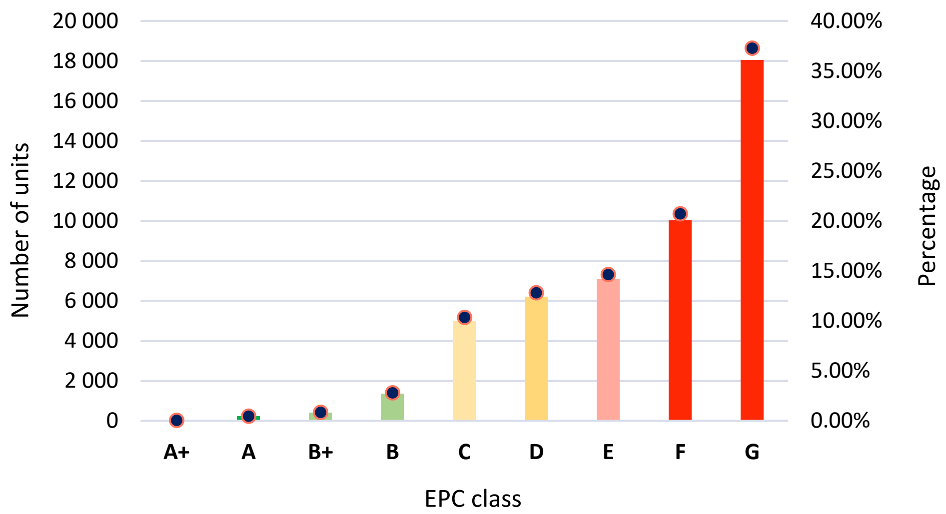


Figure 14. Distribution (numbers and percentages) of the EPCs that have been issued for dwellings belonging to multi-apartment buildings in the Municipality of Piraeus.

Source: Own elaboration based on the Greek Ministry of the Environment and Energy (2025c)

Beyond the energy performance of buildings, the heating systems used in dwellings provide further insight into the operational characteristics of the residential stock in Piraeus. The profile of heating systems in the municipality reveals a strong dependence on carbon-intensive and often inefficient technologies. More specifically, 32,509 dwellings (67.16%) rely on oil boilers for heating, making oil by far the dominant heating source. A further 4,801 dwellings (9.92%) use gas boilers, while 8,967 dwellings (18.52%) rely on electricity for heating, including electric heaters or air-conditioning units (Greek Ministry of the Environment and Energy, 2025c).

This distribution is particularly relevant in the context of private multi-apartment buildings, as it may reflect several structural challenges. The continued predominance of oil boilers suggests a potential decarbonisation gap, while the limited penetration of gas indicates that the transition away from oil remains gradual. At the same time, the use of electricity for heating may reflect both the uptake of air-conditioning units and the use of portable electric heaters in households where central systems are not fully operational. In a dense municipality such as Piraeus, these patterns can be associated with issues of energy poverty, thermal comfort and uneven access to energy services across different apartment households.

More specifically, following the bottom-up methodology for estimating energy poverty outlined in LOCATEE's report ("***Varieties of domestic energy deprivation in private multi-apartment buildings: Insights from Poland, Portugal and Greece***") (Frankowski *et al.*, 2025), approximately 28% of apartments in multi-apartment buildings in Piraeus are likely to be affected by energy poverty (13,552 out of 48,405 apartments). The analysis is conducted at the apartment level, based on the availability of relevant data such as EPC classes and heating systems. This preliminary estimation will be further refined as additional socio-demographic parameters (e.g., income, gender and residents' age) are incorporated into the vulnerability index, which is currently under development.

Given the characteristics of the local building stock and the challenges associated with energy poverty, promoting renovation and improving energy efficiency in residential buildings is particularly relevant in the Municipality of Piraeus. For the Municipality's policy framework, this priority is reflected in the current Sustainable Energy and Climate Action Plan (SECAP), which was updated at the end of 2024. It identifies the energy upgrading of private buildings as a necessary field for intervention for achieving local energy and climate targets (by 2030, energy savings could reach 84,866.09 MWh per year). At the same time, the municipality's more recent strategic framework has been further strengthened through the Municipal Emissions Reduction Plan (MERP/ΔηΣΜΕ, February 2026), while the Building Energy Performance Plan (BEMP/ΣΕΑΚ, October 2024) provides an additional operational basis for energy planning in the municipal building stock. Taken together, these documents indicate that Piraeus has developed a broader and more structured climate governance framework, within which actions related to building energy efficiency, emissions reduction, public awareness and social resilience can be better coordinated.

In the case of private multi-apartment buildings, the role of the municipality is mainly enabling, coordinating and supportive, since the main financial instruments for residential energy renovation are designed and implemented at the national level. In this context, the SECAP emphasises promoting energy upgrades in private buildings and improving energy use conditions in the residential sector, while the broader municipal climate policy also includes awareness-raising and climate governance mechanisms, such as the Climate Change Office/CLIMATE PIRAEUS and related information initiatives. Therefore, the contribution of the municipality is better understood as facilitating access to information, mobilising citizens, linking local needs with available programmes and strengthening the local institutional environment for renovation, rather than directly financing large-scale interventions in private dwellings.

This enabling role is especially important in relation to vulnerable households that may face overlapping social and energy-related disadvantages. The updated policy documents of the Municipality of Piraeus highlight a broader system of social support and inclusion measures, including actions to widen access of vulnerable groups to social care services, networks for the prevention and response to discrimination, and the Social Innovation Piraeus/KODEP mechanism for immediate social intervention. These structures do not constitute dedicated building-renovation instruments as such, but they provide institutional channels through which households at risk can be identified, approached, and supported. In this respect, municipal services and collaborating organisations could act as intermediaries for the diagnosis of housing and energy needs through LOCATEE tools and methodologies, and for referral to appropriate technical support and advisory services on national renovation schemes.

3 Methods

This section presents the adopted approach to assess the potential impact of energy renovation scenarios on energy performance, energy efficiency, and carbon dioxide (CO_2) footprint, and their cost-effectiveness for reducing energy demand for representative dwellings in each pilot area. Firstly, the dwelling characterisation is presented, employing a dwelling typology-based approach to identify representative dwelling types based on the distribution of dwellings in each pilot area according to period of construction, EPC class, and heating system. Secondly, the model for assessing the energy performance of dwelling typologies and the impact of energy-efficiency interventions is presented, with a detailed description of the energy-demand method and the corresponding input and output variables. Thirdly, the different energy efficiency scenarios are described, reflecting a selection of energy efficiency measures tailored to each specific context.

3.1 Dwelling stock typology characterisation

The first step in the comprehensive analysis of energy efficiency scenarios and their implications for energy poverty vulnerability in the pilot regions is a process of dwelling characterisation and parametrisation. Firstly, detailed datasets on multifamily buildings in the City of Rumia (Poland), the City of Torres Vedras (Portugal), and the Municipality of Piraeus (Greece) were collected from multiple sources, including national statistical authorities, Energy Performance Certificate (EPC) databases, ministries of energy, and other relevant institutional repositories. These datasets constitute the empirical foundation for the typology development presented in this section.

The collected data covered key aspects of the residential building stock, such as construction period, EPC class, total (habitable) dwelling area, heating system type, and primary and final energy consumption. Building envelope parameters, including surface areas and thermophysical properties (e.g., U-values of walls, roofs, floors, and windows), and heating systems parameters (e.g., type, nominal capacity, and coefficient of performance) were collected, using national building regulations, regulatory databases, EPC microdata, and relevant technical standards for each construction period.

Information on occupancy and activity patterns was not uniformly available at the local level and was therefore derived using national statistical data (PT (INE, 2021b; INE,2021c), PL (Statistics Poland, 2022), GR (Greek Ministry of the Environment and Energy, 2025b; ELSTAT, 2026) and established analytical approaches, allowing the estimation of representative household size, number of working members, and indicative working schedules for each pilot region.

Based on the collected datasets, aiming to capture dwelling stock variability and address its complexity, representative dwelling typologies were defined for each pilot region. Each typology provides consistent inputs for simulations. Model multifamily buildings from the TABULA database (TABULA, 2026) were also used as a reference for the residential housing stock in the pilot areas. The typology development followed a structured disaggregation approach. First, dwellings were grouped according to construction period, reflecting differences in construction practices and energy performance regulatory frameworks over time. Construction periods representing a larger share of the dwelling stock were assigned a proportionally higher number of typologies to ensure adequate representation. Subsequently, within each construction period, additional differentiation was performed based on the distribution of dwellings by EPC class, capturing variations in energy performance within that period. It is important to note that the EPC classification system is not harmonised across Europe. The same

EPC class might have different criteria, thus cross-country comparisons between typologies of different countries should be treated with caution.

Within the EPC class, the type of heating system was also used to differentiate subcategories, given its impact on the selection of potential energy efficiency measures to be applied. The typologies in Rumia and Torres Vedras were selected based on the frequency and representativeness of each category to capture relevant differences within the dwelling stock. In Piraeus, a more systematic method was applied. To assign representative energy consumption values to each construction period/EPC class pair, the mean primary or final energy consumption was calculated. For the calculation of the mean (primary/final) energy consumption for each construction period/EPC class pair, the following formula was used:

$$\mathrm{EC_{mean,p,c}} = \frac{1}{\mathrm{n_{p,c}}} \cdot \sum_{\mathrm{i=1}}^{\mathrm{n_{p,c}}} \mathrm{EC_i} \quad \left[\frac{\mathrm{kWh}}{\mathrm{m^2 \cdot year}}\right]$$

Where:

- p denotes the construction period of the dwelling,
- c denotes the EPC class,
- $\mathrm{EC_i}$ is the (primary/final) energy consumption of dwelling i (in kWh per m^2 per year) belonging to pair (p, c),
- $\mathrm{n_{p,c}}$ is the number of dwellings in that pair.

A weighted average approach was then applied within each construction period, based on the number of dwellings in each EPC class, ensuring that the resulting typologies reflect the statistical distribution observed in the pilot datasets. The weighted average approach based on EPC classes within each construction period was computed as follows:

$$\mathrm{EC_{weighted}} = \frac{\sum_{\mathrm{j=1}}^{\mathrm{m_{p,c}}} \mathrm{EC_{mean,p,c}} \cdot \mathrm{N_{p,c}}}{\sum_{\mathrm{j=1}}^{\mathrm{m_{p,c}}} \mathrm{N_{p,c}}} \quad \left[\frac{\mathrm{kWh}}{\mathrm{m^2 \cdot year}}\right]$$

Where:

- $\mathrm{m_{p,c}}$ denotes the total number of dwellings in the construction period/EPC class pair (p, c),
- $\mathrm{EC_{mean,p,c}}$ is the mean (primary/final) energy consumption for each construction period/EPC class pair as calculated above,
- $\mathrm{N_{p,c}}$ is the number of dwellings in EPC class c within construction period p.

After calculating the $\mathrm{EC_{weighted}}$, to define which EPC class is matched to each dwelling typology, the $\mathrm{EC_{weighted}}$ is matched with the closest $\mathrm{EC_{mean,p,c}}$. Then, for each typology, the (primary/final) energy consumption (for heating/cooling), the heated/cooled area of the dwelling and the dominant heating system, the household members and the working household members are matched, based on the datasets available for each pilot area. A similar approach is followed for each construction period.

Based on the methodological process described above, a set of representative dwelling typologies was developed for each pilot region. In total, the **five (5)** typologies were defined for the City of Rumia

(Poland), **ten (10)** typologies for the City of Torres Vedras (Portugal), and **eight (8)** typologies for the Municipality of Piraeus (Greece), whose main characteristics are presented in **Table 1**.

Table 1. Main description of Dwelling typologies

Typology ID	Pilot Location (Country)	EPC Class	Period of Construction
PL_1	Rumia (Poland)	B	1980 and before
PL_2	Rumia (Poland)	C	1980 and before
PL_3	Rumia (Poland)	C	1980 and before
PL_4	Rumia (Poland)	B	After 1980
PL_5	Rumia (Poland)	B	After 1980
PT_1	Torres Vedras (Portugal)	C or D	Before 1981
PT_2	Torres Vedras (Portugal)	E or F	Before 1981
PT_3	Torres Vedras (Portugal)	C or D	1981-2000
PT_4	Torres Vedras (Portugal)	C or D	1981-2000
PT_5	Torres Vedras (Portugal)	E or F	1981-2000
PT_6	Torres Vedras (Portugal)	E or F	1981-2000
PT_7	Torres Vedras (Portugal)	C or D	2001-2010
PT_8	Torres Vedras (Portugal)	C or D	2001-2010
PT_9	Torres Vedras (Portugal)	E or F	2001-2010
PT_10	Torres Vedras (Portugal)	E or F	2001-2010
GR_1	Piraeus (Greece)	D	Before 1981
GR_2	Piraeus (Greece)	F	Before 1981
GR_3	Piraeus (Greece)	G	Before 1981
GR_4	Piraeus (Greece)	C	1981-2010
GR_5	Piraeus (Greece)	C	1981-2010
GR_6	Piraeus (Greece)	E	1981-2010
GR_7	Piraeus (Greece)	G	1981-2010
GR_8	Piraeus (Greece)	G	1981-2010

The full detailed information on the dwelling typologies is displayed in **Annex A**

, in **Table A1 to Table** A6. The number of typologies per pilot reflects the distribution of dwellings across construction periods and EPC classes, as well as the relative heterogeneity of the local building stock.

Each typology represents a distinct combination of construction period and EPC class and is characterised by specific geometric, thermophysical, and energy-related parameters. These include total habitable area, envelope surface areas, U-values of main building components (walls, floors, roofs, and windows), and representative energy performance indicators. These typologies capture structural differences between older and newer building segments, as well as variations in thermal performance within the same construction period.

3.2 Modelling Approach and Parameterisation

The **D**ynamic high-**R**esolution d**E**mand-sid**E** **M**anagement (**DREEM**) model is employed to assess the energy performance of representative building typologies identified in the pilot regions and to evaluate the potential impact of energy efficiency interventions. DREEM is a dynamic, bottom-up, high-resolution building energy demand model that simulates energy consumption by incorporating key physical and technical parameters, including building geometry, material composition, thermal resistance, and heating and cooling system characteristics (Stavrakas and Flamo, 2020). DREEM is part of the TEESlab modelling (TEEM) suite. All the model's modules have been developed using the "Buildings" library[1], an open-source, freely available Modelica library for building energy and control systems (Wetter, 2010; Zuo *et al.*, 2015; Bünning *et al.*, 2017). The DREEM model follows a modular architecture (**Figure 15**) comprising multiple components and modules, enabling flexible system configurations and computationally efficient, high-resolution simulations across a broad scenario space. This structure allows for the systematic exploration of energy demand dynamics and renovation pathways under varying technical and climatic conditions.

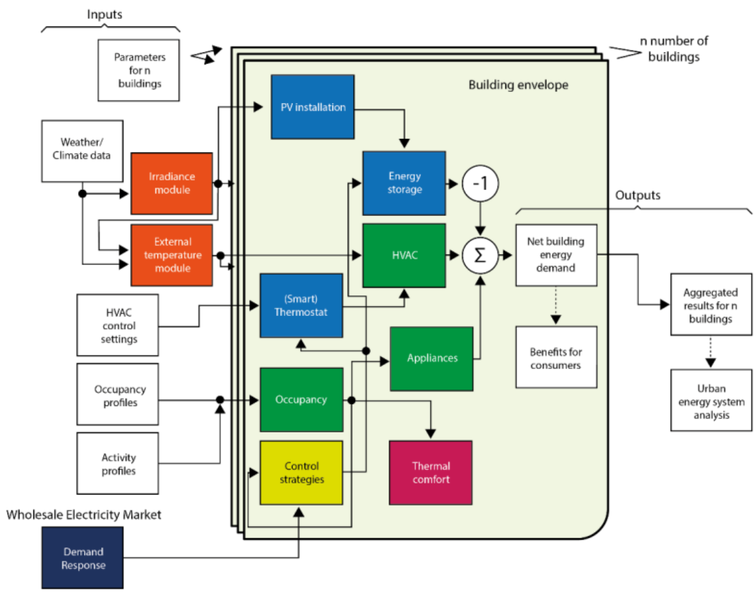


Figure 15. The original architecture of the DREEM model as presented by Stavrakas and Flamos (2020).

In the present analysis, the key DREEM components employed include:

- C_1: **Climate/ weathe**r data, which provide the exogenous boundary conditions for heating and cooling demand. It generates accurate climatic boundary conditions based on historical weather data using the Typical Meteorological Year (TMY) weather data format. These data is configured to provide a common set of time-diverse high-resolution irradiance and temperature data for the geography under study. For each pilot, meteorological data are selected using a proximity-based approach, relying on the closest available reference locations to best capture local climatic conditions. For the City of Rumia in Poland (Pilot 1), data are available for the district of Oksywie in the City of Gdynia (around 11.0 km away from Rumia).

[1] https://simulationresearch.lbl.gov/modelica/.

For the City of Torres Vedras in Portugal (Pilot 2), we use meteorological data from the Municipality of Sintra (around 34.8 km away from Torres Vedras). Finally, for the Municipality of Piraeus in Greece (Pilot 3), we utilise meteorological data from the district of Hellinikon Olympic Complex (around 8.90 km away from Piraeus).

- C_2**: Building envelope**, capturing structural and thermal characteristics such as materials, insulation levels, and heat transfer properties. The model builds on the concept of "reduced (low)-order" thermal network modelling, which represents a thermal zone by thermal resistances and capacities (RC-network), using the electrical circuit analogy, in which voltage is analogous to temperature and current is analogous to convective and radiative heat transfer (McKenna and Thomson., 2016; Harish and Kumar, 2016). The respective module represents all the main thermal masses of the building/dwelling under study as four elements, accompanied by supportive features for consideration of solar radiation (as visualised by Stavrakas and Flamos, 2020). To parameterise the envelope characteristics that correspond to each typology, information for heat transfer coefficients and thermal resistances and capacities was collected through each country's building regulation standards and regulations, national technical documentation and relevant scientific literature sources.
- C_3: **Energy demand**, modelling end-use consumption for space heating and cooling based on building and occupancy parameters. The DREEM model builds on the concept of stochastic modelling and provides simulated data about households' energy demand. This component uses a bottom-up approach to simulate energy consumption, accounting for household occupancy, appliance use, and Heating, Ventilation, and Air-Conditioning (HVAC) options. The component's individual modules use simplified assumptions to simulate various aspects of energy demand (occupancy and citizens' activity profiles, sharing of appliances, etc.) and uses collected data and, where necessary, relevant national statistical and historical datasets, from census and/or national survey.

- C_4: **Thermal comfort**, representing the benchmark indoor environmental conditions used to determine baseline energy needs and assess performance improvements following energy efficiency interventions. The model addresses the occupants' thermal comfort by utilising an individual component that aligns with international standards ("DIN EN ISO 7730", "ASHRAE 55", "EN 15251"). Built upon the Fanger (1970) approach, it employs the characteristic "Predicted Mean Vote (PMV)" and "Predicted Percentage of Dissatisfaction (PPD)" indices. The model calculated PMV and PPD, by considering environmental and personal parameters (e.g., dynamic metabolic rates and clothing insulation), adjusted based on seasonal variations. The acceptable ranges of the PMV and PPD indices are presented in **Table B1 of Annex B.** To configure suitable indoor temperature ranges and define indoor temperature setpoints for each simulation period, the analysis follows the approach proposed by Stavrakas and Flamos (2020). This approach is grounded in the relationship between mean indoor air temperature and mean outdoor air temperature across the different climate zones represented in the pilot areas, under varying weather conditions and across three (3) seasonal periods: **Period 1 - Mild conditions (**April, May, October, and November); **Period 2 - Warm conditions (**June to September; and **Period 3 - Cold conditions (**December to March). For Period 1, thermal comfort setpoints are defined using the de Dear and Brager (1997) adaptive comfort model developed for HVAC applications. For Periods 2 and 3, acceptable indoor temperature ranges are established by examining the relationship between PMV values and indoor temperatures, consistent with prior relevant studies (Brennan and Owende, 2010). Critical combinations of PMV and indoor temperature are simulated and used to derive linear trendlines, which then inform the selection of acceptable indoor temperature setpoints.

A more detailed description of each module is displayed in **Table B1 of Annex B**. Baseline energy consumption is estimated based on thermal comfort benchmarks, representing the level of energy demand required to ensure adequate indoor environmental conditions. Subsequently, renovation and energy efficiency measures (e.g., insulation upgrades, heating technology replacement) are simulated to quantify changes in energy demand and associated CO_2 emissions. CO_2 emissions are calculated using the national emission factors. For Rumia, the following emissions factors were used: electricity: 0.592 $kgCO_2/kWh$; natural gas: 0.202 $kgCO_2/kWh$; DH: 0.450 $kgCO_2/kWh$) (Ember, 2016; Bastos *et al*. 2024; PAPCHPP, 2022). For Torres Vedras, the following emission factors were applied in this study: electricity: 0.128 $kgCO_2/kWh$; natural gas: 0.202 $kgCO_2/kWh$; biomass: 0.360 $kgCO_2/kWh$ (Ember, 2016; Bastos *et al*. 2024). For Piraeus, the following emission factors were used: electricity: 0.316 $kgCO_2/kWh$; natural gas: 0.202 $kgCO_2/kWh$; fuel oil: 0.267 $kgCO_2/kWh$) (Ember, 2016; Bastos *et al*. 2024). The modelling results serve as quantitative inputs for the assessment of the cost-efficiency of different energy efficiency measures and their prioritisation across different building and household typologies.

3.3 Renovation Scenarios and Cost-effectiveness Analysis

After establishing the baseline scenario, which concerns the annual energy consumption required to maintain appropriate thermal comfort levels, the model was further used to assess the key impacts of adopting different energy-efficiency measures. The modelling simulations examine how different measures affect energy performance and energy efficiency and provide insights into CO_2 footprint reduction. It also serves as the base analysis for the identification of the most cost-effective measures. Building envelope, HVAC system replacement and PV installation scenarios were tested across the methodologies. The following measures were tested individually:

- Dwelling envelope improvement: external wall insulation and window replacement in every typology, towards the improvement of thermal performance to each country's regulation standards.
- Heating system upgrade: Two different approaches were applied. Firstly, the replacement of gas boilers, biomass boilers and district heating systems with a higher-efficiency option of the same type of system. This aims to account for cases where the context is either marked by access to cheap fuel (e.g. biomass in Portugal), technological difficulties in certain groups preventing adaptation to a different system, reduced installation costs, and dwelling compatibility. Secondly, replacement of all heating systems by heat pumps, which are the most efficient system available in the market, linked to a deeper shift in the current HVAC stock a faster and fuller decarbonisation and electrification of the domestic energy system.
- Renewable electricity production: the installation of a renewable PV system in every typology.

The tested energy efficiency measures analysed are summarised in **Table 2**.

Table 2. The renovation scenarios, the respective measures and the applicable typologies.

Type of Scenario	Included measures	Applicable typologies
Dwelling envelope improvement	*Wall insulation & windows upgrade*	All
Heating system upgrade	*Boiler upgrade (Upgrading boiler to a high-efficiency condensing gas boiler)*	GR_1-7, *PT_4, PT_8, PT_10, PL_2, PL_5*
	Biomass heating system upgrade	*PT_3, PT_6, PT_7*
	District heating (DH) connection (Replacing gas boiler with connection to the local DH system)	*PL_2, PL_5*
	Heat pump installation	*All*
Renewable eletricity production	*Installation of a residential photovoltaic (PV) system*	All

The technical specifications (i.e., U-values for thermal insulation of walls and windows, nominal capacity and coefficient of performance of the different heating systems) for the renovation scenarios are presented in **Table C1 of Annex C.** These values are based on the official building thermal regulations in each country.

Subsequently, the investment cost for each renovation measure - including material and estimated person-hours for implementation and excluding taxes - was obtained from a market-based budget generation tool (CYPE, 2026). This tool presents prices for the Portuguese context. Thus, in order to estimate prices for Poland and Greece, the Price level indices (Eurostat, 2026a) were used, as displayed in the following formula:

$$Price_B = Price_A \times \frac{PLI_B}{PLI_A}$$

Where $Price_B$ represents the price of a measure in Poland or Greece; $Price_A$ represents the price of the same measure for Portugal, according to CYPE (2026); PLI_B represents the Price Level Index for Poland or Greece; PLI_A represents the Price Level Index for Portugal. For each measure, different thermal parameters were collected. For building envelope measures, those were selected based on the target thermal transmittance (u-value) level for each typology. The thermal resistance of the new insulation or solution was added to the existing resistance to estimate the new u-value.

$$U_{new} = \frac{1}{R_{existing} + R_{insulation}}$$

U_{new} represents the new u-value of the building element; $R_{existing}$ is the thermal resistance of the existing solution; $R_{insulation}$ is the thermal resistance of the new insulation material. In cases where the existing solution is replaced with a new one, the new solution's thermal characteristics directly reflect the upgraded parameters. For each typology, whenever possible, three measures that enable the achievement of the targeted energy efficiency levels (either for envelope renovation and heating systems) were considered, aiming to estimate a cost range for each measure. The selected measures correspond to the minimum performing solutions required to reach the target performance levels. Window thermal transmittance is calculated using the thermal transmittance of both the window frame and window glazing. The full description of building envelope measures and equipment upgrades can be found in **Table C2** and **Table C3 of Annex C.**

The **cost-effectiveness** of each measure is calculated based on energy savings and carbon dioxide emissions averted, i.e. the kWh of energy demand saved, and carbon emissions reduced, respectively, per euro (€) invested. It is estimated from the simulation results before and after the measure is implemented, similarly to the approach of Palma *et al*. (2022). It is important to highlight that while cost-effectiveness is an important dimension in the measure selection process, other aspects and externalities impact the suitability and benefit of the different measures, such as digital literacy, other environmental impacts, such as air quality issues, low fuel costs, long-term indoor comfort, local availability, grid capacity, and unexpected greenhouse gas emissions.

Finally, potential energy bill reduction is also estimated by calculating energy expenditure before and after the renovation scenarios according to the respective energy systems split, and fuels. Data on electricity and gas prices (Eurostat, 2026b; Eurostat, 2026c), biomass market price for Portugal (Continente, 2026), oil prices for Greece (GlobalPetrolPrices, 2026), and the average DH regulated energy price for Poland (Energy Regulatory Office, 2025) were used. The energy prices are presented in **Table C4 of Annex C**.

4 Results

This section presents the results of the energy performance analysis for the selected dwelling typologies in each pilot case study. The results cover annual energy consumption, energy savings, renewable energy production, and related carbon emissions reduction, for both space heating and cooling. It also identifies the most cost-effective measures for each dwelling typology.

4.1 Rumia

Representative dwelling typologies in the Municipality of Rumia are examined under baseline conditions and for a set of renovation measures, including thermal insulation, boiler upgrade, heat pump installation, and transition to a more efficient district heating system. This enables a clear comparison of how each intervention affects annual energy consumption, energy savings, and related carbon emissions across dwellings with different technical and thermal characteristics. As no cooling system is present in the analysed dwelling typologies, the assessment focuses primarily on heating-related consumption. In addition, the potential contribution of residential-scale PV systems is evaluated across all typologies. The main characteristics of the dwelling typologies, including the building envelope, heating system specifications, and household composition, are presented in **Table A1** and **Table A2** of **Annex A**.

4.1.1 Dwellings constructed before 1980

This section presents the results of the dwelling typologies built in 1980 or earlier in the Municipality of Rumia. These dwellings account for around **24.63%** of the local dwelling stock and are therefore particularly relevant for examining the potential of renovation measures in the municipality. This analysis helps illustrate how improvements to the building envelope and heating systems may contribute to improving energy performance and support decarbonisation objectives.

4.1.1.1 Typology PL_1

Typology “**PL_1**” corresponds to a residential unit classified as EPC class B, with district heating (COP = 0.90) as the primary heating source. For “**PL_1**”, only thermal insulation and heat pump installation are examined as renovation measures.

Baseline (current situation)

Under the baseline scenario, typology “**PL_1**” records annual energy consumption of **8,105 kWh**, corresponding to approximately **142.70 kWh/m²**. Of this total, **4,030 kWh** are attributed to space heating and **4,076 kWh** to appliance electricity consumption (**Figure 16**).

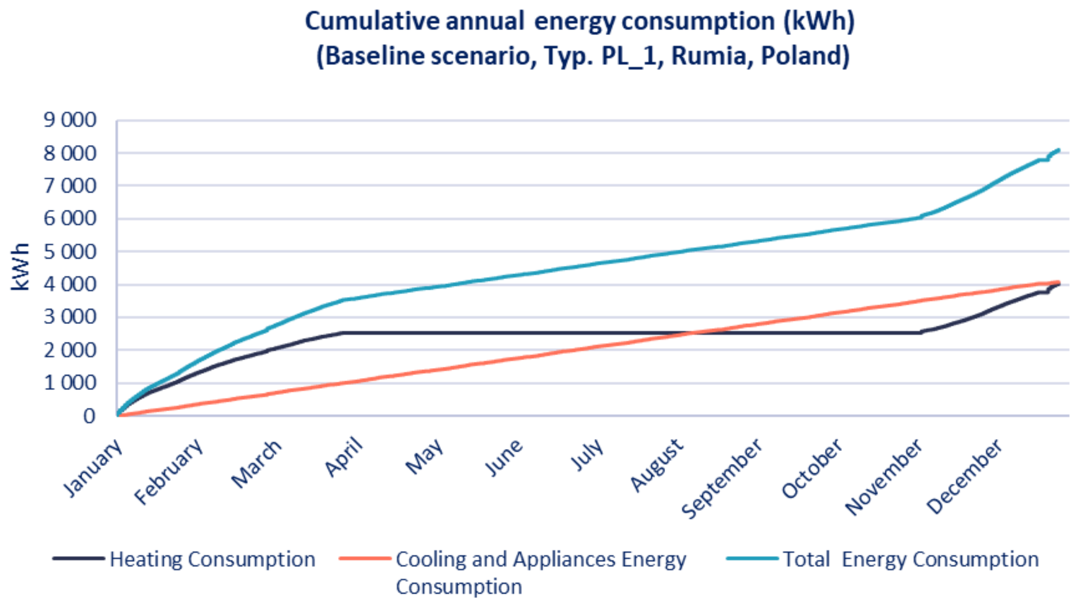


Figure 16. Cumulative annual energy consumption for typology "PL_1" (baseline scenario).

Renovation scenarios

Figure 17 presents the annual heating and total energy consumption for the typology "**PL_1**" under the two renovation scenarios examined: dwelling envelope renovation and heat pump installation. Heat pump installation results in the lowest heating consumption, reducing annual heating demand to **1,036 kWh**, which is approximately **74.3%** lower than the baseline. By comparison, thermal insulation reduces heating consumption to **1,936 kWh**, for a space heating energy consumption reduction of almost **52%**. Regarding the total annual energy consumption (Figure 18), the results are similar, with the heat pump installation resulting in the lowest total energy consumption, estimated at **5,112 kWh/year**, while thermal insulation also leads to a substantial reduction, lowering total consumption to **6,012 kWh/year,** for annual energy savings of respectively **2,934 kWh/year and 2,094 kWh/year**, relative to the baseline scenario. Both measures perform well, although the heat pump yields a greater reduction in final energy consumption, reflecting the additional efficiency gains associated with the heating system itself, whereas thermal insulation primarily reduces heat losses through the building envelope.

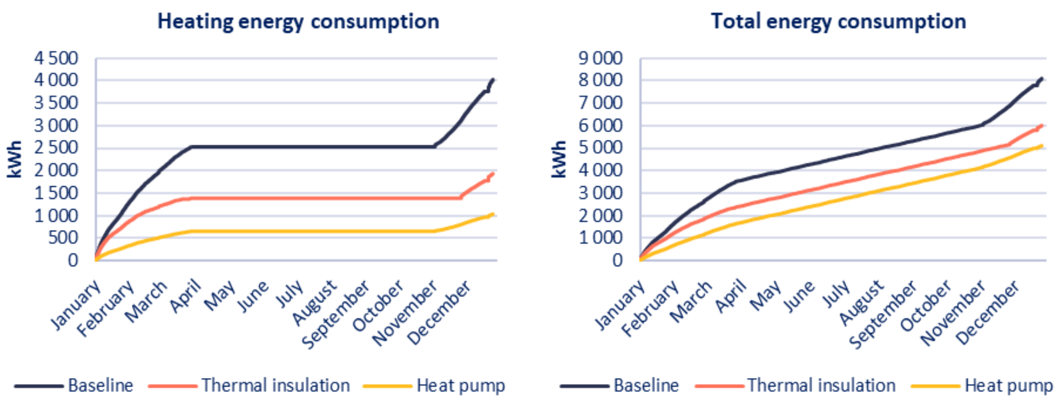


Figure 17.Cumulative total (right) and space heating (left) annual energy consumption per different "future" renovation scenario in typology "PL_1".

Figure 18 presents the annual carbon emissions produced and averted under the baseline and renovation scenarios for typology "**PL_1**". Under the baseline scenario, the dwelling produces approximately **4,226 kgCO_2/year**, while emissions decrease to around **3,284 kgCO_2/year** with thermal insulation, corresponding to **942 kgCO_2 averted**, and to approximately **3,026 kgCO_2/year** after heat pump installation, corresponding to **1,200 kgCO_2 averted**.

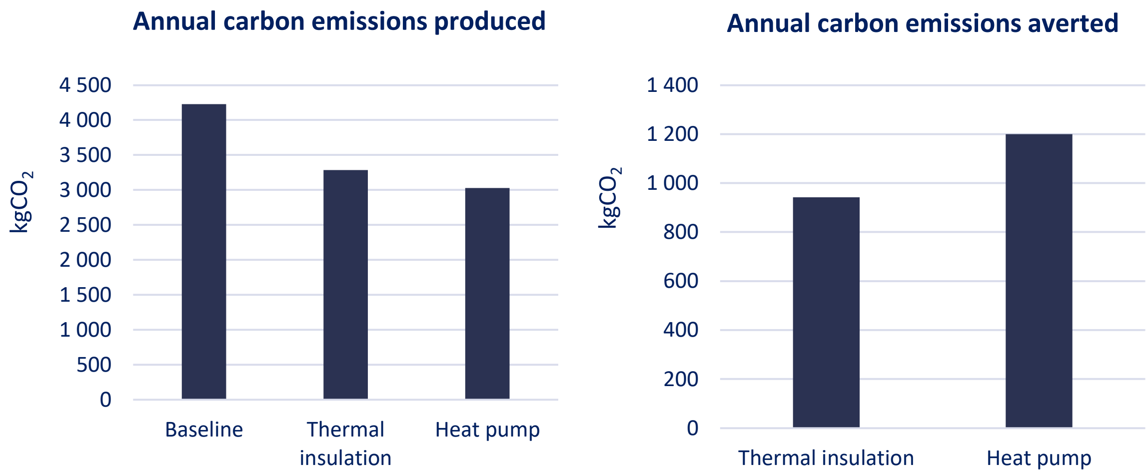


Figure 18. Annual CO_2 emissions (kg) produced and averted in the baseline ("current" situation) and in the renovation scenarios ("future" situations) in typology "PL_1".

4.1.1.2 Typology PL_2

Typology "PL_2" corresponds to a residential unit classified as EPC class C, with a non-condensing natural gas boiler (COP = 0.80) as the primary heating source. For "**PL_2**", four renovation measures are examined: thermal insulation, boiler upgrade, heat pump installation, and transition to a DH system.

Baseline (current situation)

Under the baseline scenario, typology "**PL_2**" records annual energy consumption of **9,908 kWh**, corresponding to approximately **174.43 kWh/m²**. Of this total, **5,832 kWh** are attributed to space heating and **4,076 kWh** to appliance electricity consumption (**Figure 19**). Compared with the district heating system examined in typology "**PL_1**", the existing non-condensing gas boiler in "**PL_2**" operates with lower efficiency, which explains its higher final energy requirement for meeting space heating demand.

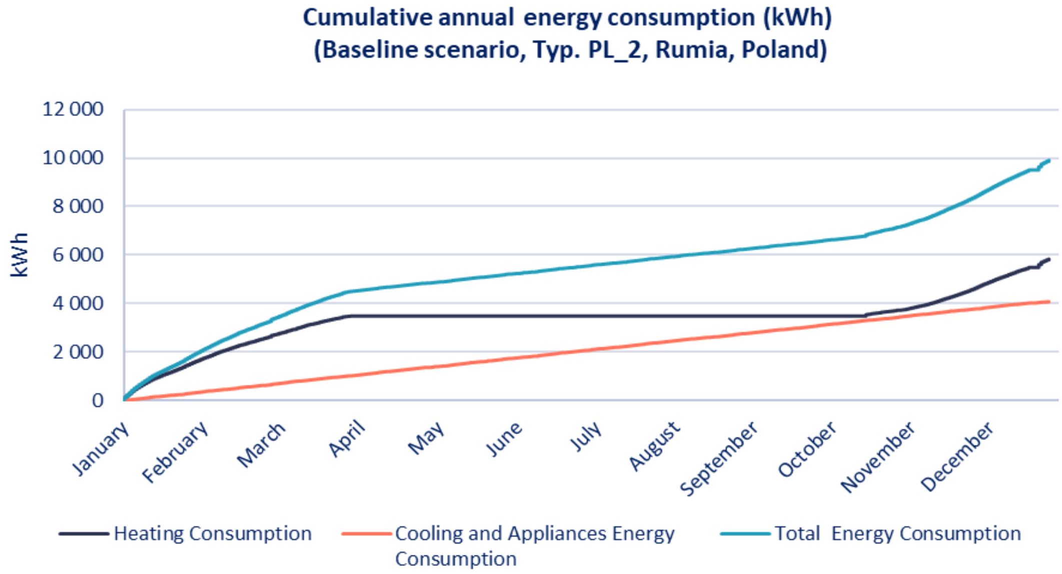


Figure 19. Cumulative annual energy consumption for typology "PL_2" (baseline scenario).

Renovation scenarios

Figure 20 presents the annual heating and total energy consumption for typology "**PL_2**" under the four renovation scenarios examined. Heat pump installation results in the lowest heating consumption, reducing annual heating demand to **1,333 kWh**, equivalent to a decrease of **77.1%** relative to the baseline. Thermal insulation reduces heating consumption to **3,135 kWh**, corresponding to a reduction of **46.2%**, while boiler upgrade lowers it to **4,761 kWh** (**18.4% reduction**). Transition to district heating results in a smaller reduction, with heating consumption reaching 5,184 kWh (**11.1% reduction**). Appliance electricity consumption remains unchanged across the renovation scenarios at approximately **4,076 kWh/year.**

Regarding the total annual energy consumption, the results follow a similar trend. Heat pump installation again results in the lowest total energy consumption, estimated at **5,409 kWh/year**, yielding the largest annual energy savings for typology "**PL_2**", at approximately **4,499 kWh/year.** Thermal insulation reduces total consumption to approximately **7,210 kWh/year**, while boiler upgrade and transition to DH result in **8,837 kWh/yea**r and **9,2560 kWh/year**, respectively. Thermal insulation also delivers substantial savings of around **2,698 kWh/year**, while boiler upgrade and transition to district heating achieve more limited reductions of **1,072 kWh/year** and **648 kWh/year**, respectively.

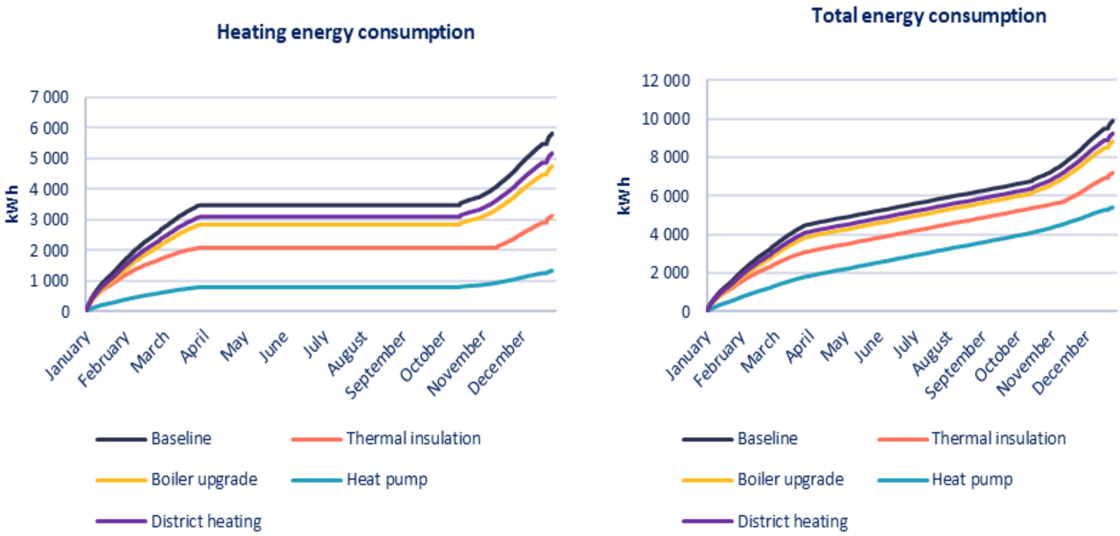


Figure 20. Cumulative total (right) and space heating (left) annual energy consumption per different renovation scenario in typology "PL_2".

Figure 21 presents the annual carbon emissions produced and averted under the baseline and renovation scenarios for typology "**PL_2**". Based on the emission factors applied in this study, thermal insulation achieves the lowest annual emissions. Under the baseline scenario, the dwelling produces approximately **3,591 kgCO_2/year**, while emissions decrease to around **3,046 kgCO_2/year** with thermal insulation, corresponding to **545 kgCO_2 averted**. Boiler upgrade reduces emissions to approximately **3,375 kgCO_2/year**, equivalent to **216 kgCO_2 averted**, while heat pump installation lowers them to around **3,202 kgCO_2/year**, corresponding to **389 kgCO_2 averted**. By contrast, transition to district heating increases annual emissions to approximately **4,746 kgCO_2/year**, representing an increase of about **1,155 kgCO_2** relative to the baseline.

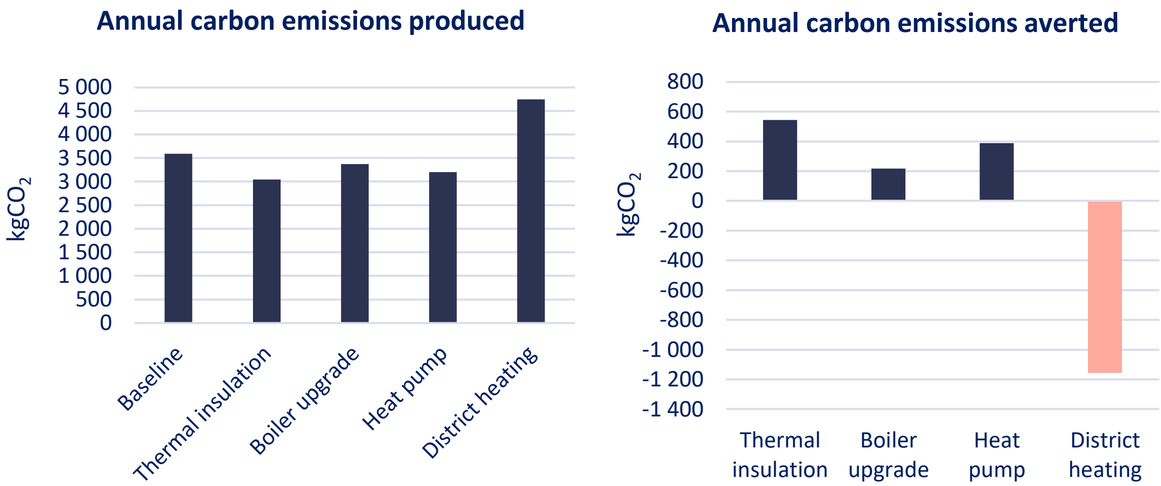


Figure 21. Annual CO_2 emissions (kg) produced and averted in the baseline ("current" situation) and in the renovation scenarios ("future" situations) in typology "PL_2".

4.1.1.3 Typology PL_3

Typology "PL_3" corresponds to a residential unit classified as EPC class C, with district heating (COP = 0.90) as the primary heating source. For "PL_3", only thermal insulation and heat pump installation are examined as renovation measures

Baseline (current situation)

Under the baseline scenario, typology "**PL_3**" records annual energy consumption of **8,262 kWh**, corresponding to approximately **145.45 kWh/m²**. Of this total, **4,186 kWh** are attributed to space heating and **4,076 kWh** to appliance electricity consumption (**Figure 22**).

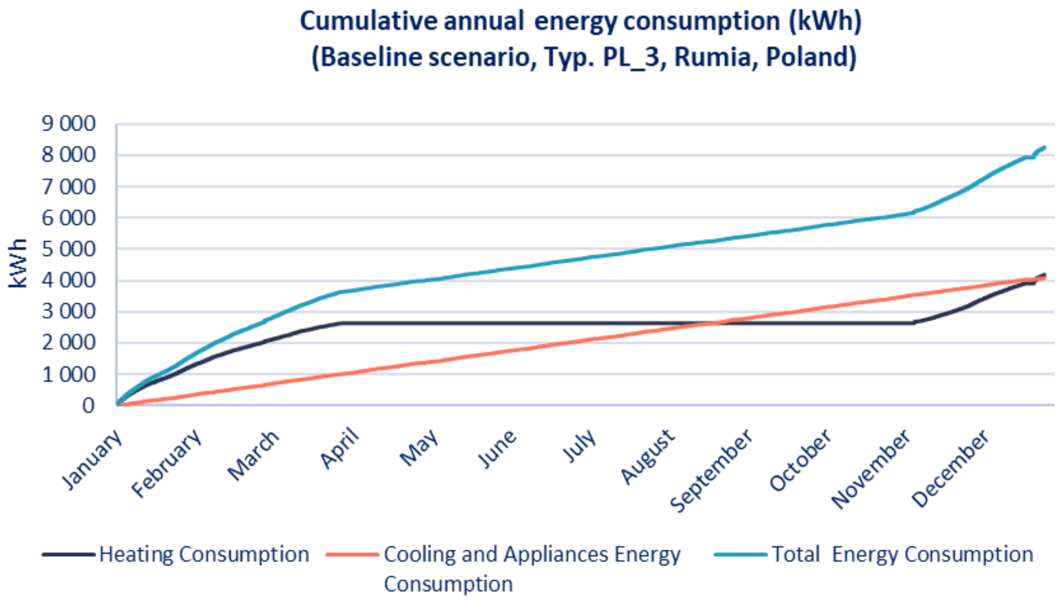


Figure 22. Cumulative annual energy consumption for typology "PL_3" (baseline scenario).

Renovation scenarios

Figure 23 presents the annual heating and total energy consumption for typology "**PL_3**" under the two renovation scenarios examined. Heat pump installation results in the lowest heating consumption, reducing annual heating demand to **1,076 kWh**, equivalent to a reduction of around **76.3%** relative to the baseline. By comparison, thermal insulation reduces heating consumption to **1,826 kWh**, corresponding to a reduction of **56.4%**. Appliance electricity consumption remains unchanged across the renovation scenarios at approximately **4,076 kWh/year**. Heat pump installation also achieves the lowest total energy consumption, estimated at **5,152 kWh/year**, while thermal insulation still leads to a substantial reduction, lowering total consumption to **5,902 kWh/year**, for respective savings of approximately **3,110 kWh/year** and **2,360 kWh/year**.

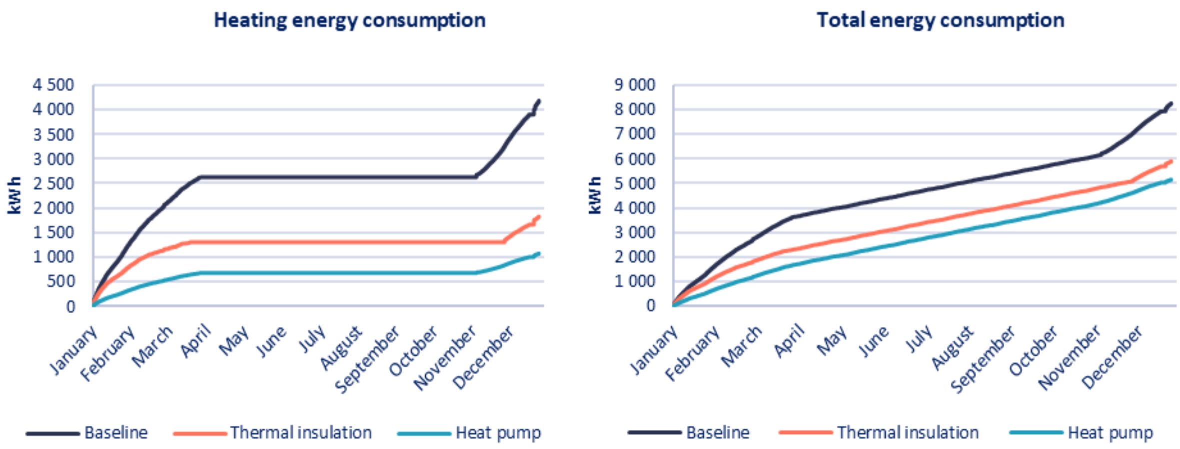


Figure 23. Cumulative total (right) and space heating (left) annual energy consumption per different renovation scenario in typology "PL_3".

Figure 24 shows the annual carbon emissions produced and averted under the baseline and renovation scenarios. Under the baseline scenario, the dwelling produces **4,297 kgCO_2 per year**, and potential emissions decrease to around **3,235 kgCO_2** with thermal insulation, corresponding to **1,062 kgCO_2 averted**, and to approximately **3,050 kgCO_2** annually after heat pump installation, corresponding to **1,247 kgCO_2 averted**.

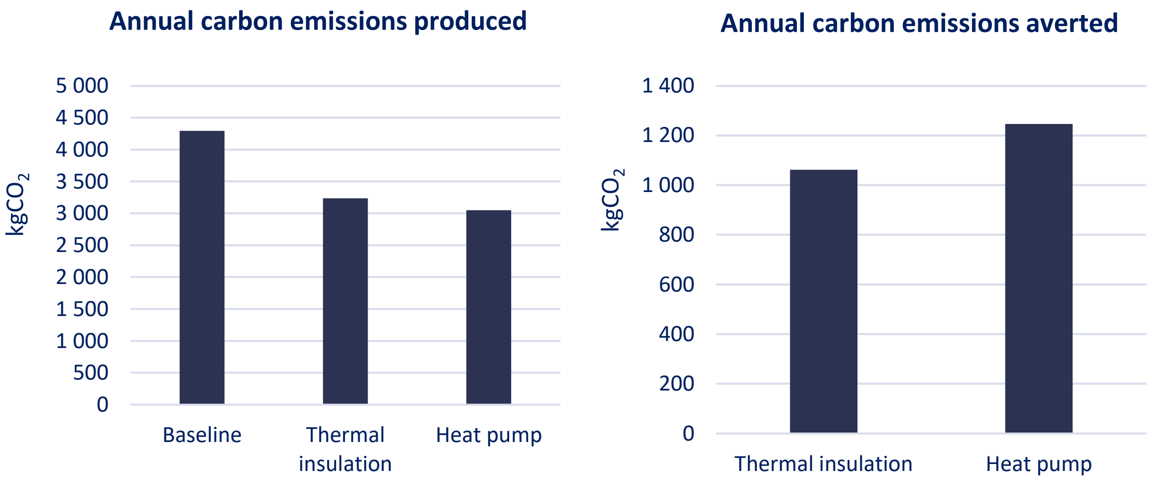


Figure 24. Annual CO_2 emissions (kg) produced and averted in the baseline ("current" situation) and in the renovation scenarios ("future" situations) in typology "PL_3".

4.1.2 Dwellings constructed after 1980

This section examines the dwelling typologies constructed after 1980 in the Municipality of Rumia. These dwellings account for **75.37%** of the local multifamily dwelling stock and therefore represent the dominant segment of Rumia's residential stock. Their analysis enables an assessment of the extent to which further energy performance improvements can still be achieved in more recent typologies through renovation measures, including building envelope upgrades and more efficient heating systems.

4.1.2.1 Typology PL_4

Typology "**PL_4**" corresponds to a residential unit classified as EPC class B, with district heating (COP = 0.90) as the primary heating source. For "**PL_4**", thermal insulation and heat pump installation are examined as renovation measures.

Baseline (current situation)

Under the baseline scenario, typology "**PL_4**" records annual energy consumption of **6,311 kWh**, corresponding to **100.97 kWh/m²**. Of this total, **2,235 kWh** are attributed to space heating and **4,076 kWh** to appliance electricity consumption (**Figure 25**).

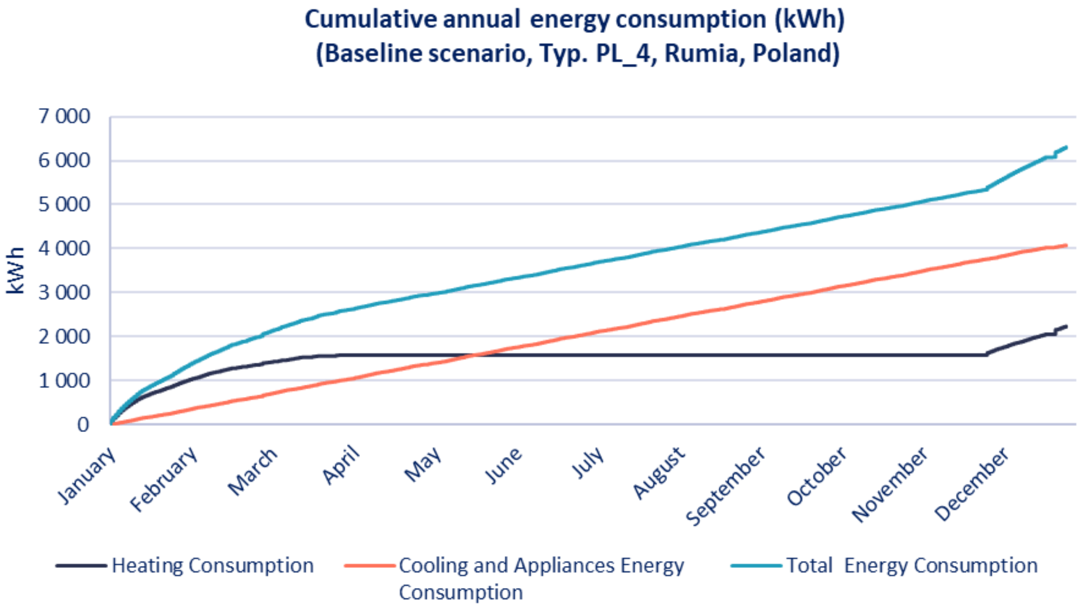


Figure 25. Cumulative annual energy consumption for typology "PL_4" (baseline scenario).

Renovation scenarios

Figure 26 presents the annual heating and total energy consumption for typology "**PL_4**" under the two renovation scenarios examined. Heat pump installation results in the lowest heating consumption, reducing annual heating demand to **575 kWh**, equivalent to a decrease of **74.3%** relative to the baseline. By comparison, thermal insulation reduces heating consumption to **937 kWh**, corresponding to a reduction of **58.1%**.

Appliance electricity consumption remains unchanged across the renovation scenarios at approximately **4,076 kWh/year**. Heat pump installation also leads to the lowest total energy consumption, estimated at **4,650 kWh/year**, for the largest annual energy savings for typology "**PL_4**", at **1,661 kWh/year,** while thermal insulation results in a substantial reduction, lowering total consumption to **5,012 kWh/year**, saving around **1,299 kWh/year**.

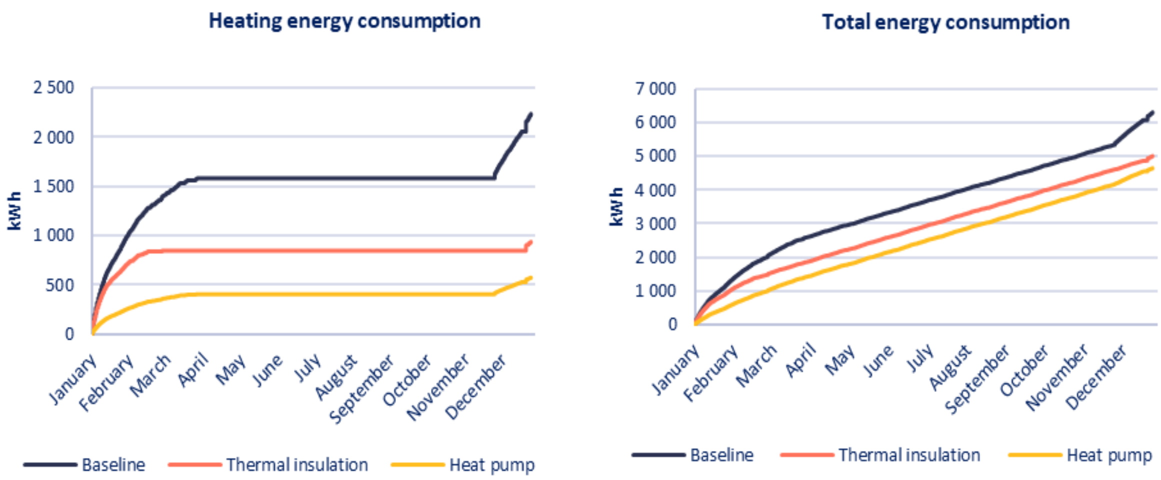


Figure 26. Cumulative total (right) and space heating (left) annual energy consumption per different renovation scenario in typology "PL_4".

Figure 27 presents the annual carbon emissions produced and averted under the baseline and renovation scenarios. Under the baseline scenario, the dwelling produces approximately **3,419 kgCO$_2$ per year**, decreasing to around **2,834 kgCO$_2$/year** with thermal insulation, corresponding to **584 kgCO$_2$ averted**, and to approximately **2,753 kgCO$_2$/year** after heat pump installation, corresponding to **666 kgCO$_2$ averted.**

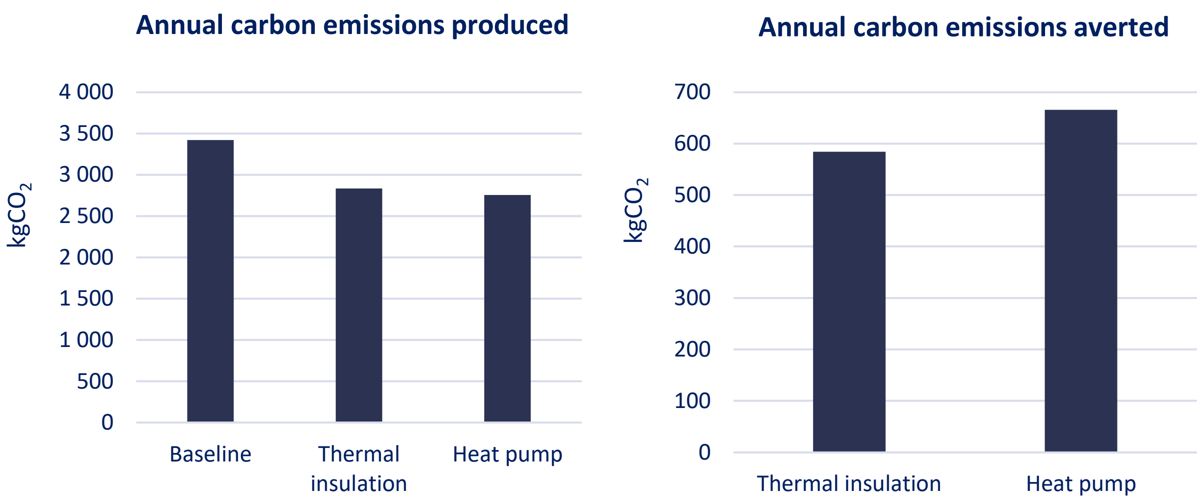


Figure 27. Annual CO$_2$ emissions (kg) produced and averted in the baseline ("current" situation) and in the renovation scenarios ("future" situations) in typology "PL_4".

4.1.2.2 Typology PL_5

Typology "**PL_5**" corresponds to a residential unit classified as EPC class B, with a non-condensing natural gas boiler (COP = 0.80) as the primary heating source. For "**PL_5**", four renovation measures are examined: thermal insulation, boiler upgrade, heat pump installation, and transition to a district heating system.

Baseline (current situation)

Under the baseline scenario, typology “**PL_5**” records annual energy consumption of **6,589.5 kWh**, corresponding to approximately **105.43 kWh/m²**. Of this total**, 2,514 kWh** are attributed to space heating and **4,076 kWh** to appliance electricity consumption (**Figure 28**).

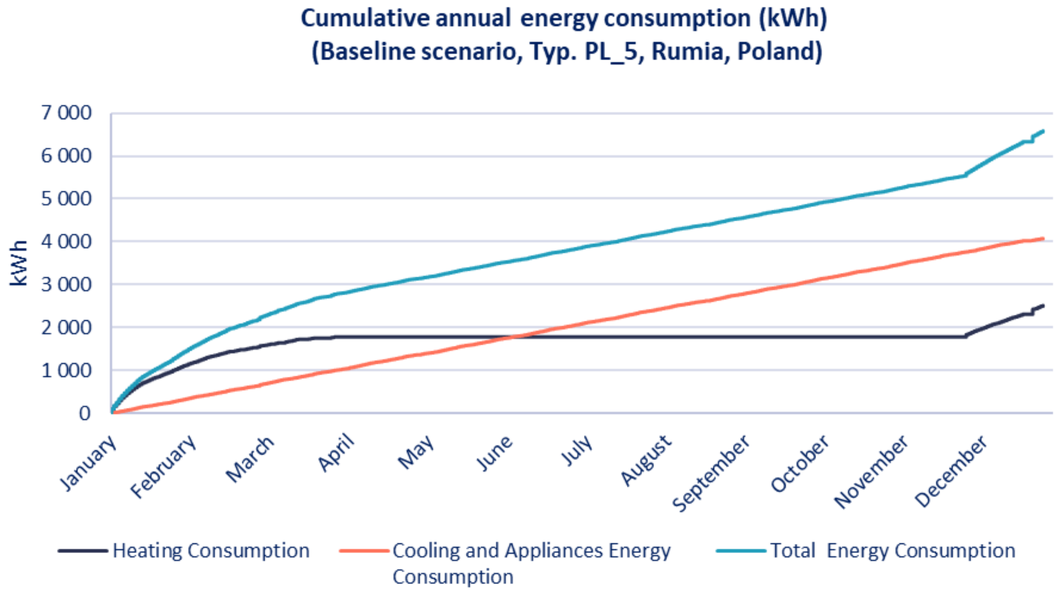


Figure 28. Cumulative annual energy consumption for typology “PL_5” (baseline scenario).

Renovation scenarios

Figure 29 presents the annual heating and total energy consumption for typology “**PL_5**” under the four renovation scenarios examined. Heat pump installation results in the lowest heating consumption, reducing annual heating demand to **575 kWh**, a **77.1%** reduction relative to the baseline. Thermal insulation lowers heating consumption to **1,054 kWh**, corresponding to a reduction of **58.1%**, while boiler upgrade reduces it to **2,053 kWh**, equivalent to an **18.4% reduction**. Transition to district heating lowers heating consumption to **1,551 kWh** (**38.3%** reduction**)**. Appliance electricity consumption remains unchanged across the renovation scenarios at **4,076.**

Heat pump installation results in the lowest total energy consumption, estimated at **4,650 kWh/year**, for energy savings of approximately **1,939 kWh/year.** Thermal insulation reduces total consumption to approximately **5,130 kWh/year**, while boiler upgrade and transition to district heating result in **6,128 kWh/year** and **5,627 kWh/year**, respectively. They can yield energy savings of respectively **1,460 kWh/year**, **461 kWh/year** and **963 kWh/year**.

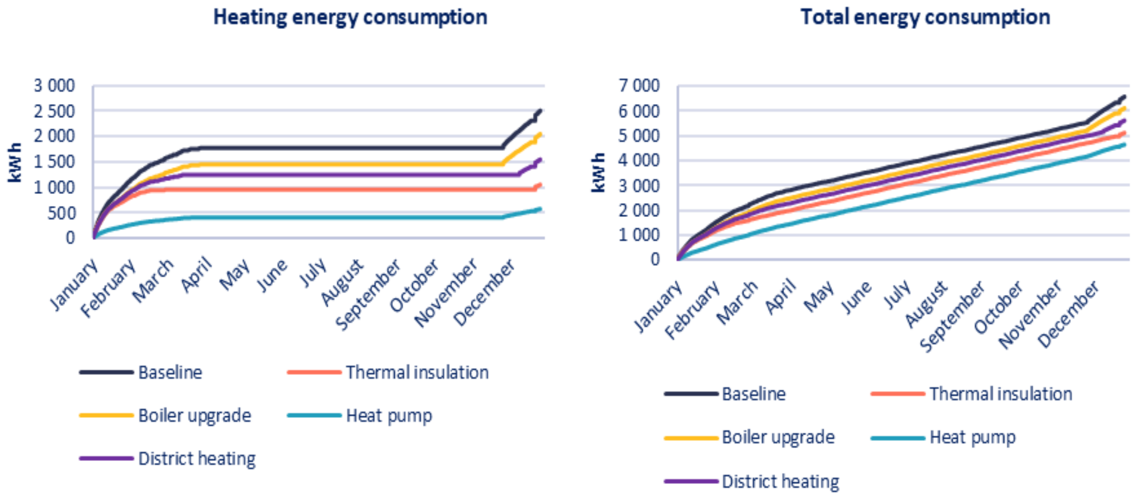


Figure 29. Cumulative total (right) and space heating (left) annual energy consumption per different renovation scenario in typology "PL_5".

Figure 30 presents the annual carbon emissions produced and averted under the baseline and renovation scenarios for typology "**PL_5**". Under the baseline scenario, the dwelling produces approximately **2,921 kgCO_2/year**. Thermal insulation results in the lowest annual emissions, with total emissions decreasing to around **2,626 kgCO_2/year**, corresponding to **295 kgCO_2 averted**. Boiler upgrade reduces emissions to approximately **2,828 kgCO_2/year**, equivalent to **93 kgCO_2 averted**, while heat pump installation lowers them to around **2,753 kgCO_2/year**, corresponding to **168 kgCO_2 averted**. By contrast, transition to district heating increases annual emissions to approximately **3,111 kgCO_2/year**, representing an increase of about **190 kgCO_2** relative to the baseline.

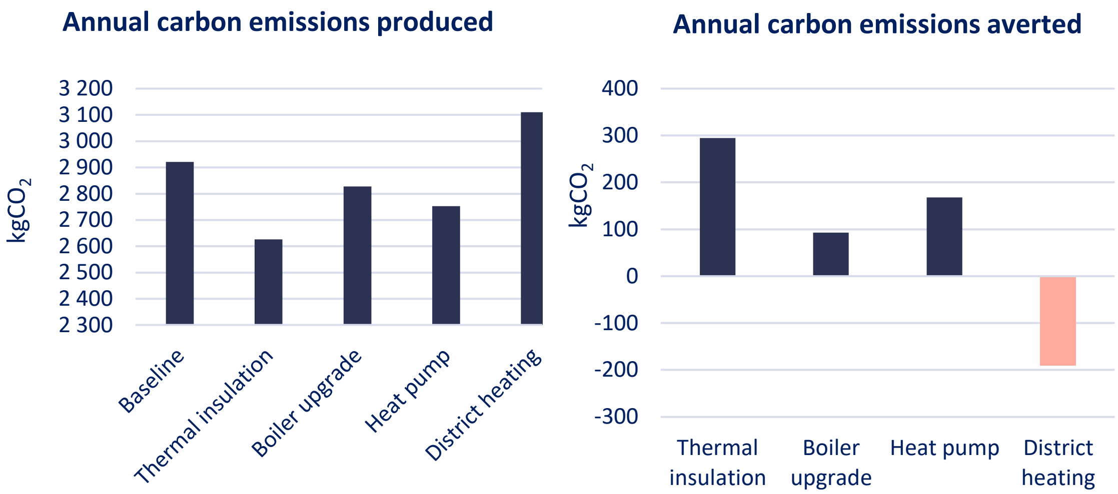


Figure 30. Annual CO_2 emissions (kg) produced and averted in the baseline ("current" situation) and in the renovation scenarios ("future" situations) in typology "PL_5".

4.1.3 PV installation

To further explore applicable interventions for vulnerable households, the role of renewable energy systems should also be considered. In this context, PV systems are particularly relevant, as they can reduce grid electricity demand while also laying the groundwork for increased prosumer participation, greater interaction with the grid, and the future integration of storage and other flexible energy solutions. This is especially pertinent in Poland, where the expansion of PVs and other prosumer-oriented energy arrangements has become increasingly relevant in recent years and can gain further momentum in the coming years (IEO, 2026). However, limited capacity in the electricity network to accept new generation means financial viability is dependent on the electricity being mostly consumed where it is produced.

In this study, a typical residential PV system is simulated for the Municipality of Rumia. The system has a nominal capacity of 3 kWp and requires an installation area of approximately 16 m². The cumulative annual energy production of the PV system across all examined typologies reaches a total of **4,017 kWh/year**. **Table 3** compares total electricity consumption under baseline and renovation conditions with the corresponding percentage of PV coverage. The results indicate that PV systems can make a substantial contribution to meeting household electricity demand. PV coverage ranges from **74.3%** to **98.6%,** depending on the typology and scenario. The results are relatively homogeneous across the analysed typologies, reflecting the broadly similar dwelling characteristics and occupancy patterns observed across the Municipality of Rumia.

At the same time, PV coverage decreases in renovation scenarios that include heat pump installation, due to the higher electricity demand associated with electrified heating. This finding highlights the complementary nature of these interventions: while heat pumps increase electricity consumption, they also support the decarbonisation of heating. When combined with PV systems, they can contribute to a more integrated pathway towards building electrification, greater energy autonomy, and the alleviation of energy poverty in vulnerable households.

Table 3. Total electricity consumption and PV coverage across all dwelling typologies under baseline and renovation scenarios in the Municipality of Rumia.

Typology	Scenario and heating source	Total electricity consumption (kWh)	Percentage of coverage
PL_1	Baseline (district heating), Thermal insulation (district heating)	4,076	98.6%
	Heat pump (electricity)	5,112	78.6%
PL_2	Baseline (gas), Thermal insulation (gas), Boiler upgrade (gas), District heating connection (district heating)	4,076	98.6%
	Heat pump (electricity)	5,409	74.3%
PL_3	Baseline (district heating), Thermal insulation (district heating)	4,076	98.6%
	Heat pump (electricity)	5,152	78.0%
PL_4	Baseline (district heating), Thermal insulation (district heating)	4,076	98.6%
	Heat pump (electricity)	4,650	86.4%
PL_5	Baseline (gas), Thermal insulation (gas), Boiler upgrade (gas), District heating connection (district heating)	4,076	98.6%
	Heat pump (electricity)	4,650	86.4%

4.1.4 Cost-effectiveness analysis

Table 4 presents the investment costs, the cost-effectiveness for energy saving and carbon dioxide emissions savings for the most cost-effective measure, and the respective potential energy bill reduction. The highest costs for thermal insulation are observed in typologies with the highest thermal transmittance standards, which are PL_3 and the most recent typologies, PL_4 and PL_5. On the other hands, cost-effectiveness for energy consumption savings is more significant in older typologies PL_1 and PL_2, respectively **0.42 kWh/€** and **0.44 kWh/€**. These typologies not only present lower renovation costs but also higher energy consumption linked to lower energy performance.

Heat pump installation is the renovation measure with the highest cost-effectiveness, with its highest value for typology PL_2, approximately **2.65 kWh/€**. As previously described, this system enables considerable energy consumption reductions for space heating due to its high efficiency and has generally lower prices than its alternatives. Gas boiler upgrades present competitive cost-effectiveness values with the thermal insulation, with its peak value of **0.57 kWh/€** for PL_2. The same occurs for the transition to district heating from lower-efficiency gas boilers. The highest cost-effectiveness value is observed in typology PL_5. Higher potential energy bill savings are linked to heat pump installation in every typology, on average **278.6 €/year**, while thermal insulation (**184.6 €/year**) outperforms both gas boilers and district heating, respectively ranging from **76.5 €/year** and **177.7 €/year** and **42.7 €/year** to **82.8 €/year**.

Cost-effectiveness for carbon emissions reduction is more level across typologies. PL_1 presents the highest value, **0.19 kgCO_2/€,** followed by PL_3, with **0.12 kgCO_2/€.** In both typologies, the absolute value CO_2 emissions averted is also highest. As for energy savings, heat pump installation offers the highest cost-effectiveness for carbon emissions reduction across all typologies, even though the absolute emissions are not always higher than those from thermal insulation. Conversely, current district heating has negative cost-effectiveness for carbon emissions reduction, since the transition to this heating system results in additional emissions compared to existing gas boilers. Considering total energy generation, polycrystalline PV panels with 3 kWp of power can yield **1.71 kWh/€** in Rumia.

Table 4. Investment cost, cost-effectiveness for energy savings and carbon dioxide emissions reduction and potential energy bills reduction for each renovation scenario in the Municipality of Rumia.

	PL_1	PL_2	PL_3	PL_4	PL_5
Investment cost interval (€/per dwelling)					
Overall Thermal insulation	3,597-6,171	4,681-7,285	6,949-9,387	5,729-8,872	5,729-8,872
Walls	724-991	1,236-2101	2,101	1,297-2,209	1,297-2,209
Window	2,873-5,180	2,873-5,180	4,843-7,281	4,431-6,663	44,31-6,663
Heat pump	1,699-2,464	1,699-2,464	1,699-2,464	1,699-2,464	1,699-2,464
Gas boiler	-	1,888-4,053	-	-	1,888-4,053
District Heating	-	1,500-4,000	-	-	1,500-4,000

Polycrystalline PV panels	4,017	4,017	4,017	4,017	4,017
Highest cost-effectiveness for energy saving (kWh/€ | kWh/€/m²)					
Thermal insulation	0.42	0.44	0.26	0.17	0.19
Heat pump	1.76	2.65	1.83	0.98	1.14
Gas boiler	-	0.57	-	-	0.24
Biomass boiler	-	-	-	-	-
District Heating	-	0.43	-	-	0.64
Highest cost-effectiveness for carbon dioxide emissions' saving (kg/€)					
Thermal insulation	**0.19**	0.09	0.12	0.08	0.04
Heat pump	0.71	0.23	**0.73**	0.39	0.10
Gas boiler	-	**0.11**	-	-	0.05
Biomass boiler		-	-	-	-
District Heating	-	-0.77	-	-	-0.13
Potential energy bill reduction (€/year)					
Thermal insulation	197.8	**246.3**	223.0	122.6	133.2
Heat pump	300.3	**429.1**	312.2	166.6	184.9
Gas boiler	-	**177.7**	-	-	76.5
Biomass boiler	-	-	-	-	-
District Heating	-	42.7	-	-	**82.8**

4.2 Torres Vedras

As in the other case studies examined in this report, the results for the Municipality of Torres Vedras are organised by construction period to reflect differences in the age, thermal performance, and technical characteristics of the housing stock. Within each construction period, representative dwelling typologies are assessed under a baseline scenario and a set of alternative renovation scenarios, allowing for a systematic comparison of their effects on annual energy consumption, energy savings, and associated carbon emissions. This enables the impact assessment of different interventions across dwellings with distinct envelope conditions and heating-related characteristics, while also highlighting the broader decarbonisation potential of residential energy upgrades in the local context. In addition, the possible contribution of residential-scale PV systems is examined across all typologies.

4.2.1 Dwellings constructed before 1981

Dwellings constructed before 1981 constitute the oldest and most energy-inefficient segment of the dwelling stock in the Municipality of Torres Vedras, accounting for approximately **11.80%** of all dwellings. In contrast to dwellings built in more recent periods, this category is characterised by a relatively homogeneous mix of heating systems, predominantly based on electric heaters. The main characteristics of these typologies, including building envelope properties, heating system specifications, and household composition, are outlined in **Table A3** and **Table A4** of **Annex A**.

4.2.1.1 Typology PT_1

For the pilot area of the Municipality of Torres Vedras, the first dwelling typology (“PT_1”) corresponds to a residential unit classified as EPC class C or D, with electric heaters (COP = 1.00) as the primary heating source. No cooling system is assumed for this dwelling typology. In addition, only thermal insulation and heat pump installation are examined as energy efficiency measures for this case.

Baseline (“current” situation)

Under the baseline scenario, modelling results indicate an annual energy consumption of **9,987 kWh**, corresponding to **124.95 kWh/m²**, for typology “**PT_1**”. Of this total, **6,191 kWh** are attributed to space heating, while **3,793 kWh** correspond to appliances (**Figure 31**).

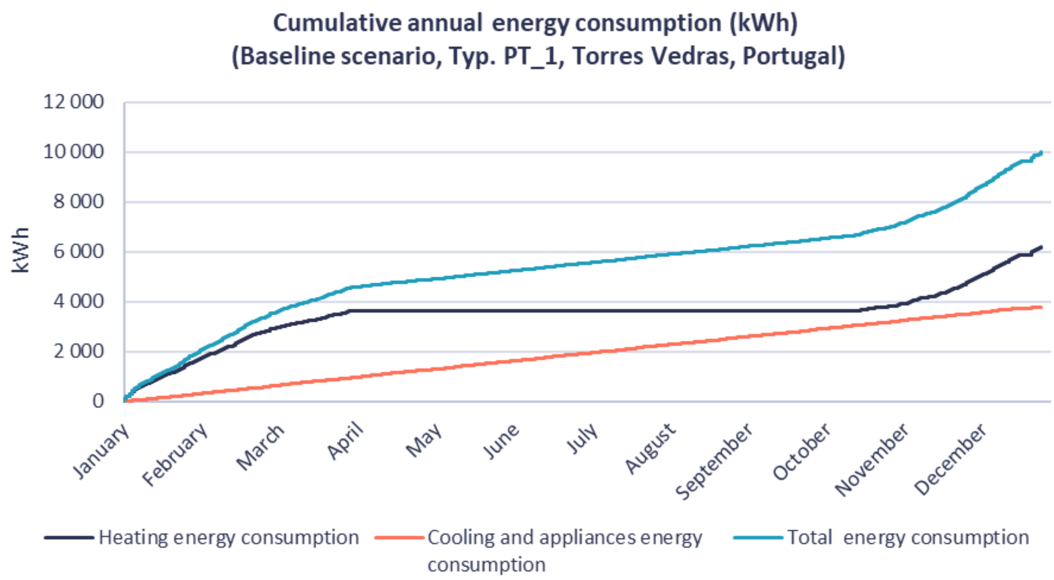


Figure 31. Cumulative annual energy consumption for typology “PT_1” (baseline scenario).

Renovation scenarios

Figure 32 presents the annual heating and total energy consumption for the “PT_1” typology under the two examined renovation scenarios. Heat pump installation yields the largest reduction, lowering annual heating energy consumption to **1,769 kWh**, representing a **71.4% decrease** relative to the baseline. By comparison, thermal insulation reduces heating consumption to **5,316 kWh**, equivalent to a **14.1% reduction**. With regard to appliances, no variation is observed across the different renovation scenarios, as appliance-related energy consumption is assumed to remain unchanged, all scenarios result in annual appliances consumption of **3,796 kWh**. The total annual energy consumption for the three renovation scenarios is derived by combining heating, cooling, and appliance consumption for every typology. The total annual energy consumption for each renovation scenario is derived by combining heating and appliances consumption. Heat pump installation results in the lowest total annual energy consumption, estimated at **5,565 kWh**, while thermal insulation also improves performance, reducing total annual consumption to **9,112 kWh**, with respective annual savings of approximately **4,422 kWh** and **875 kWh**.

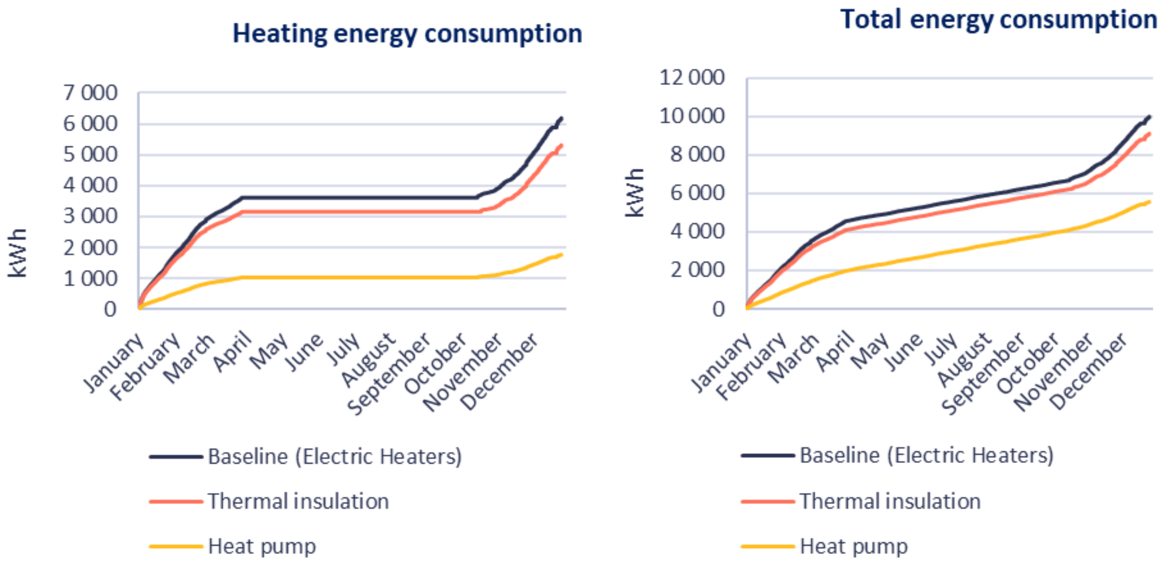


Figure 32. Cumulative total (right) and space heating (left) annual energy consumption per different renovation scenario in the typology "PT_1" in the Municipality of Torres Vedras in Portugal.

Figure 33 presents the annual carbon emissions produced and averted (in $kgCO_2$) under the baseline ("current" situation) and the renovation scenarios ("future" situations). Under the baseline scenario, the dwelling produces approximately **1,278 $kgCO_2$ per year**, and emissions decrease to approximately **1,166 $kgCO_2$** with thermal insulation (**112 $kgCO_2$ averted**), and **712 $kgCO_2$** after heat pump installation (**566 $kgCO_2$ averted**).

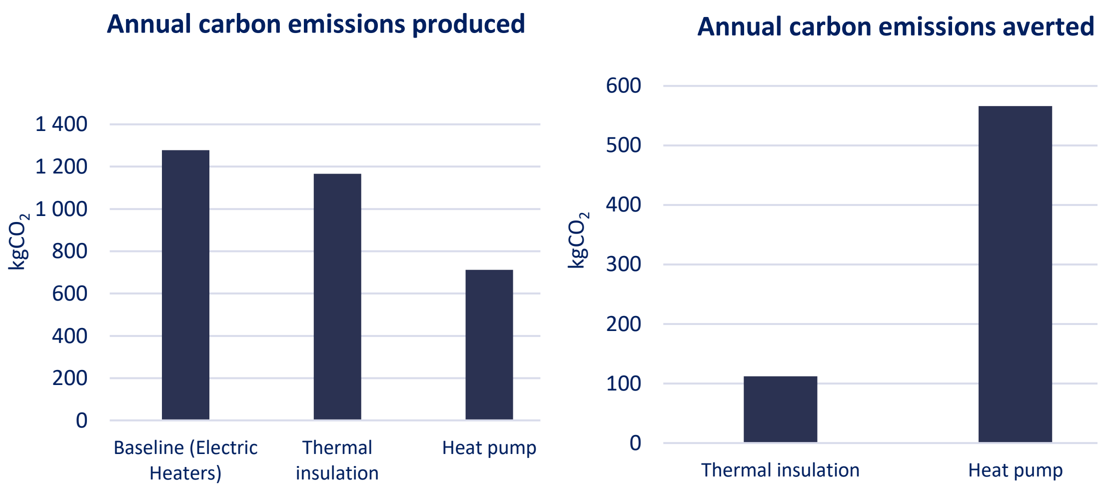


Figure 33. Annual CO_2 emissions (kg) produced and averted in the baseline ("current" situation) and in the renovation scenarios ("future" situations) in typology "PT_1".

4.2.1.2 Typology PT_2

Typology ("**PT_2**") corresponds to a residential unit classified as EPC class E or F, with electric heaters (COP = 1.00) as the primary heating source. As in typology "**PT_1**", no cooling system is foreseen in this case. Likewise, only thermal insulation and heat pump installation are examined as energy efficiency measures for this typology.

Baseline ("current" situation)

Under the baseline scenario, modelling results indicate annual energy consumption at **14,789 kWh** (**163.29 kWh/m^2**) for typology "**PT_2**". Of this total, **10,993 kWh** correspond to space heating needs, while **3,796 kWh** are associated with appliances (**Figure 34**), indicating a considerably higher baseline energy consumption than typology "**PT_1**".

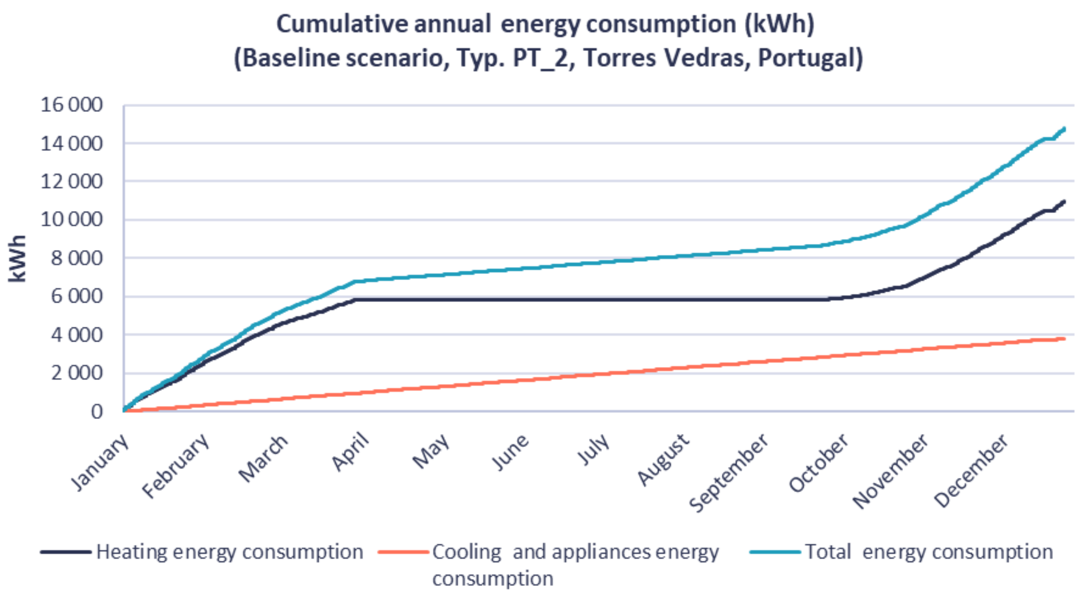


Figure 34. Cumulative annual energy consumption for typology "PT_2" (baseline scenario).

Renovation scenarios

Figure 35 presents the annual heating and total consumption for typology "**PT_2**" for the two renovation scenarios under study. The results indicate that heat pump installation leads to the lowest heating energy consumption, reducing annual heating demand to **3,141 kWh**, equivalent to a 71.4% decrease relative to the baseline. By comparison, thermal insulation lowers heating consumption by **13.5%** to **9,508 kWh**. Similarly to the "**PT_1**" typology, no variation is observed in appliances consumption across the renovation scenarios, as appliance-related energy consumption is assumed to remain constant at **3,796 kWh**. Heat pump installation again provides the lowest total annual energy consumption, estimated at **6,937 kWh**, while thermal insulation leads to a more limited improvement, with total annual consumption reaching **13,305 kWh,** for annual savings of **7,856 kWh** and **1,485 kWh** per year, respectively.

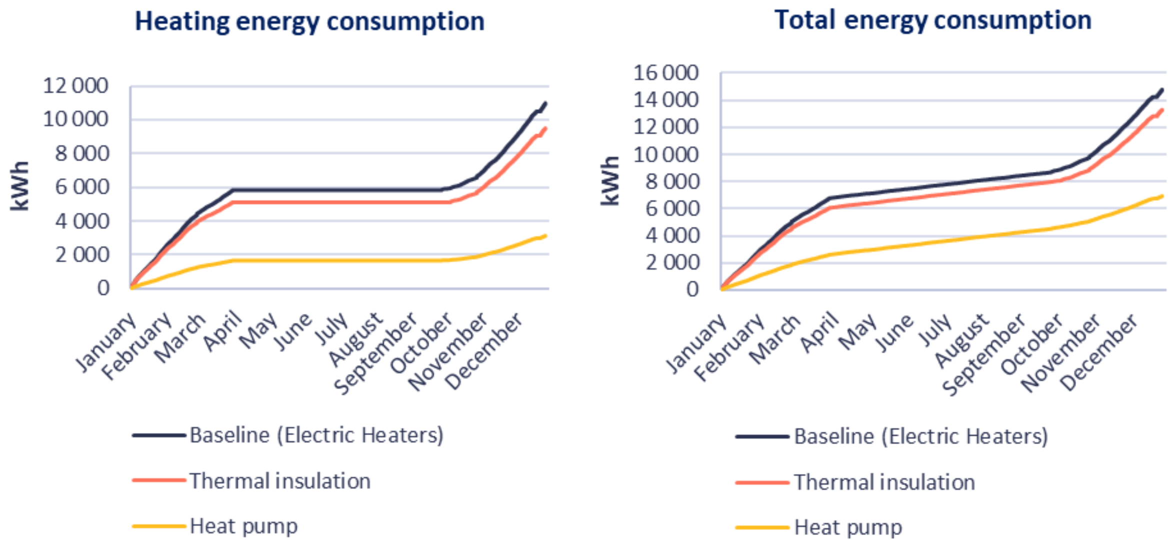


Figure 35. Cumulative total (right) and space heating (left) annual energy consumption per different renovation scenario in the typology "PT_2" in the Municipality of Torres Vedras in Portugal.

Figure 36 presents the annual carbon emissions produced and averted (in $kgCO_2$) under the baseline ("current") and the renovation ("future") scenarios. Under the baseline scenario, the dwelling produces approximately **1,893 $kgCO_2$ per year**. Emissions are reduced to approximately **1,703 $kgCO_2$** with thermal insulation (**109 $kgCO_2$ averted**), and **888 $kgCO_2$** after heat pump installation (**1,005 $kgCO_2$ averted**).

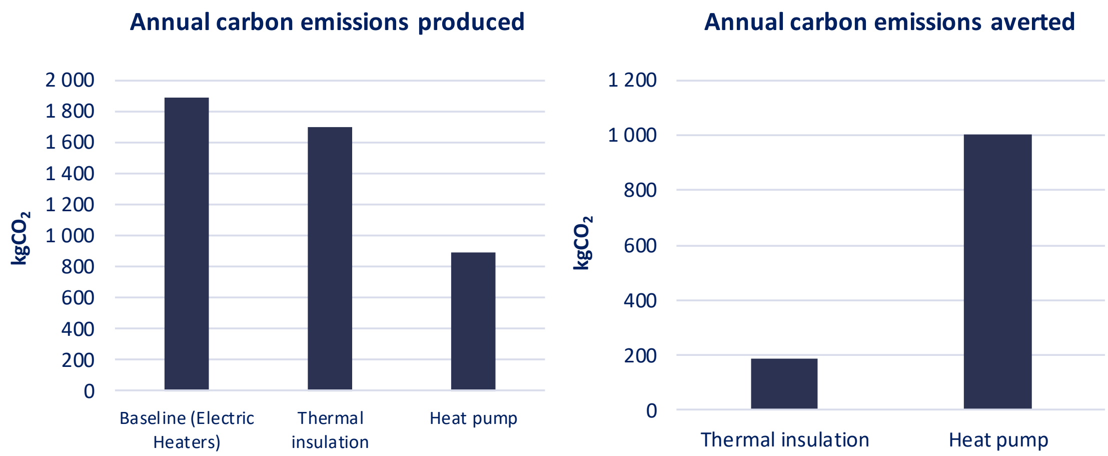


Figure 36. Annual CO_2 emissions (kg) produced and averted in the baseline ("current" situation) and in the renovation scenarios ("future" situations) in typology "PT_2".

4.2.2 Dwellings constructed between 1981 and 2000

Dwellings constructed between 1981 and 2000 constitute a substantial share of the dwelling stock in the Municipality of Torres Vedras, accounting for around **43.8%** of all dwellings. Compared with the oldest segment, this period reflects a more heterogeneous mix of construction characteristics and building services. As a result, it is particularly relevant for defining representative typologies that capture variation in thermal performance, system efficiencies, and occupant energy use patterns.

4.2.2.1 Typology PT_3

Typology ("**PT_3**") corresponds to a residential unit classified as EPC class C or D with a biomass heat recovery system (COP = 0.66) as the primary heating source. Unlike typologies "**PT_1**" and "**PT_2**", this dwelling includes a cooling system. In addition, thermal insulation, heat pump installation, and boiler upgrade to a higher-efficiency biomass boiler are examined as energy efficiency measures for this typology.

Baseline ("current" situation)

Under the baseline scenario, modelling results indicate an annual energy consumption of **12,358 kWh** (**143.35 kWh/m^2**) for typology "**PT_3**". Of this total, **8,141 kWh** correspond to space heating, while **4,217 kWh** correspond to cooling and appliances (**Figure 37**).

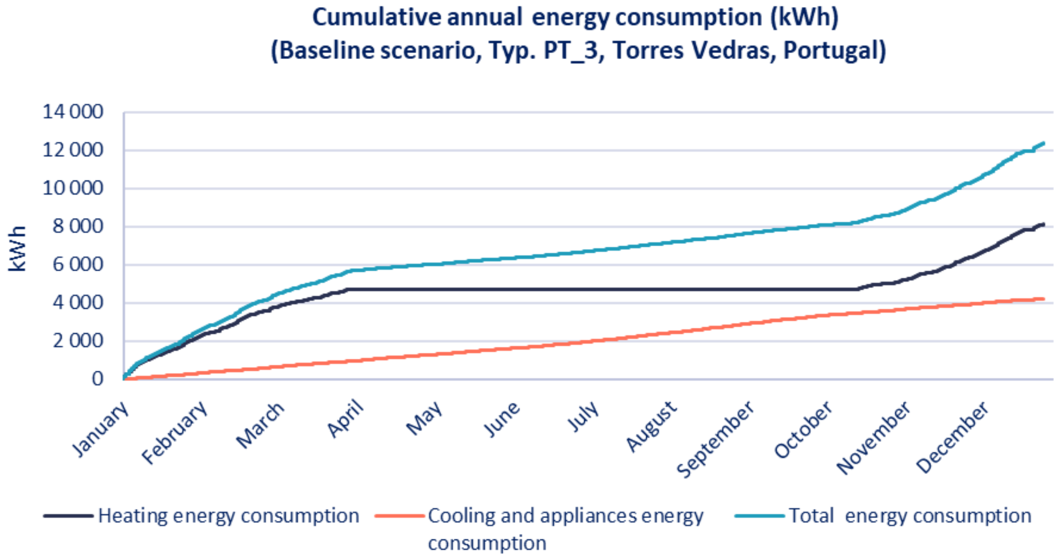


Figure 37. Cumulative annual energy consumption for the typology "PT_3" (baseline scenario).

Renovation scenarios

Figure 38 presents the annual heating and total energy consumption under the three renovation scenarios examined. Heat pump installation yields the largest reduction, lowering annual heating demand to **1,548 kWh**, representing an **81.0% decrease** relative to the baseline. Thermal insulation results in a more limited reduction, bringing heating demand down to **7,312 kWh** (**10.2% reduction**), while replacing the existing biomass system with a higher-efficiency biomass boiler reduces heating consumption to **5,971 kWh** (**26.7% reduction**).

For cooling and appliances consumption, differences between renovation scenarios are limited. Heat pump installation again results in the lowest annual cooling and appliances consumption, estimated at **4,152 kWh**, while thermal insulation and biomass boiler upgrade result in **4,267 kWh** and **4,217 kWh**, respectively. Heat pump installation provides the lowest total annual energy consumption, estimated at **5,700 kWh per** year, resulting in 6,658 kWh saved annually. By comparison, thermal insulation reduces total annual consumption to **11,578 kWh**, while biomass boiler upgrade leads to **10,188 kWh**, yielding energy savings of approximately 780 kWh, and **2,170 kWh** per year, respectively.

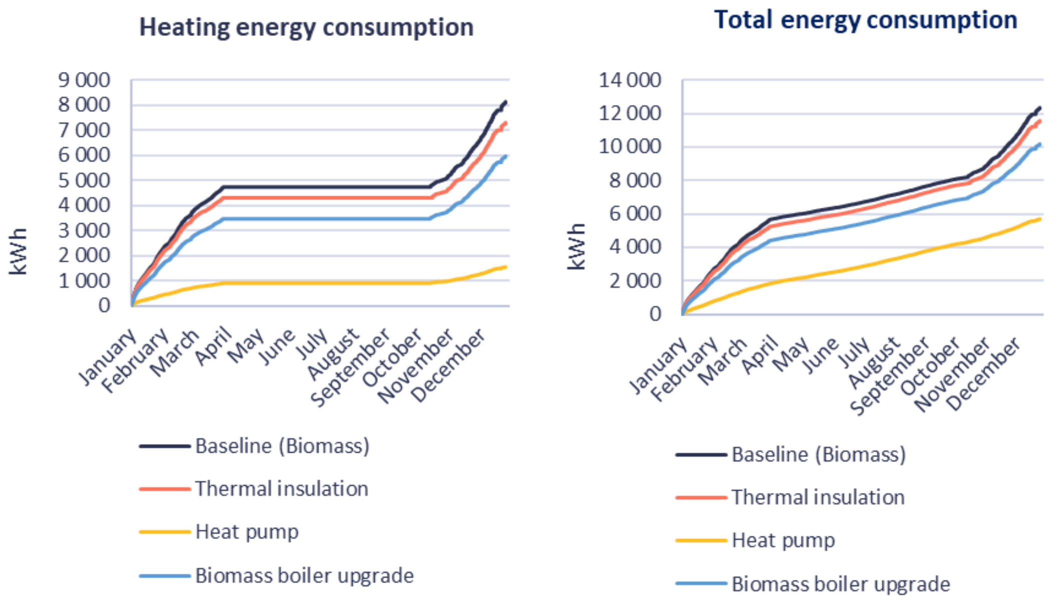


Figure 38. Cumulative total (right) and space heating (left) annual energy consumption per different "future" renovation scenario in the typology "PT_3".

Figure 39 presents the annual carbon emissions produced and averted (in kgCO_2) under the baseline ("current") and the renovation scenarios. Under the baseline scenario, the dwelling produces approximately **3,471 kgCO_2** per year. Emissions decrease to approximately **3,178 kgCO_2** with thermal insulation, corresponding **to 292 kgCO_2** averted, to **2,690 kgCO_2** following biomass boiler upgrade (**781 kgCO_2** averted), and **730 kgCO_2** after heat pump installation (**2,741 kgCO_2** averted).

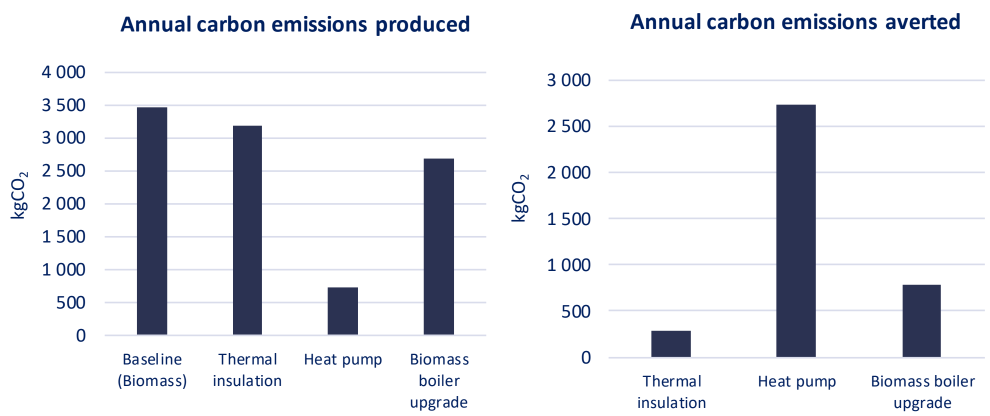


Figure 39. Annual CO_2 emissions (kg) produced and averted in the baseline ("current" situation) and in the renovation scenarios ("future" situations) in typology "PT_3".

4.2.2.2 Typology PT_4

Typology "**PT_4**" corresponds to a residential unit classified as EPC class C or D with a non-condensing gas boiler (COP = 0.87) as the primary heating source. This typology also includes a cooling system. Thermal insulation, heat pump installation, and boiler upgrade to a higher-efficiency condensing gas boiler are examined as energy efficiency measures for this typology.

Baseline ("current" situation)

Under the baseline scenario, modelling results indicate annual energy consumption at **10,654 kWh** (**123.59 kWh/m²**) for typology "**PT_4**". Of this total, **6,438 kWh** correspond to space heating, while **4,217 kWh** are associated with cooling and appliances (**Figure 40**).

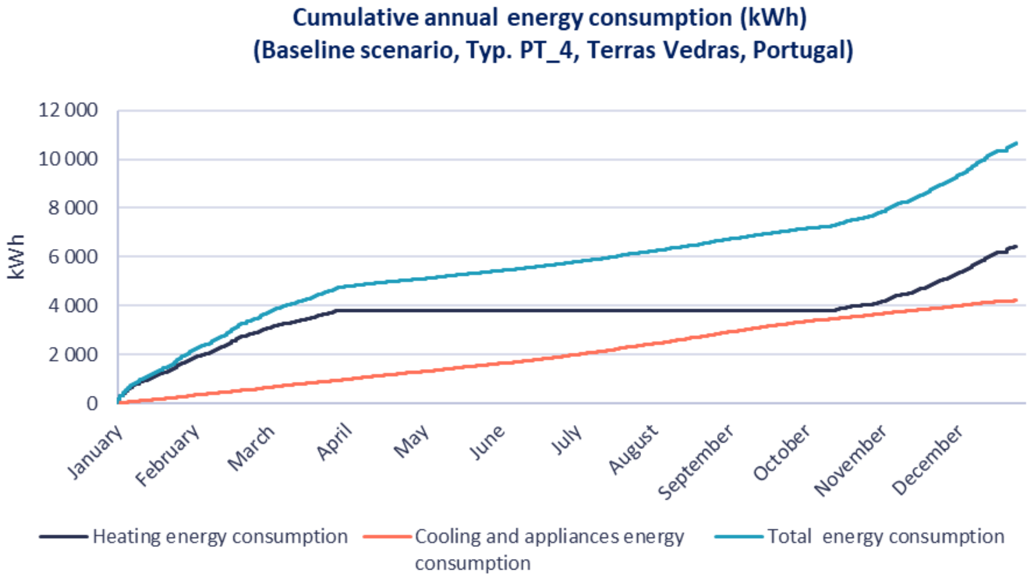


Figure 40. Cumulative annual energy consumption for the typology "PT_4" (baseline scenario).

Renovation scenarios

Figure 41 illustrates the annual heating consumption for the "**PT_4**" dwelling typology across the three renovation scenarios. Among the measures considered, heat pump installation achieves the greatest reduction, lowering annual heating demand to **1,548 kWh**, corresponding to around a **76.0%** decrease. Thermal insulation has a comparatively limited effect, reducing heating demand to **5,765 kWh** (**10.5% reduction**), while upgrading from a non-condensing gas boiler to a high-efficiency condensing gas boiler lowers heating consumption to **5,715 kWh** (**11.2% reduction**).

For cooling and appliances, differences between scenarios are again very limited, with heat pump installation resulting in the lowest annual consumption, estimated at **4,152 kWh**, while thermal insulation and boiler upgrade result in **4,267 kWh** and **4,217 kWh**, respectively. Heat pump installation provides the lowest total annual energy consumption, estimated at **5,700 kWh per year, for 4,954 kWh** saved annually. Thermal insulation reduces total annual consumption to **10,031 kWh**, while boiler upgrade results in **9,934 kWh**, amounting to approximately **623 kWh** and **721 kWh energy savings per year**, respectively.

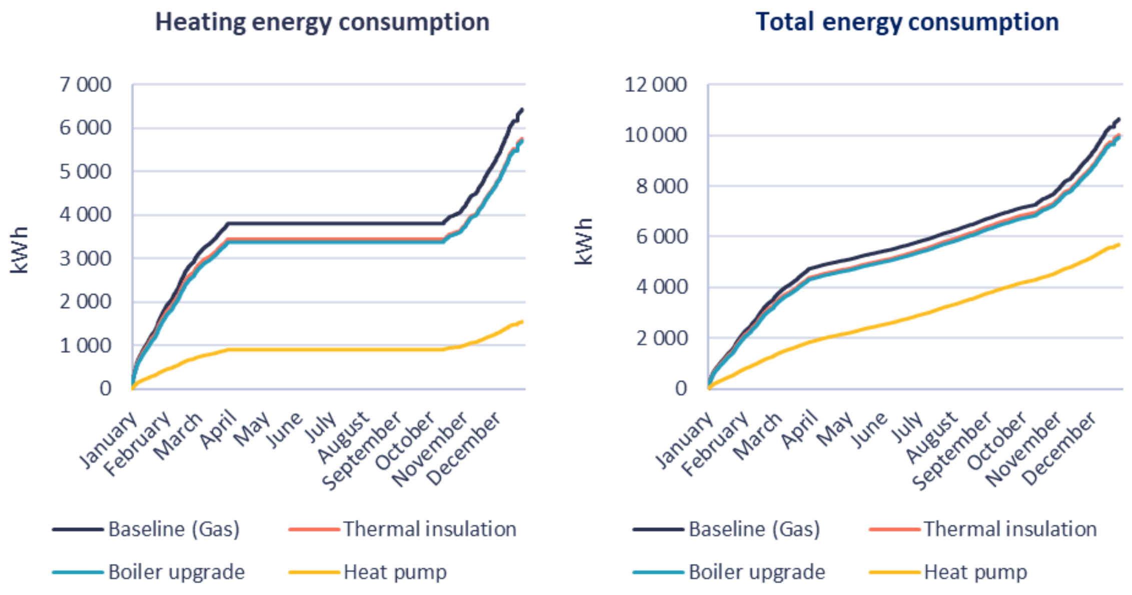


Figure 41. Cumulative total (right) and space heating (left) annual energy consumption per different "future" renovation scenario in the typology "PT_4".

Figure 42 presents the annual carbon emissions produced and averted (in kgCO_2) under the baseline ("current" situation) and the renovation scenarios ("future" situations). Under the baseline scenario, the dwelling produces approximately **1,840 kgCO_2 per year**, while emissions decrease to approximately **1,711 kgCO_2** with thermal insulation (**130 kgCO_2** averted), **1,695 kgCO_2** following biomass boiler upgrade (**146 kgCO_2** averted), and **730 kgCO_2** after heat pump installation (**1,111 kgCO_2** averted).

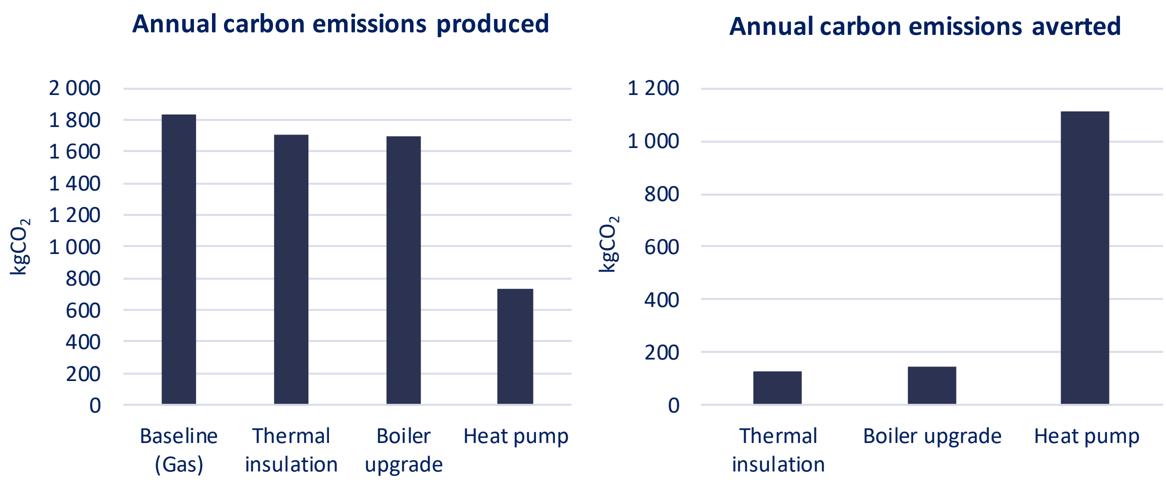


Figure 42. Annual CO_2 emissions (kg) produced and averted in the baseline ("current" situation) and in the renovation scenarios ("future" situations) in typology "PT_4".

4.2.2.3 Typology PT_5

Typology ("**PT_5**") corresponds to a residential unit classified as EPC class E or F, with electric heaters (COP = 1.00) as the primary heating source. No cooling system is foreseen for this dwelling typology. In addition, only thermal insulation and heat pump installation are examined as energy efficiency measures for this typology.

Baseline ("current" situation)

Under the baseline scenario, modelling results indicate an annual energy consumption of **12,560 kWh** corresponding to **146.17 kWh/m²**. Of this total, **8,764 kWh** are attributed to space heating, while **3,796 kWh** are associated with appliances (**Figure 43**).

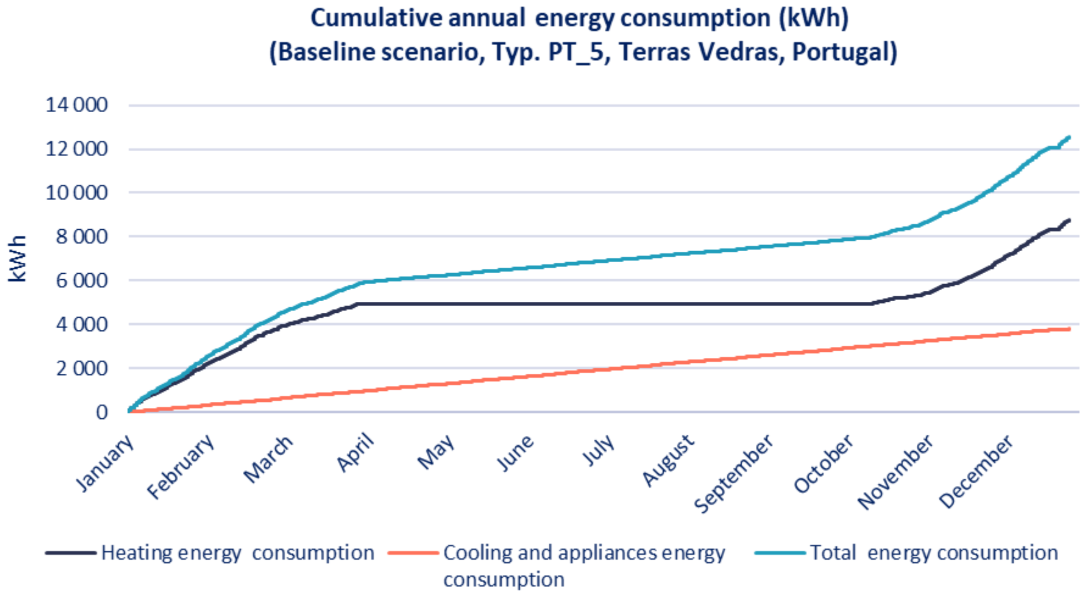


Figure 43. Cumulative annual energy consumption for typology "PT_5" (baseline scenario).

Renovation scenarios

Figure 44 presents the annual heating and total consumption for the "PT_5" typology under the two examined renovation scenarios. Heat pump installation achieves the largest reduction, lowering annual heating demand to **2,504 kWh (71.4% reduction),** while thermal insulation appears to have a more limited effect, reducing heating demand to **7,621 kWh (13.0% reduction).**

Regarding appliances, no variation is observed across the different renovation scenarios, as appliance-related energy consumption is assumed to remain unchanged **(3,796 kWh).** Heat pump installation provides the lowest total annual energy consumption, estimated at 6,300 kWh per year, while thermal insulation reduces total annual consumption to **11,417 kWh**, resulting in energy savings of approximately **6,260 kWh and 1,143 kWh.**

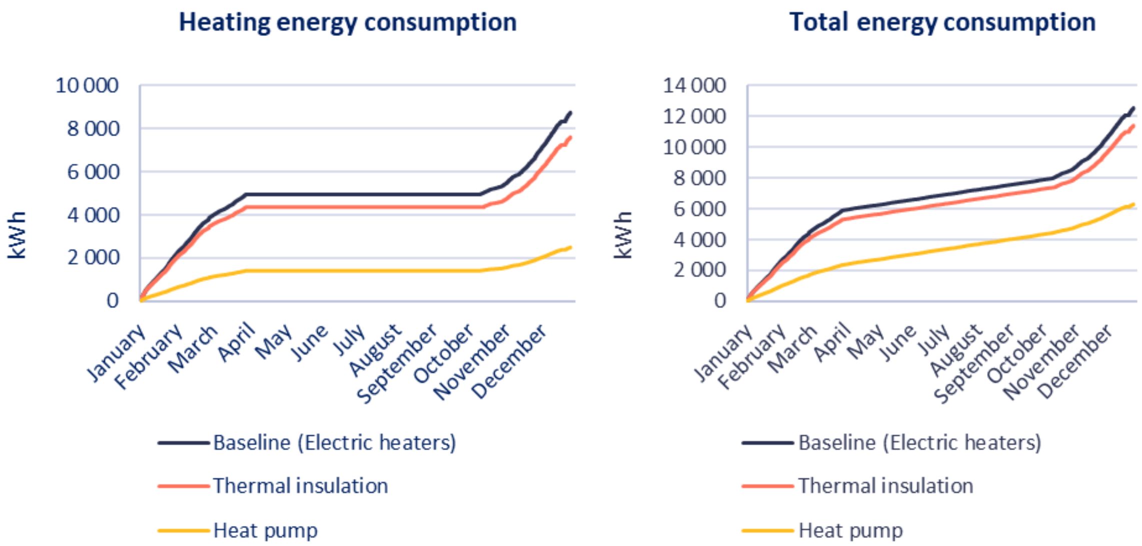


Figure 44. Cumulative total (right) and space heating (left) annual energy consumption per different "future" renovation scenario in the typology "PT_5".

Figure 45 presents the annual carbon emissions produced and averted (in $kgCO_2$) under the baseline ("current") and renovation scenarios. Under the baseline scenario, the dwelling produces approximately 1,462 $kgCO_2$ per year, while emissions decrease to approximately 1,166 $kgCO_2$ with thermal insulation (146 $kgCO_2$ averted), and around 806 $kgCO_2$ after heat pump installation (approximately 801 $kgCO_2$ averted).

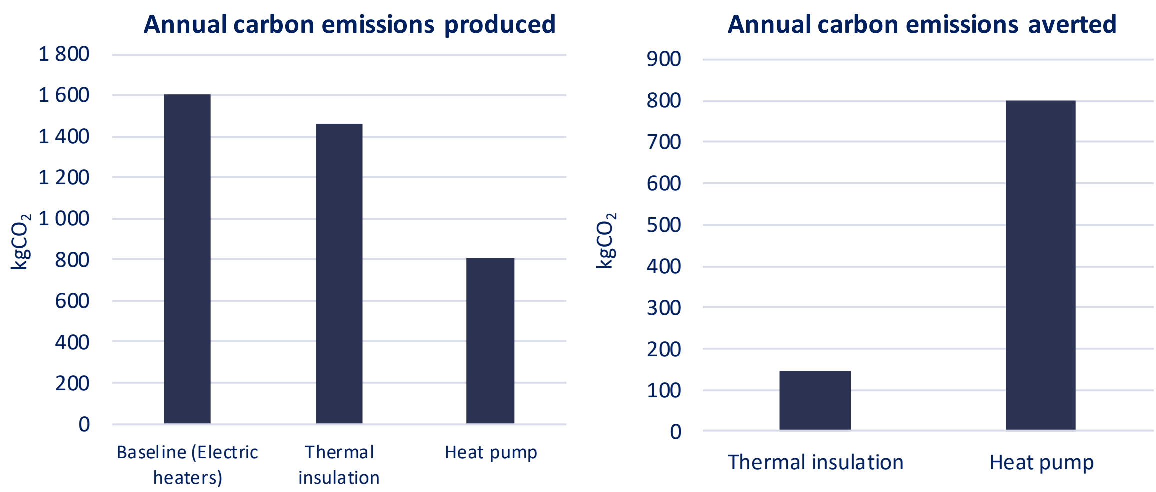


Figure 45. Annual CO_2 emissions (kg) produced and averted in the baseline ("current" situation) and in the renovation scenarios ("future" situations) in typology "PT_5".

4.2.2.4 Typology PT_6

Typology ("**PT_6**") corresponds to a residential unit classified as EPC class E or F with a biomass heat recovery system (COP = 0.65) as the primary heating source. No cooling system is assumed for this dwelling typology. Thermal insulation, heat pump installation, and upgrading the existing boiler to a higher-efficiency biomass boiler are examined as energy-efficiency measures for this typology.

Baseline ("current" situation)

Under the baseline scenario, modelling results indicate annual energy consumption at **15,233 kWh** (**177.27 kWh/m²**) for typology "**PT_6**". Of this total, **11,437 kWh** correspond to space heating, while **3,796 kWh** are associated with appliances (**Figure 46**). This is the highest baseline energy consumption among the dwelling typologies examined for this construction period.

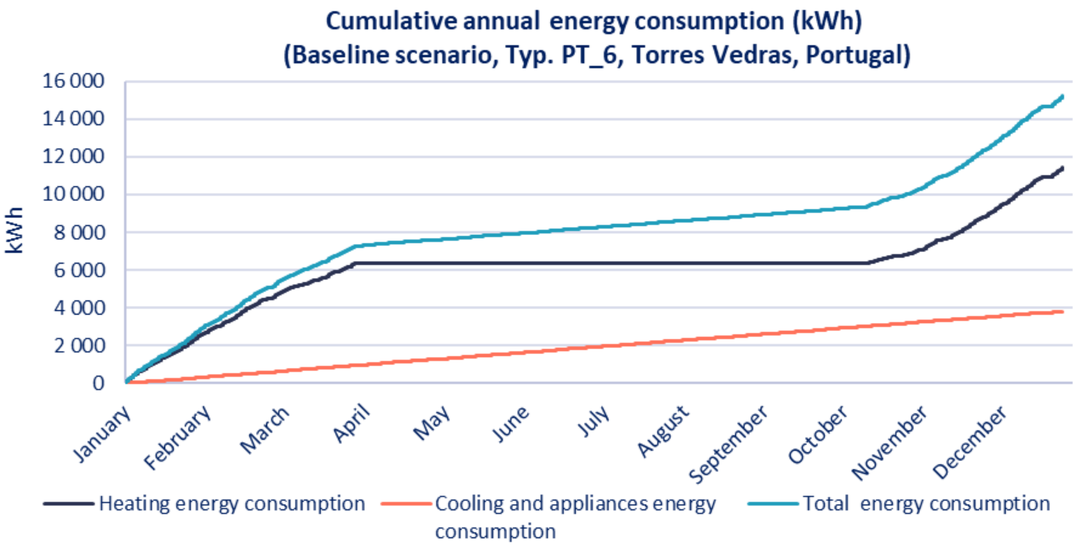


Figure 46. Cumulative annual energy consumption for the typology "PT_6" (baseline scenario).

Renovation scenarios

Figure 47 presents the annual heating and total energy consumption for typology "**PT_6**" under the three renovation scenarios examined. Heat pump installation results in the largest reduction, lowering annual heating demand to **2,240 kWh**, which corresponds to an approximately **80.4% decrease**. Thermal insulation reduces heating demand to **9,845 kWh** (**13.9% reduction**), while replacing the existing biomass system with a higher-efficiency biomass boiler lowers heating consumption to **8,260 kWh** (**27.8% reduction**).

For appliances, no variation is observed across the different renovation scenarios, as appliance-related energy consumption is assumed to remain constant at **3,796 kWh**. Regarding total energy consumption, Heat pump installation provides the lowest value, estimated at **6,036 kWh per year**, for an energy saving of approximately 9,197 kWh saved annually. Thermal insulation reduces total annual consumption to **13,641 kWh**, while the biomass boiler upgrade results in approximately **12,056 kWh**, yielding an energy consumption reduction of approximately 1,592 kWh and 3,177 kWh per year.

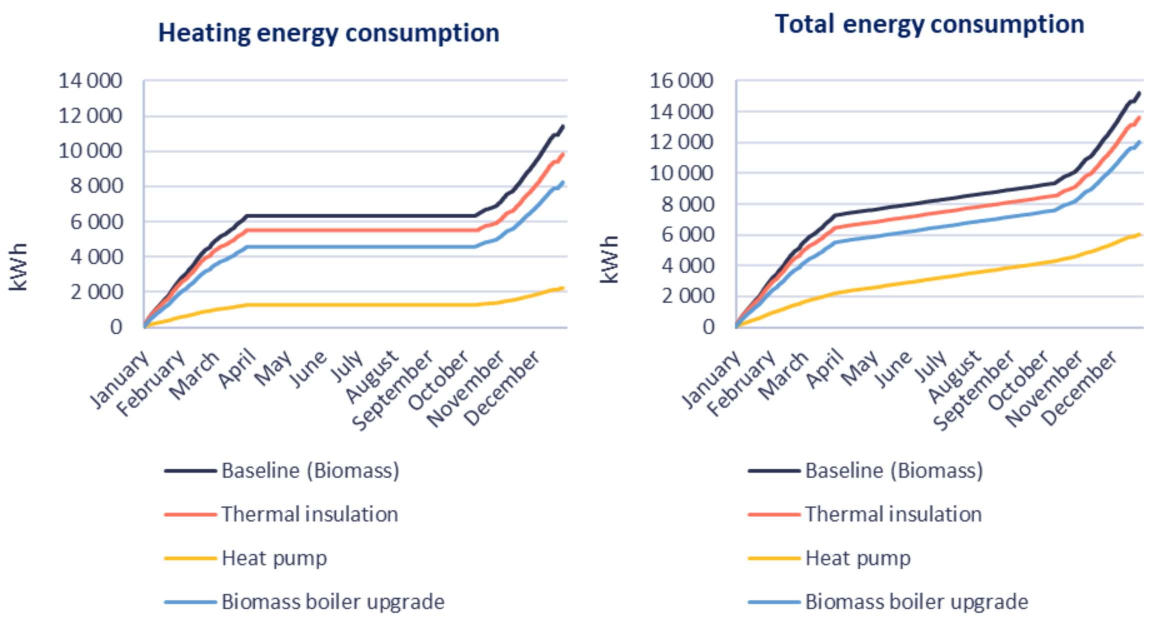


Figure 47. Cumulative total (right) and space heating (left) annual energy consumption per different "future" renovation scenario in the typology "PT_6".

Figure 48 presents the annual carbon emissions produced and averted (in kgCO_2) under the baseline ("current" situation) and the renovation scenarios ("future" situations). Under the baseline scenario, the dwelling produces approximately 4,603 kgCO_2 per year. Emissions decrease to approximately 4,030 kgCO_2 with thermal insulation (573 kgCO_2 averted), 3,459 kgCO_2 following biomass boiler upgrade (1,144 kgCO_2 averted), and 773 kgCO_2 after heat pump installation (around 3,831 kgCO_2 averted).

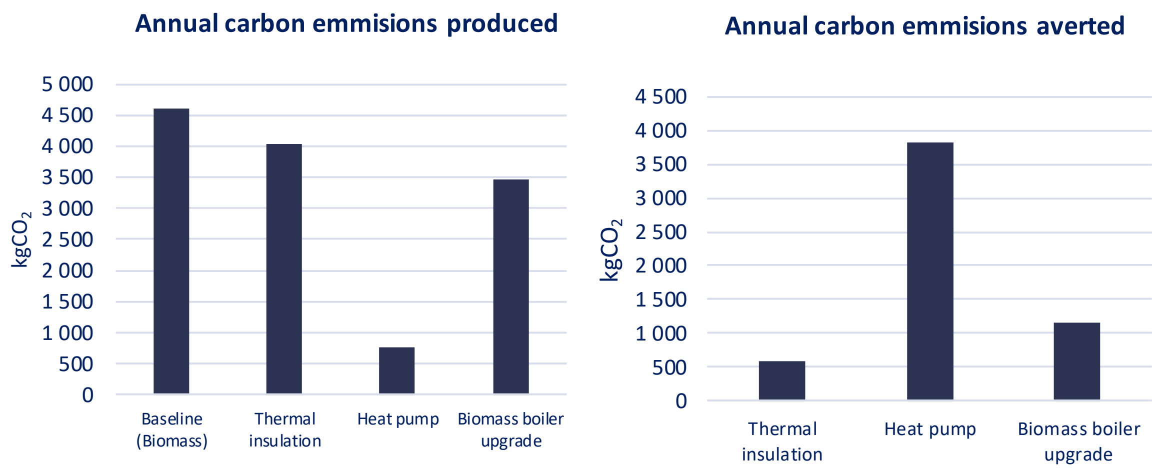


Figure 48. Annual CO_2 emissions (kg) produced and averted in the baseline ("current" situation) and in the renovation scenarios ("future" situations) in typology "PT_6".

4.2.3 Dwellings constructed between 2001 and 2010

Dwellings constructed between 2001 and 2010 constitute an important share of the dwelling stock in the Municipality of Torres Vedras, accounting for around **30.3%** of all multifamily dwellings. Similar to the previous construction period (1981-2000), this group reflects a relatively heterogeneous mix of construction characteristics and building services.

4.2.3.1 Typology PT_7

Typology "**PT_7**" corresponds to dwellings of EPC class C or D, with a biomass heat recovery system (COP = 0.70) as a primary heating source. This typology also includes a cooling system. Thermal insulation, heat pump installation, and boiler upgrade to a higher-efficiency biomass boiler are examined as energy efficiency measures for this typology.

Baseline ("current" situation)

Under the baseline scenario, modelling results indicate annual energy consumption of **15,327 kWh**, corresponding to **130.54 kWh/m²**. Of this total, around **10,838 kWh** are attributed to space heating, while **4,490 kWh** are associated with cooling and appliances (**Figure 49**).

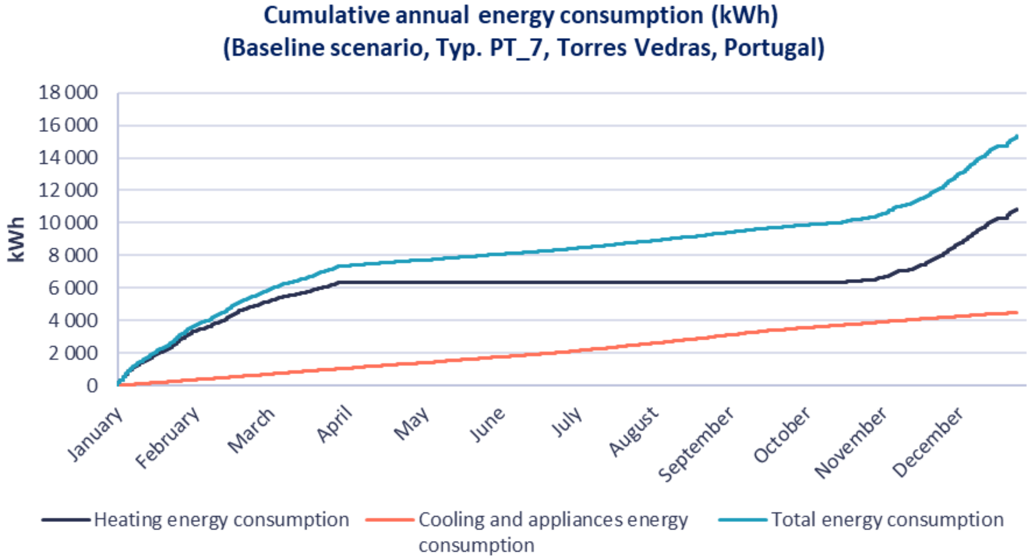


Figure 49. Cumulative annual energy consumption for typology "PT_7" (baseline scenario).

Renovation scenarios

Figure 50 presents the annual heating and total energy consumption for typology "**PT_7**" under the three renovation scenarios examined. Heat pump installation leads to the largest reduction, lowering annual heating demand to **2,168 kWh**. Thermal insulation reduces heating demand to **10,069 kWh**, while upgrading the biomass heat recovery system lowers heating consumption to **8,431 kWh**. For cooling and appliances, the differences between renovation scenarios are reduced. Heat pump installation results in the lowest annual cooling and appliances consumption, estimated at **4,428 kWh**, while thermal insulation and biomass system upgrade results in **4,528** kWh and **4,490 kWh**, respectively. As for the total annual energy consumption for the three renovation scenarios, heat pump installation provides the lowest total energy consumption, estimated at **6,596 kWh** per year. By comparison, thermal insulation reduces total annual consumption to **14,596 kWh**, while biomass system upgrade reduces it to **12,921 kWh**. Heat pump installation yields the largest reduction, with approximately **8,732 kWh** saved annually. Thermal insulation leads to annual savings of approximately **731 kWh**, while biomass system upgrade results in savings of around **2,407 kWh per year**.

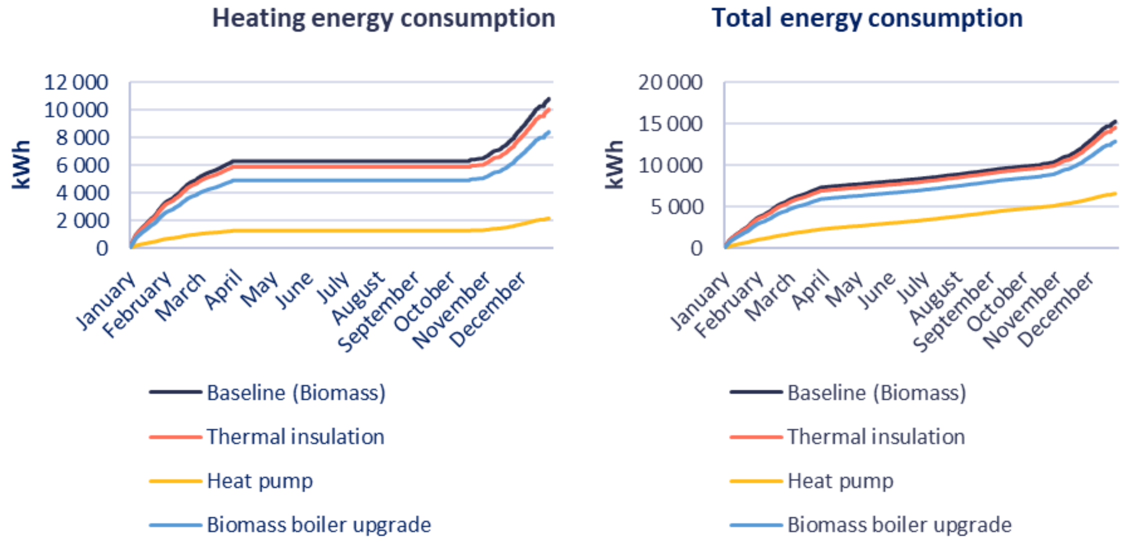


Figure 50. Cumulative total (right) and space heating (left) annual energy consumption per different "future" renovation scenario in the typology "PT_7".

Figure 51 presents the annual carbon emissions produced and averted (in $kgCO_2$) under the baseline ("current") and renovation ("future") scenarios. Under the baseline scenario, the dwelling produces approximately **4,476 $kgCO_2$ per year**, while emissions decrease to approximately **4,204 $kgCO_2$** with thermal insulation, corresponding to **272 $kgCO_2$ averted**; to **3,610 $kgCO_2$** following biomass system upgrade, corresponding to **866 $kgCO_2$ averted**; and to **844 $kgCO_2$** after heat pump installation, corresponding to **3,632 $kgCO_2$** averted.

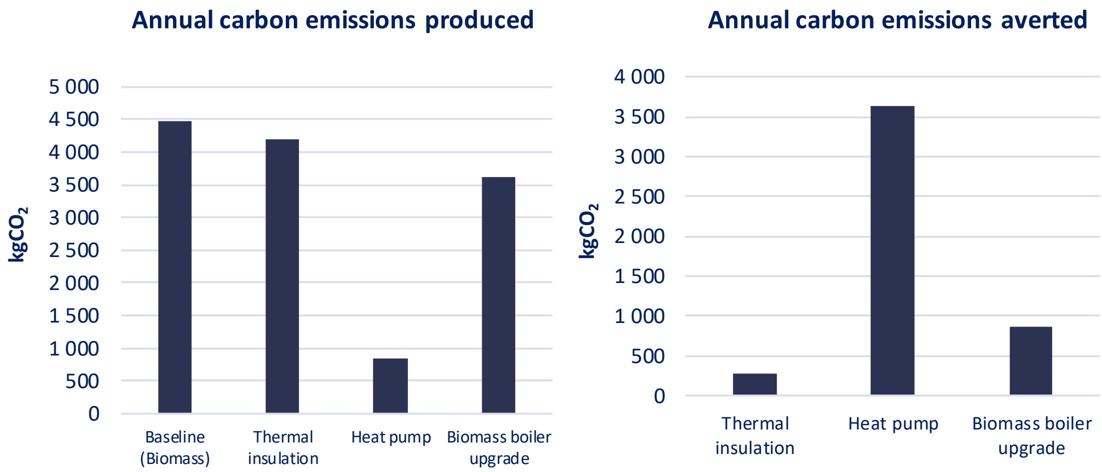


Figure 51. Annual CO_2 emissions (kg) produced and averted in the baseline ("current" situation) and in the renovation scenarios ("future" situations) in typology "PT_7".

4.2.3.2 Typology PT_8

Typology "**PT_8**" corresponds to a residential unit classified as EPC class C or D, with a non-condensing gas boiler (COP = 0.91) as the primary heating source. This typology also includes a cooling system. Thermal insulation, heat pump installation, and boiler upgrade to a higher-efficiency condensing gas boiler are examined as energy efficiency measures for this typology.

Baseline ("current" situation)

Under the baseline scenario, modelling results indicate annual energy consumption of **13,140 kWh**, corresponding to **111.91 kWh/m²**, for typology "**PT_8**". Of this total, **8,650 kWh** are attributed to space heating, while **4,490 kWh** are associated with cooling and appliances (**Figure 52**).

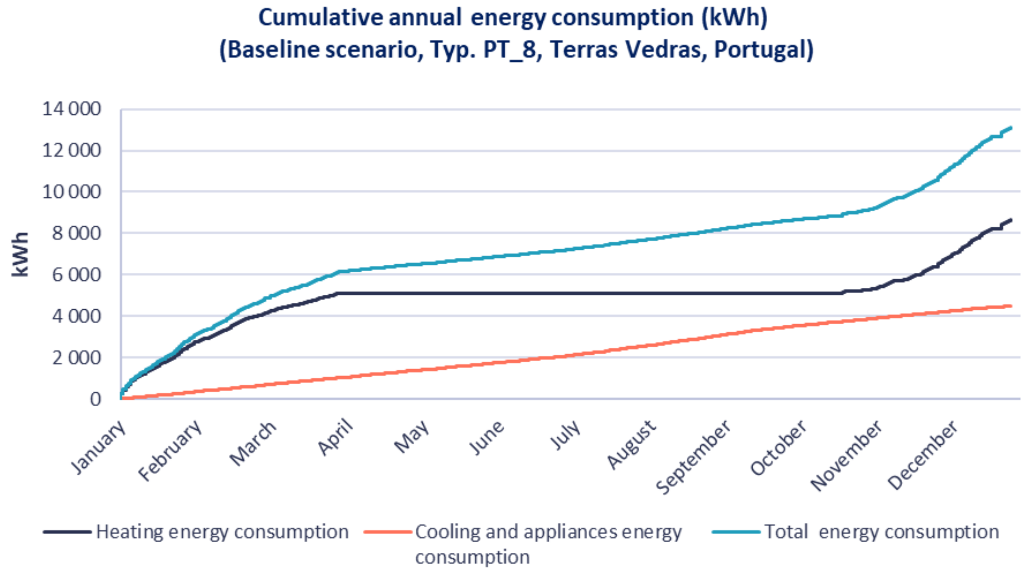


Figure 52. Cumulative annual energy consumption for typology "PT_8" (baseline scenario).

Renovation scenarios

Figure 53 illustrates the annual heating and total energy consumption for typology "**PT_8**" across the three renovation scenarios examined. Heat pump installation achieves the greatest reduction, lowering annual heating demand to **2,168 kWh**. Thermal insulation reduces heating demand to **8,022 kWh**, while upgrading from a non-condensing gas boiler to a higher-efficiency condensing gas boiler lowers it to **8,036 kWh**.

For cooling and appliances, differences between renovation scenarios remain limited. Heat pump installation again results in the lowest annual cooling and appliance consumption, estimated at **4,428 kWh**, while thermal insulation and boiler upgrade result in **4,527 kWh** and **4,490 kWh**, respectively. As for the total annual energy consumption across the three renovation scenarios, heat pump installation yields the lowest, estimated at **6,596 kWh per year**. Thermal insulation reduces total annual consumption to **12,550 kWh**, while boiler upgrade results in a very similar value of around **12,525 kWh**. Heat pump installation yields the largest reduction, with approximately **6,544 kWh** saved annually. Thermal insulation leads to annual savings of approximately **591 kWh**, while boiler upgrade results in similarly limited savings of around **615 kWh** per year.

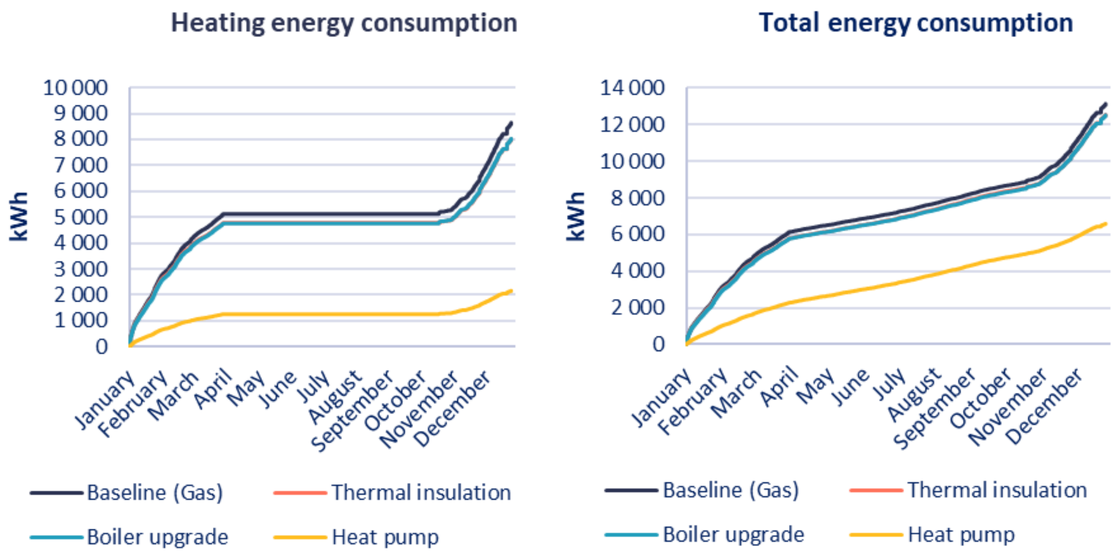


Figure 53. Cumulative total (right) and space heating (left) annual energy consumption per different "future" renovation scenario in the typology "PT_8".

Figure 54 presents the annual carbon emissions produced and averted (in $kgCO_2$) under the baseline ("current") and renovation ("future") scenarios. Using the emission factors applied in this study, heat pump installation leads to the lowest annual emissions. Under the baseline scenario, the dwelling produces approximately **2,322 $kgCO_2$** per year, while emissions decrease to approximately **2,200 $kgCO_2$** with thermal insulation, corresponding to **122 $kgCO_2$ averted**, to **2,198 $kgCO_2$** following boiler upgrade, corresponding to **124 $kgCO_2$ averted**, and to **844 $kgCO_2$** after heat pump installation, corresponding to **1,478 $kgCO_2$ averted**.

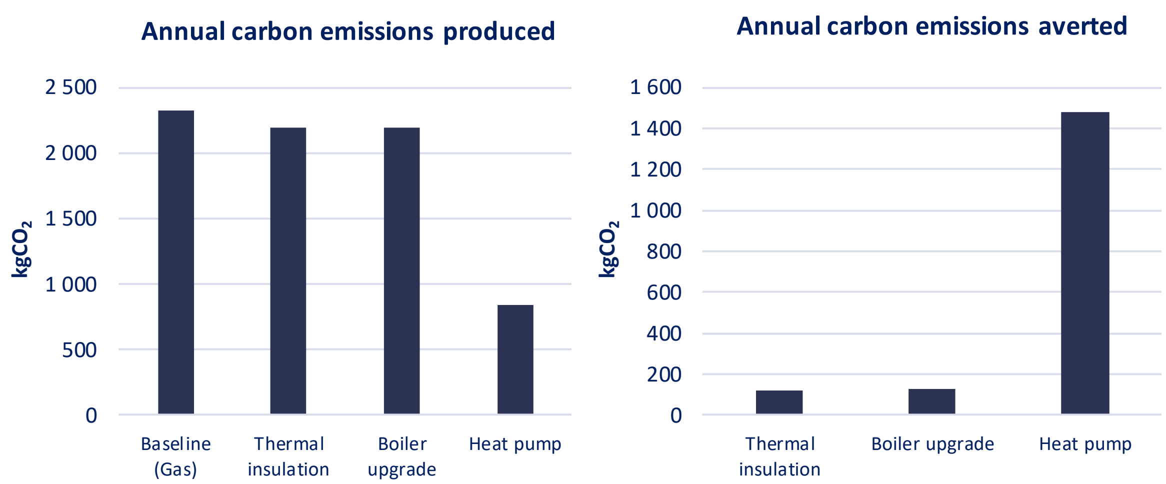


Figure 54. Annual CO_2 emissions (kg) produced and averted in the baseline ("current" situation) and in the renovation scenarios ("future" situations) in typology "PT_8".

4.2.3.3 Typology PT_9

Typology "**PT_9**" corresponds to a residential unit classified as EPC class C or D, with electric heaters (COP = 1.00) as the primary heating source. No cooling system is foreseen for this dwelling typology. Moreover, only thermal insulation and heat pump installation are examined as energy efficiency measures for this typology.

Baseline ("current" situation)

Under the baseline scenario, modelling results indicate annual energy consumption of **17,461 kWh**, corresponding to approximately **137.42 kWh/m²**, for typology "**PT_9**". Of this total, **13,380 kWh** are attributed to space heating, while **4,080 kWh** are associated with appliances (**Figure 55**).

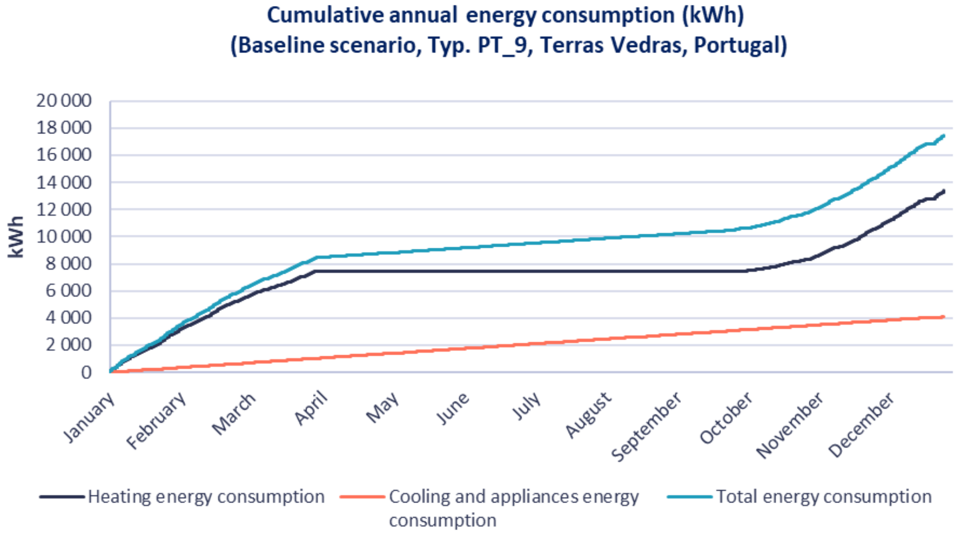


Figure 55. Cumulative annual energy consumption for typology "PT_9" (baseline scenario).

Renovation scenarios

Figure 56 presents the annual heating energy consumption for typology "**PT_9**" under the two renovation scenarios examined. Heat pump installation achieves the largest reduction, lowering annual heating demand to **3,823 kWh**, while thermal insulation reduces heating demand to **12,590 kWh**. For appliances, no variation is observed across the different renovation scenarios, as appliance-related energy consumption is assumed to remain unchanged at approximately **4,080 kWh**. Heat pump installation provides the lowest total annual energy consumption, estimated at **7,904 kWh** per year, while thermal insulation reduces total annual consumption to **16,671 kWh**, with respective energy savings of approximately **9,557 kWh** and **790 kWh** per year.

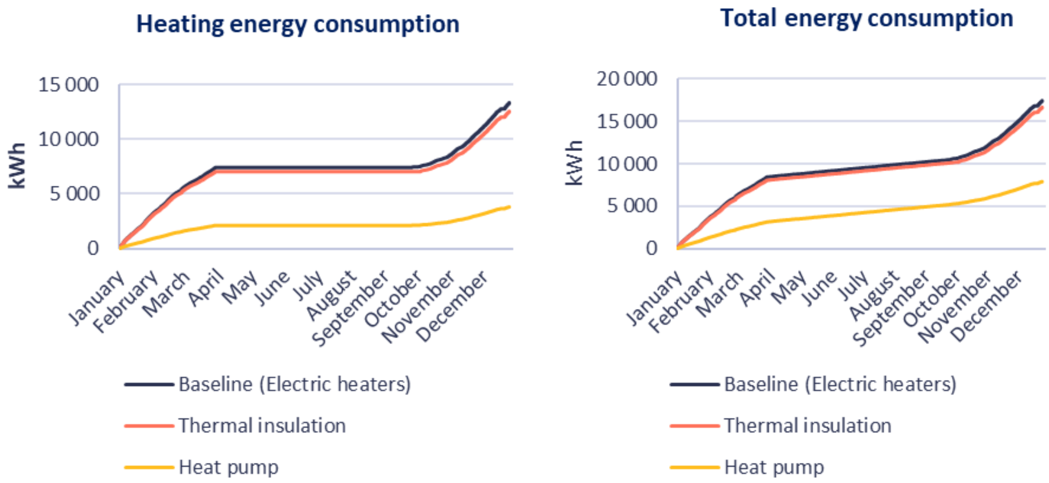


Figure 56. Cumulative total (right) and space heating (left) annual energy consumption per different "future" renovation scenario in the typology "PT_9".

Figure 57 presents the annual carbon emissions produced and averted (in kgCO_2) under the baseline ("current") and renovation ("future") scenarios. Using the emission factors applied in this study, heat pump installation yields the lowest annual emissions. Under the baseline scenario, the dwelling produces approximately **2,235 kgCO_2** per year, while emissions decrease to approximately **2,134 kgCO_2** with thermal insulation and to **1,012 kgCO_2** following heat pump installation.

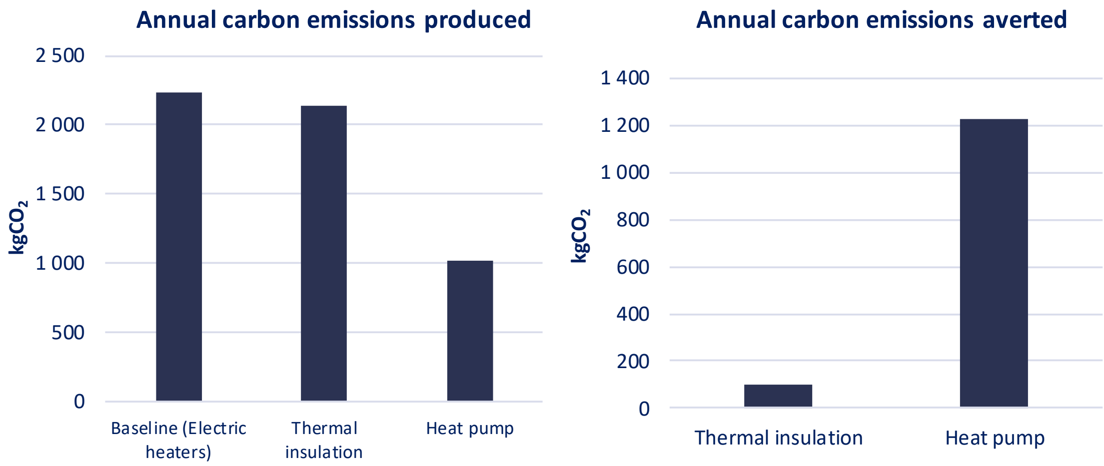


Figure 57. Annual CO_2 emissions (kg) produced and averted in the baseline ("current" situation) and in the renovation scenarios ("future" situations) in typology "PT_9".

4.2.3.4 Typology PT_10

Typology "**PT_10**" corresponds to a residential unit classified as EPC class C with a non-condensing gas boiler (COP = 0.81) as the primary heating source. This typology does not include a cooling system. Thermal insulation, heat pump installation, and boiler upgrade to a higher-efficiency condensing gas boiler are examined as energy efficiency measures for this typology.

Baseline ("current" situation)

Under the baseline scenario, modelling results indicate annual energy consumption of **18,832 kWh**, corresponding to approximately **148.21 kWh/m².** Of this total, **13,769 kWh** correspond to space heating needs, while **5,062 kWh** are associated with cooling and appliances (**Figure 58**).

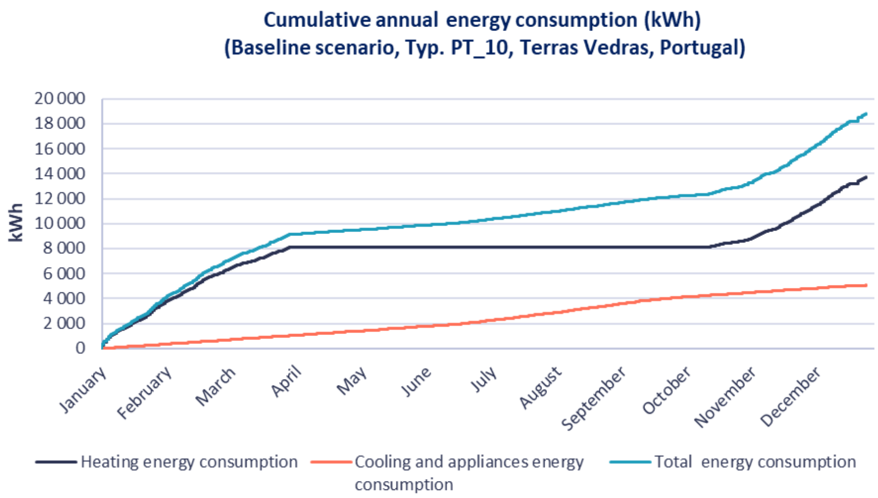


Figure 58. Cumulative annual energy consumption for typology "PT_10" (baseline scenario).

Renovation scenarios

Figure 59 illustrates the annual heating and total energy consumption for typology "**PT_10**" across the three renovation scenarios examined. Heat pump installation achieves the greatest reduction, lowering annual heating demand to **3,062 kWh**. Thermal insulation reduces heating demand to **12,888 kWh**, while upgrading from a non-condensing gas boiler to a higher-efficiency condensing gas boiler lowers consumption to **11,401 kWh**.

For cooling and appliances, heat pump installation again results in the lowest annual consumption, estimated at **4,858 kWh**, while thermal insulation and boiler upgrade result in **5,107 kWh** and **5,062 kWh**, respectively. The total annual energy consumption for the three renovation scenarios is derived by combining heating, cooling, and appliance consumption. Heat pump installation provides the lowest total annual energy consumption, estimated at **7,920 kWh** per year. Thermal insulation reduces total annual consumption to **17,995 kWh**, while boiler upgrade results in around **16,463 kWh**. Heat pump, thermal insulation and gas boiler enable approximately **10,912 kWh**, **836 kWh**, and **2,368 kWh** saved annually, respectively, relative to the baseline scenario.

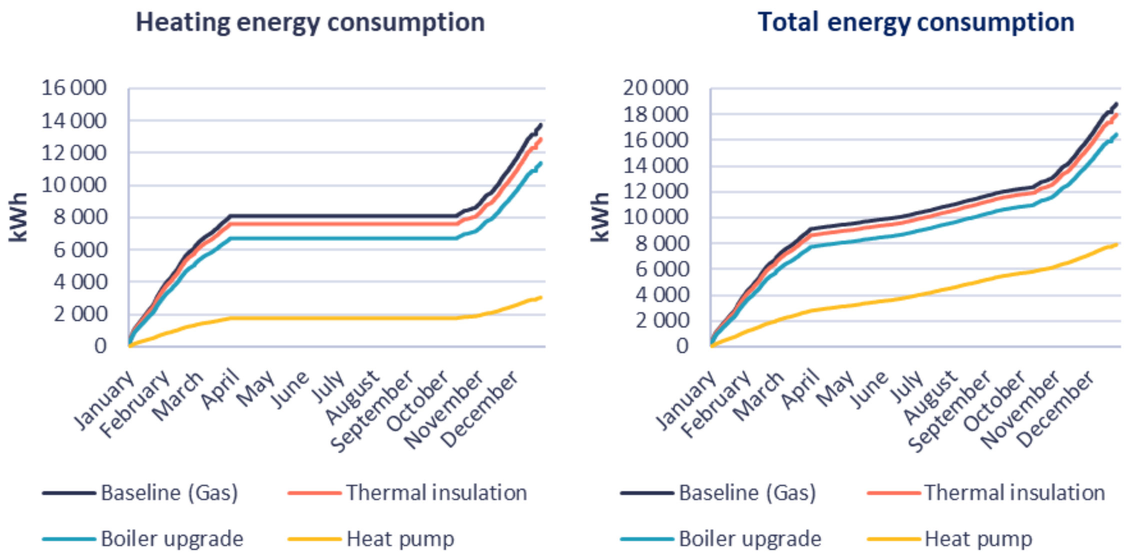


Figure 59. Cumulative total (right) and space heating (left) annual energy consumption per different "future" renovation scenario in the typology "PT_9".

Figure 60 presents the annual carbon emissions produced and averted (in kgCO_2) under the baseline ("current") and renovation ("future") scenarios. Using the emission factors applied in this study, heat pump installation leads to the lowest annual emissions. Under the baseline scenario, the dwelling produces approximately **3,429 kgCO_2** per year, while emissions decrease to approximately **3,257 kgCO_2** with thermal insulation, corresponding to **172 kgCO_2 averted**, to **2,951 kgCO_2** following boiler upgrade, corresponding to **478 kgCO_2 averted**, and to **1,014 kgCO_2** after heat pump installation, corresponding to **2,416 kgCO_2 averted**.

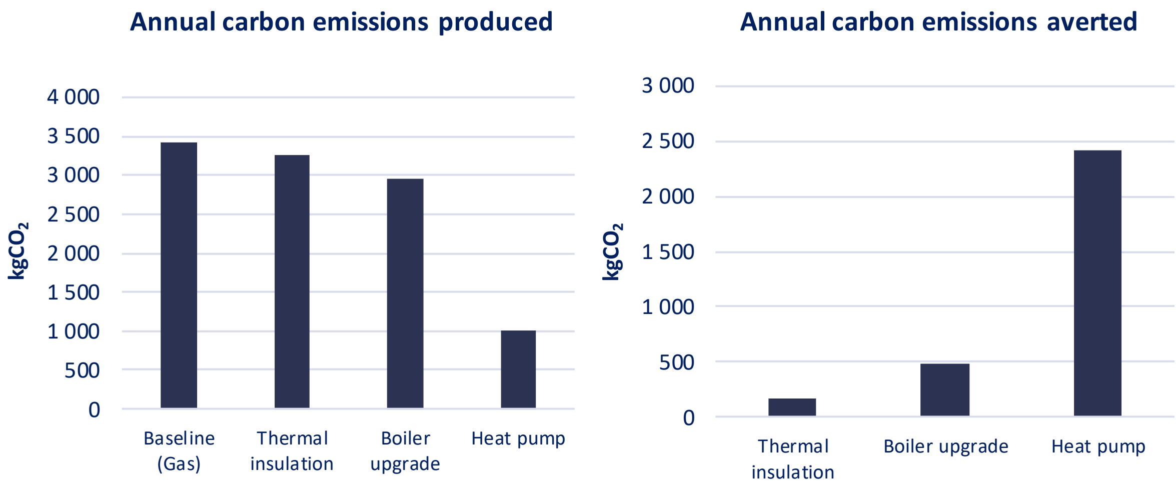


Figure 60. Annual CO_2 emissions (kg) produced and averted in the baseline ("current" situation) and in the renovation scenarios ("future" situations) in typology "PT_10".

4.2.4 Solar PV installation

To complement the assessment of energy efficiency measures and explore the potential contribution of renewable energy systems at the household level, the performance of residential-scale PV installation is also examined for the dwelling typologies of Torres Vedras. This additional analysis enables assessment of the extent to which on-site distributed electricity generation can help meet household electricity demand under baseline and renovation scenarios, thereby providing a clearer view of the role solar PV systems may play in integrated residential energy upgrade pathways.

A representative residential PV system with a nominal capacity of 3 kWp, corresponding to an installation area of approximately 16 m^2 is considered. For Torres Vedras, this PV system has a cumulative annual electricity production of **6,072 kWh** across all typologies.

Table 5 compares total electricity consumption under baseline and renovation conditions with the corresponding percentage of PV generation coverage. The results indicate that PV systems can make a substantial contribution to meeting household electricity demand. The estimated level of coverage varies considerably across typologies and scenarios. In several cases, particularly in dwellings with lower electricity demand under baseline conditions or in non-electrified renovation scenarios, the simulated PV system is sufficient to meet the full annual electricity demand and may generate a surplus. This is observed, for example, in typologies "PT_3", "PT_4", "PT_7", and "PT_8", where PV coverage exceeds 100%. By contrast, PV coverage is lower in scenarios that include heat pump installations, reflecting the increased electricity demand associated with electrified heating. Even so, the combined application of solar PV systems and heat pumps remains relevant, as it can support a broader transition towards residential electrification and lower dependence on external energy supply.

Table 5. Total electricity consumption and PV coverage across all dwelling typologies under baseline and renovation scenarios in the Municipality of Torres Vedras.

Typology	Scenario and heating source	Total electricity consumption (kWh)	Percentage of coverage
PT_1	Baseline (electricity)	9,987	60.8%
	Thermal insulation (electricity)	9,112	66.6%

	Heat pump (electricity)	5,565	109.1%
PT_2	Baseline (electricity)	14,789	41.1%
	Thermal insulation (electricity)	13,305	45.6%
	Heat pump (electricity)	6,937	87.5%
PT_3	Baseline (biomass), Thermal insulation (biomass), Heating system upgrade (biomass)	4,217	144.0%
	Heat pump (electricity)	5,700	106.5%
PT_4	Baseline (gas), Thermal insulation (gas), Boiler upgrade (gas)	4,217	144.0%
	Heat Pump (electricity)	5,700	106.5%
PT_5	Baseline (electricity)	12,560	48.3%
	Thermal insulation (electricity)	11,417	53.2%
	Heat pump (electricity)	6,300	96.4%
PT_6	Baseline (biomass), Thermal insulation (biomass), Heating system upgrade (biomass)	3,796	160.0%
	Heat pump (electricity)	6,036	100.6%
PT_7	Baseline (biomass), Thermal insulation (biomass), Heating system upgrade (biomass)	4,489	135.3%
	Heat pump (electricity)	6,596	92.1%
PT_8	Baseline (gas), Thermal insulation (gas), Boiler Upgrade (gas)	4,490	135.3%
	Heat pump (electricity)	6,596	92.1%
PT_9	Baseline (electricity)	17,461	34.8%
	Thermal Insulation (electricity)	16,671	36.4%
	Heat Pump (electricity)	7,904	76.8%
PT_10	Baseline (gas), Thermal insulation (gas), Boiler upgrade (gas)	5,062	120.0%
	Heat pump (electricity)	7,920	76.7%

4.2.5 Cost-effectiveness analysis

Table 6 presents the investment costs, the cost-effectiveness for energy saving and carbon dioxide emissions savings for the most cost-effective measure, and the respective potential energy bill reduction.

More recent typologies incur the highest costs for thermal insulation, namely PT_7 to PT_10. These typologies have larger building element areas and higher energy performance, which requires more investment to improve. Conversely, lower cost-effectiveness values for thermal renovation in terms of energy consumption savings are observed in these typologies. The highest value, **0.18kWh/€**, is observed in typology PT_2 for this type of measure. On the other hand, heat pump installation is the most cost-effective renovation measure across all typologies, especially in more recent ones. Typologies PT_9 and PT_10 present the highest values, respectively **4.69 kWh/€** and **5.36 kWh/€**. Heat pumps have considerable performance efficiency and relatively low costs compared to other solutions. Biomass boiler upgrades have a higher average cost-effectiveness compared to gas boiler upgrades. Nevertheless, the highest value is recorded for typology PT_10, **1.05 kWh/€**, for a condensing gas boiler.

The potential energy bill savings are overwhelmingly higher after simulating a heat pump installation, due to the higher absolute reduction in total energy consumption. The highest value is achieved for typology PT_9: approximately **3,326 €/year** for all energy services, assuming a thermal comfort standard is maintained every day of the year. Due to more significant energy consumption reductions, biomass boiler upgrades also yield considerable potential energy bill reduction, especially in typology PT_6 (**1,027 €/year**).

Cost-effectiveness of thermal renovation for carbon emissions reduction is very low across all typologies, never surpassing **0.05 kgCO_2/€** (Typology PT_6). Heat pump installation has the highest cost-effectiveness for carbon emissions reduction across all typologies, peaking at **1.88 kgCO_2/€** in typology PT_6. Considering total energy generation, polycrystalline PV panels with 3 kWp of power can yield **2.16 kWh/€** in Torres Vedras.

Table 6. Investment cost, cost-effectiveness for energy savings and carbon dioxide emissions reduction and potential energy bills reduction for each renovation scenario in the Municipality of Torres Vedras.

	PT_1	PT_2	PT_3	PT_4	PT_5	PT_6	PT_7	PT_8	PT_9	PT_10
Investment cost interval (€/per dwelling)										
Overall Thermal insulation	7,839-14,675	8,476-15,716	10,601-20,033	10,601-20,033	10,586-20,005	10,586-20,005	12,015-22,684	12,015-22,684	12,500-23,598	12,500-23,598
Walls	1030-1401	1226-1592	1070-1464	1068-1462	1068-1462	1248-1709	1248-1709	1299-1778	1299-1778	1299-1778
Window	6,809-13,265	7,250-14,123	9,532-18,569	9,532-18,569	9,519-18,543	9,519-18,543	10,767-20,975	10,767-20,975	11,201-21,821	11,201-21,821
Heat pump	2,037-2,954	2,037-2,954	2,037-2,954	2,037-2,954	2,037-2,954	2,037-2,954	2,037-2,954	2,037-2,954	2,037-2,954	2,037-2,954
Gas boiler	-	-	-	2,264-4,860	-	-	-	2,264-4,860	-	2,264-4,860
Biomass boiler	-	-	4,083-6,651	-	-	4,083-6,651	4,083-6,651	-	-	-
Polycrystalline PV panels	6,072	6,072	6,072	6,072	6,072	6,072	6,072	6,072	6,072	6,072
Highest cost-effectiveness for energy saving (kWh/€ | kWh/€/m²)										
Thermal insulation	0.11	**0.18**	0.08	0.06	0.11	0.15	0.06	0.05	0.06	0.07
Heat pump	2.17	3.85	3.27	2.43	3.07	4.51	4.29	3.21	4.69	**5.36**

Gas boiler	-	-	-	0.32	-	-	-	0.26	-	**1.05**
Biomass boiler	-	-	0.53	-	-	**0.78**	0.59	-	-	-
Highest cost-effectiveness for carbon dioxide emissions' saving (kg/€)										
Thermal insulation	0.01	0.01	0.03	0.01	0.01	**0.05**	0.02	0.01	0.01	0.01
Heat pump	0.28	0.44	0.00	0.36	0.39	**1.88**	1.78	0.41	0.60	1.19
Gas boiler	-	-	-	0.06	-	-	-	0.05	-	**0.21**
Biomass boiler	-	-	0.18	-	-	**0.28**	0.21	-	-	-
Potential energy bill reduction (€/year)										
Thermal insulation	237	**402**	140	84	309	299	124	77	214	126
Heat pump	1,539	2,733	1,402	834	2,179	1,973	1,737	1,052	**3,326**	1,969
Gas boiler	-	-	-	198	-	-	-	159	-	**679**
Biomass boiler	-	-	695	-	-	**1,027**	745	-	-	-

4.3 Piraeus

To present the results for the Municipality of Piraeus in a structured way, the analysed dwelling stock is grouped according to construction period, reflecting differences in building envelope characteristics, heating systems, and overall energy performance. Within each construction period category, representative dwelling typologies are analysed under a baseline scenario and a set of alternative renovation scenarios (i.e., thermal insulation, boiler upgrade, and heat pump installation) to assess changes in annual energy consumption, energy savings, and associated CO_2 emissions. In addition, the potential contribution of residential-scale PV systems is evaluated across all typologies. The main characteristics of each typology- including building envelope, heating and cooling systems specifications, and household composition- are outlined in **Table A5** and **Table A6** of **Annex A**.

4.3.1 Dwellings constructed before 1981

Dwellings constructed before 1981 represent the largest share of the residential building stock in the Municipality of Piraeus, accounting for approximately **63.72%** of all dwellings. Buildings from this period are typically characterised by lower thermal performance and older heating technologies, which makes them particularly relevant for assessing the potential impacts of energy efficiency interventions and renovation pathways.

Within this category, three representative dwelling typologies ("**GR_1**", "**GR_2**", and "**GR_3**") are analysed. For each of them, modelling simulations compare the baseline situation, with three renovation scenarios, i.e., thermal insulation, boiler upgrade and heat pump installation, in order to evaluate changes in annual energy consumption, energy savings and associated CO_2 emissions, under standard indoor thermal comfort assumptions.

4.3.1.1 Typology GR_1

For the pilot area of the Municipality of Piraeus, the first dwelling typology ("**GR_1**") corresponds to a residential unit classified as EPC class D with an oil boiler (COP = 0.75) as the primary heating source. This typology includes a cooling system. Thermal insulation, heat pump installation, and boiler upgrade to a higher-efficiency condensing gas boiler are examined as energy efficiency measures for this typology.

Baseline scenario ("current" situation)

Under the baseline scenario, modelling results indicate annual energy consumption at **12,737 kWh** (approximately **157.38 kWh/m²**) for typology "**GR_1**". Of this total, **6,611 kWh** correspond to space heating needs, while **6,126 kWh** are associated with cooling and appliances (**Figure 61**).

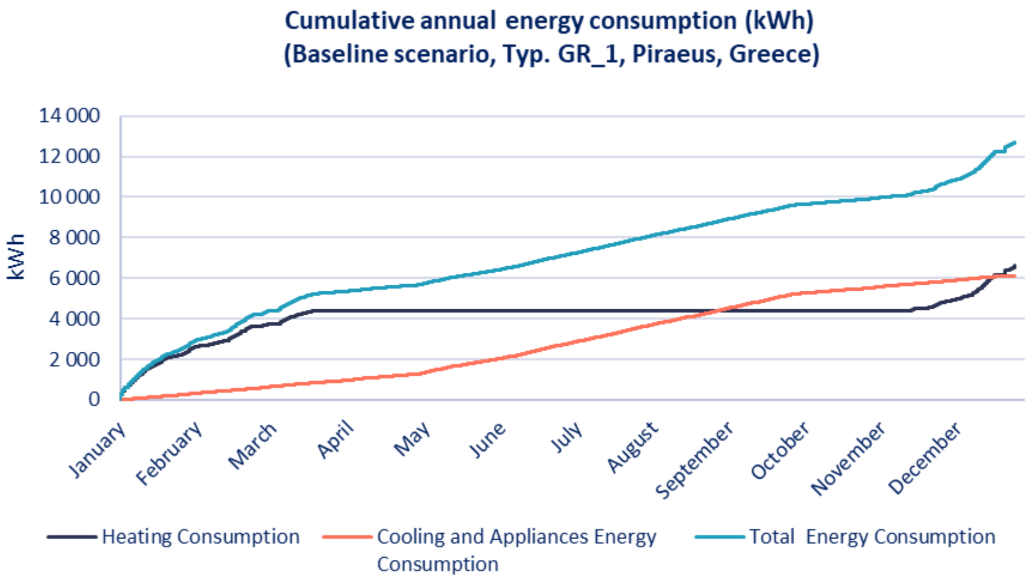


Figure 61. Cumulative annual energy consumption for typology "GR_1" (baseline scenario).

Renovation scenarios

Figure 62 presents the annual heating and total consumption for typology "**GR_1**" under the three renovation scenarios examined. Heat pump installation achieves the greatest reduction, lowering annual heating demand to **1,416 kWh** (**approximately 78.6% reduction**). Thermal insulation results in a heating demand of **5,788 kWh** (**12.4% reduction**), while upgrading from an oil boiler (COP=0.72) to a high-efficiency condensing natural gas boiler leads to a consumption level of **5,058 kWh** (**23.5% reduction**). For cooling and appliances consumption, the differences between renovation scenarios are relatively limited. Heat pump installation again results in the lowest annual consumption, estimated at **5,660 kWh**, while thermal insulation and boiler upgrade result in **6,109 kWh** and **6,126 kWh**, respectively.

The total annual energy consumption for the three different renovation scenarios is derived by combining heating, cooling and appliances consumption. Heat pump installation provides the lowest total energy consumption, estimated at **7,076 kWh** per year, for annual savings of **5,660 kWh** saved annually, corresponding to a **44.4% decrease.** Thermal insulation and boiler upgrade show a similar overall effect, resulting in approximately **11,898 kWh** and **11,184 kWh** annually, respectively, reducing energy consumption in approximately **839 kWh** per year (**6.6% reduction**) and **1,552 kWh** (**12.2% reduction**).

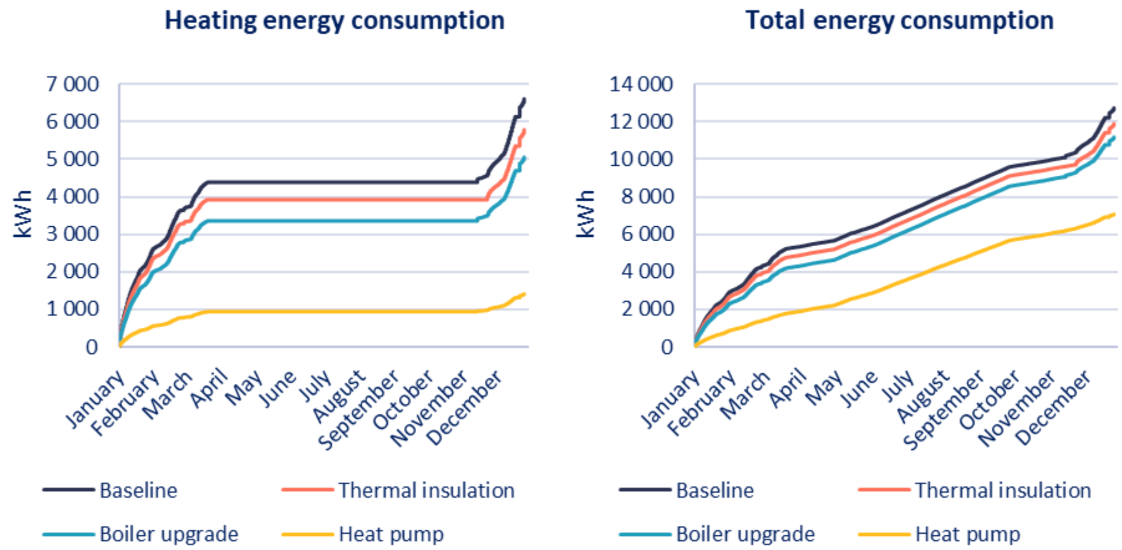


Figure 62. Cumulative total (right) and space heating (left) annual energy consumption per different renovation scenario in the typology "GR_1".

Figure 63 presents the annual carbon emissions produced and averted (in $kgCO_2$) under the baseline ("current" situation) and the renovation scenarios ("future" situations). The heat pump installation results in the lowest annual emissions. Under the baseline scenario, the dwelling produces approximately **3,701 $kgCO_2$ per year**, while emissions decrease to approximately **3,476 $kgCO_2$** with thermal insulation (**225 $kgCO_2$ averted**), **2,958 $kgCO_2$** following boiler upgrade (**743 $kgCO_2$ averted**), and **2,236 $kgCO_2$** after heat pump installation (**1,465 $kgCO_2$ averted**).

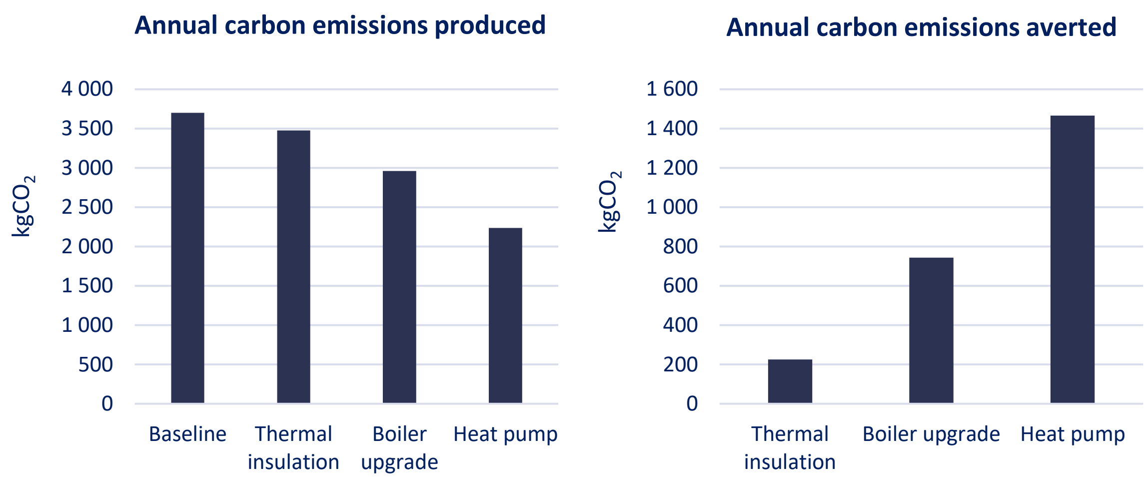


Figure 63. Annual CO_2 emissions (kg) produced and averted in the baseline ("current" situation) and in the renovation scenarios ("future" situations) in typology "GR_1".

4.3.1.2 Typology GR_2

For the pilot area of the Municipality of Piraeus, the second dwelling typology ("**GR_2**") corresponds to a residential unit classified as EPC class F with an oil boiler (COP = 0.75) as primary heating source. This typology includes a cooling system. Thermal insulation, heat pump installation, and boiler upgrade to a higher-efficiency condensing gas boiler are examined as energy efficiency measures for this typology.

Baseline ("current" situation)

Under the baseline scenario, modelling results indicate annual energy consumption at **15,451 kWh** (approximately **222.29 kWh/m²**) for typology "**GR_2**". Of this total, **8,876 kWh** correspond to space heating needs, while **6,575 kWh** are associated with cooling and appliances (**Figure 64**), indicating higher baseline energy consumption than typology "**GR_1**".

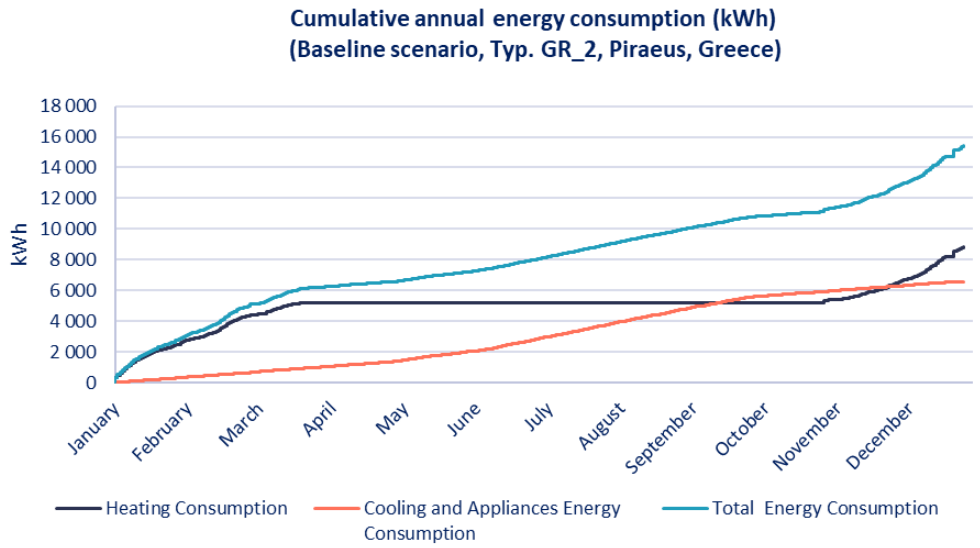


Figure 64. Cumulative annual energy consumption for the typology "GR_2" (baseline scenario).

Renovation scenarios

Figure 65 presents the annual heating consumption for typology "GR_2" for the three renovation scenarios under study. The results indicate that heat pump installation leads to the lowest heating energy consumption, reducing annual heating demand to **1,902 kWh** (almost **80%** decrease). By comparison, heating energy consumption is reduced by **12.4%** with thermal insulation, reaching **7,776 kWh**, and by **23.5%** following the upgrade from an oil boiler to an improved-efficiency condensing natural gas boiler, reaching **6,793 kWh**.

For cooling and appliances consumption, heat pump installation again results in the lowest annual consumption, estimated at **6,075 kWh**, while thermal insulation and boiler upgrade result in **6,527 kWh** and **6,574 kWh**, respectively. Heat pump installation provides the lowest total energy consumption, estimated at **7,977 kWh** per year. Thermal insulation and boiler upgrade show a similar overall effect, resulting in approximately **14,303 kWh** and **13,367 kWh** annually, respectively. Heat pump installation yields the largest reduction, with approximately **7,474 kWh** saved annually, corresponding to a **48.4%** decrease in total energy consumption. Thermal insulation results in energy savings of approximately **1,148 kWh** per year (**7.4% reduction**), while the boiler upgrade leads to slightly higher savings of around **2,084 kWh** annually (**13.5% reduction**).

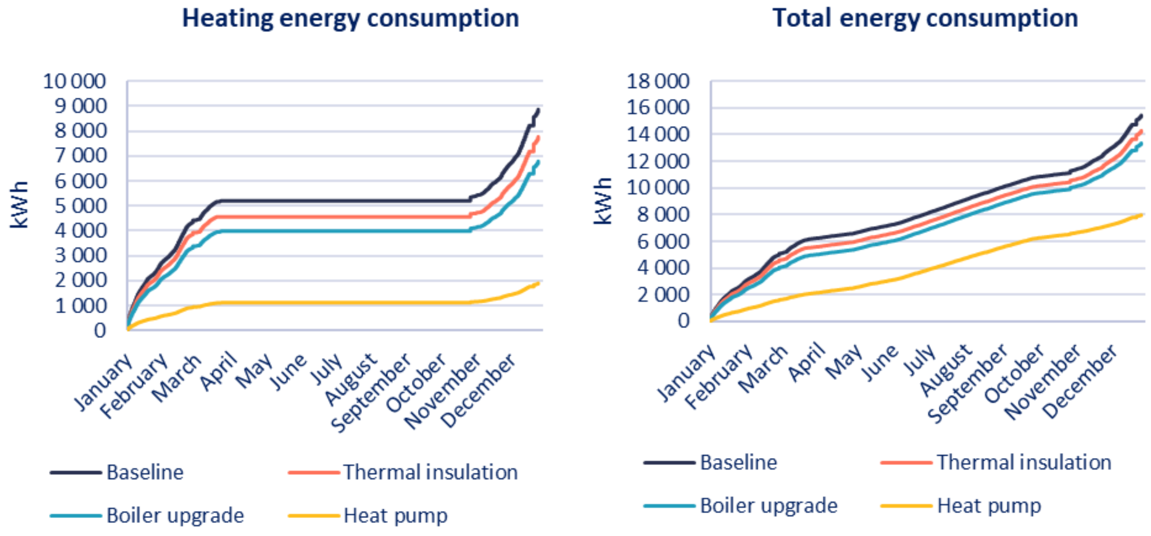


Figure 65. Cumulative total (right) and space heating (left) annual energy consumption per different renovation scenario in the typology "GR_2".

Figure 66 presents the annual carbon emissions produced and averted (in $kgCO_2$) under the baseline ("current" situation) and the renovation scenarios. Under the baseline scenario, the dwelling produces approximately **4,448 $kgCO_2$ per year**, while emissions decrease to approximately **4,139 $kgCO_2$** with thermal insulation (**309 $kgCO_2$ averted annually**), **3,450 $kgCO_2$** following boiler upgrade (**998 $kgCO_2$ averted**), and **2,521 $kgCO_2$** after heat pump installation (**1,927 $kgCO_2$ averted**).

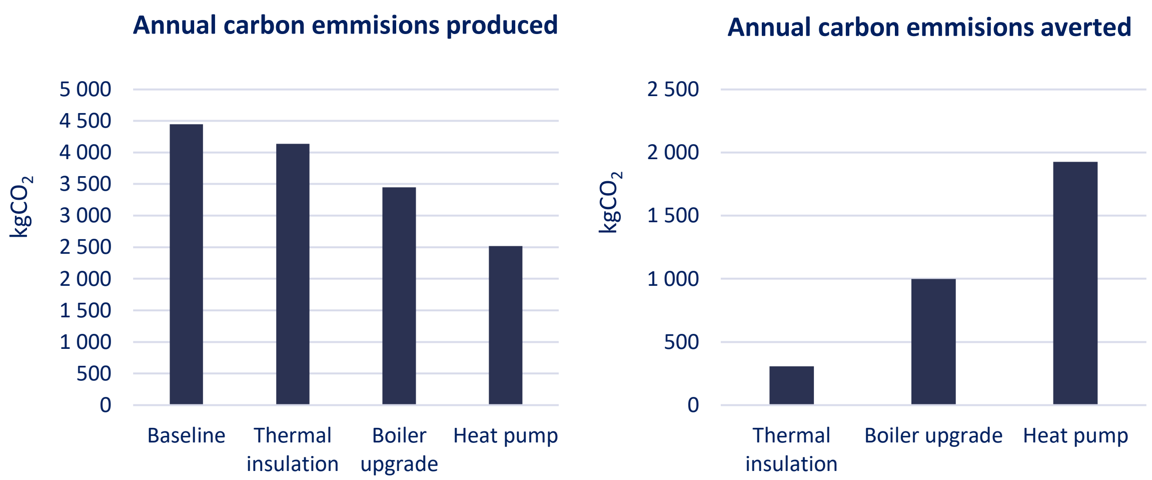


Figure 66. Annual CO_2 emissions (kg) produced and averted in the baseline ("current" situation) and in the renovation scenarios ("future" situations) in typology "GR_2".

4.3.1.3 Typology GR_3

For the pilot area of the Municipality of Piraeus, the third typology ("**GR_3**") corresponds to a residential unit classified as EPC class G with an oil boiler (COP = 0.75) as primary heating source. This typology includes a cooling system. Thermal insulation, heat pump installation, and boiler upgrade to a higher-efficiency condensing gas boiler are examined as energy efficiency measures for this typology.

Baseline ("current" situation)

Under the baseline scenario, modelling results indicate annual energy consumption at **24,997 kWh** (approximately **341.02 kWh/m²**) for typology "**GR_3**". Of this total, **16,347 kWh** correspond to space heating needs, while **8,649.5 kWh** are associated with cooling and appliances (**Figure 67**), showing the highest baseline energy demand among the pre-1981 typologies.

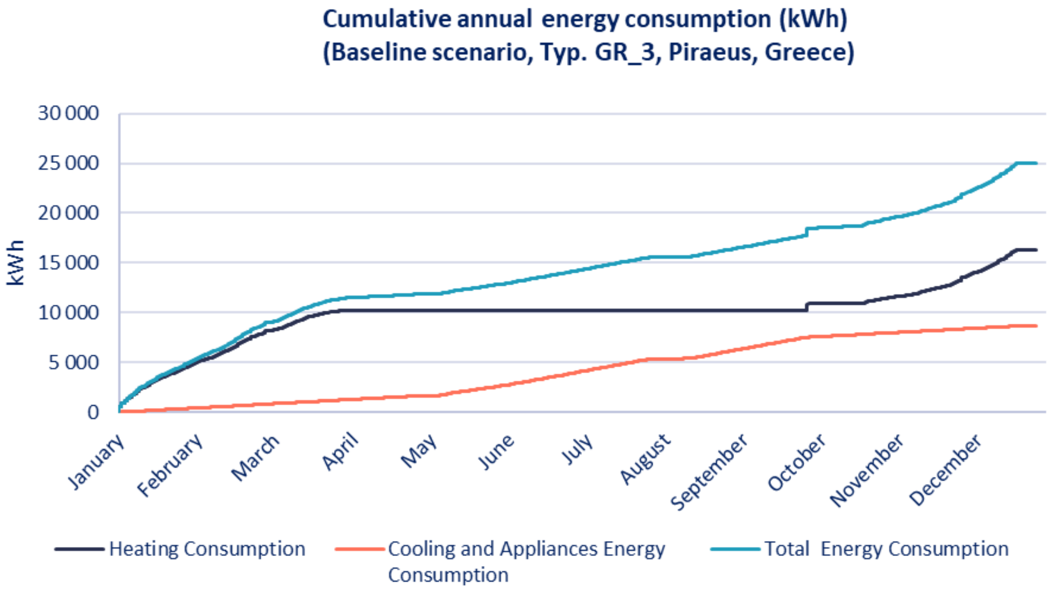


Figure 67. Cumulative annual energy consumption for the typology "GR_3" (baseline scenario).

Renovation scenarios

Figure 68 presents the annual heating consumption for dwelling typology "**GR_3**" for the three renovation scenarios under study. The results indicate that heat pump installation leads to the lowest heating energy consumption, reducing annual heating demand to **3,503 kWh** (**around 80%** reduction), yielding the largest reduction, with approximately **13,660 kWh** saved annually. By comparison, heating energy consumption remains higher under the other measures, reaching **14,957 kWh** with thermal insulation (**8.5%** reduction), and **12,510 kWh** following the upgrade from an oil boiler to an improved-efficiency condensing natural gas boiler (**23.5%** reduction). Thermal insulation results in energy savings of approximately **1,407 kWh** per year, while the boiler upgrade leads to higher savings of around **3,837 kWh** annually.

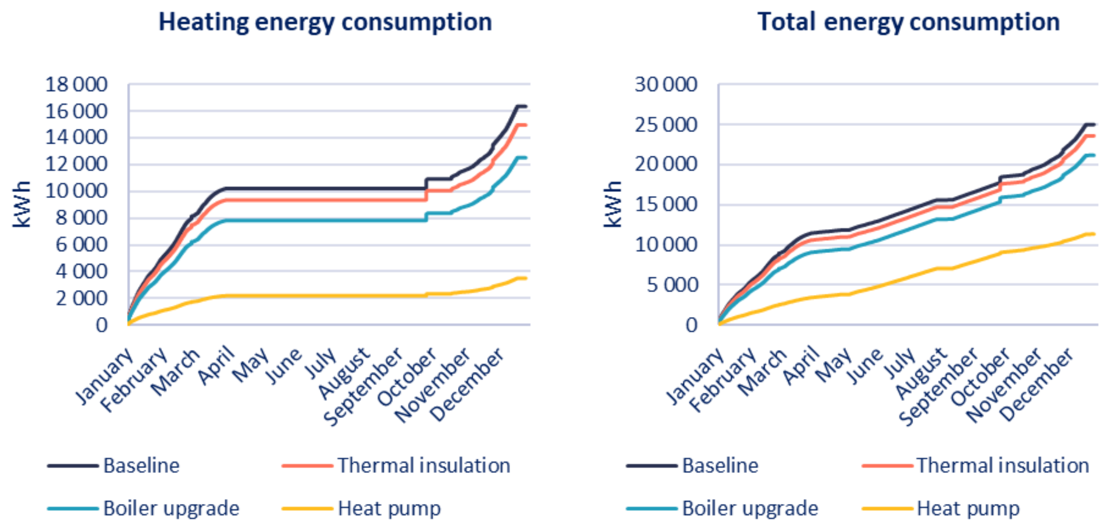


Figure 68. Cumulative total (right) and space heating (left) annual energy consumption per different renovation scenario in the typology "GR_3".

Figure 69 presents the annual carbon emissions produced and averted (in $kgCO_2$) under the baseline ("current" situation) and the renovation scenarios ("future" situations). Under the baseline scenario, the dwelling produces approximately **7,098 $kgCO_2$ per year**, while emissions decrease to approximately **6,721 $kgCO_2$** with thermal insulation (**377 $kgCO_2$ averted**), **5,260 $kgCO_2$** following boiler upgrade (**1,838 $kgCO_2$ averted**), and **3,583 $kgCO_2$** after heat pump installation (**3,515 $kgCO_2$ averted**).

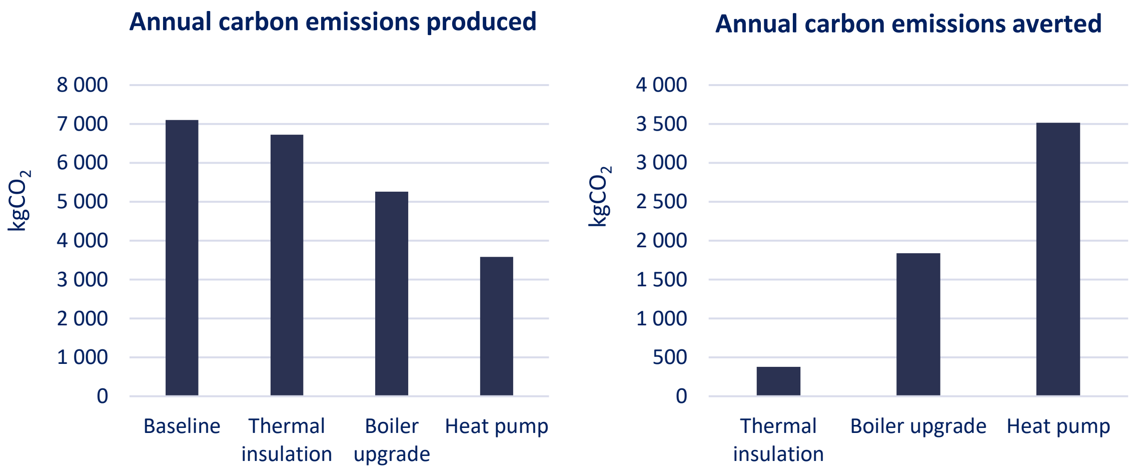


Figure 69. Annual CO_2 emissions (kg) produced and averted in the baseline ("current" situation) and in the renovation scenarios ("future" situations) in typology "GR_3".

4.3.2 Dwellings constructed between 1981 and 2010

Dwellings constructed between 1981 and 2010 constitute a substantial group of the Municipality of Piraeus' dwelling stock, accounting for around **35.14%** of all dwellings. In contrast to dwellings constructed before 1981, this period reflects a more heterogeneous mix of construction characteristics, making it particularly important for the development of representative typologies that aim to capture variations in energy performance.

4.3.2.1 Typology GR_4

Typology "**GR_4**" corresponds to a residential unit classified as EPC class C with an oil boiler (COP = 0.82) as the primary heating source. This typology includes a cooling system. Thermal insulation, heat pump installation, and boiler upgrade to a higher-efficiency condensing gas boiler are examined as energy efficiency measures for this typology.

Baseline ("current" situation)

Under the baseline scenario, modelling results indicate annual energy consumption at **9,714 kWh** (approximately **121.55 kWh/m²**) for typology "**GR_4**". Of this total, **5,263 kWh** correspond to space heating needs, while **4,451 kWh** are associated with cooling and appliances (**Figure 70**).

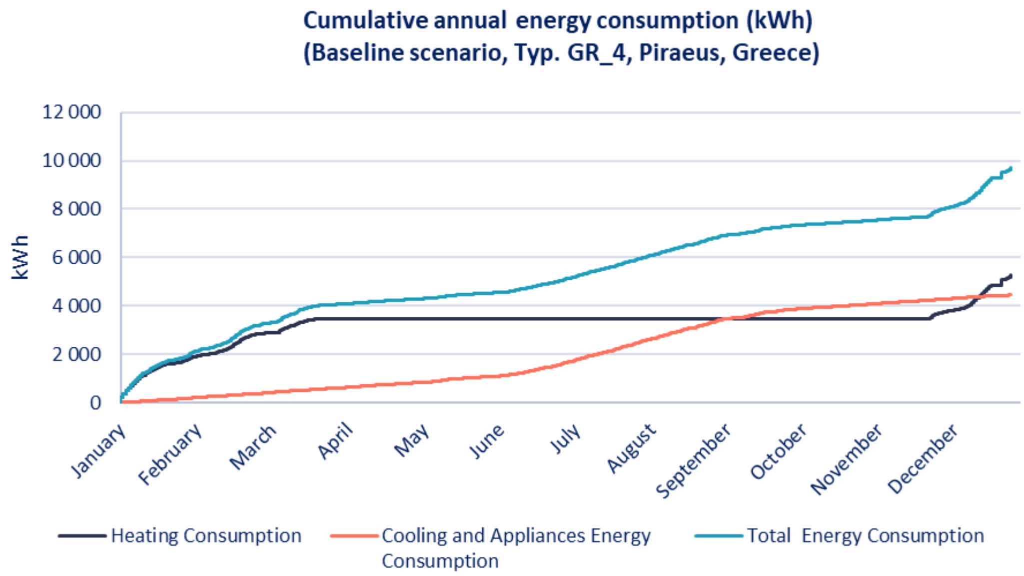


Figure 70. Cumulative annual energy consumption for the typology "GR_4" (baseline scenario).

Renovation scenarios

Figure 71 presents the annual heating consumption for the "**GR_4**" dwelling typology under the three renovation scenarios examined. The installation of a heat pump leads to the largest reduction, lowering annual heating demand to **1,233 kWh** (**76.6% reduction**). Thermal insulation also results in a substantial decrease, bringing heating demand to **2,882 kWh** (**45.2% reduction**), while replacing the oil boiler with a high-efficiency condensing natural gas boiler reduces consumption to **4,404 kWh** (**16.3% reduction**). For cooling and appliances consumption, the differences between renovation scenarios are also relatively limited. Heat pump installation again results in the lowest annual consumption, estimated at **4,054 kWh**, while thermal insulation and boiler upgrade result in **4,418 kWh** and **4,452 kWh**, respectively. Heat pump installation provides the lowest total energy consumption, estimated at **5,287 kWh** per year, with approximately 4,427 kWh saved annually. Thermal insulation appears to also have a great impact on the final energy consumption, since it results in **7,299.5 kWh**, while boiler upgrade showcases the smaller impact on the final energy consumption of this dwelling typology, since it results in around **8,857 kWh**, for energy savings of around **2,415 kWh** and **859 kWh** annually, respectively.

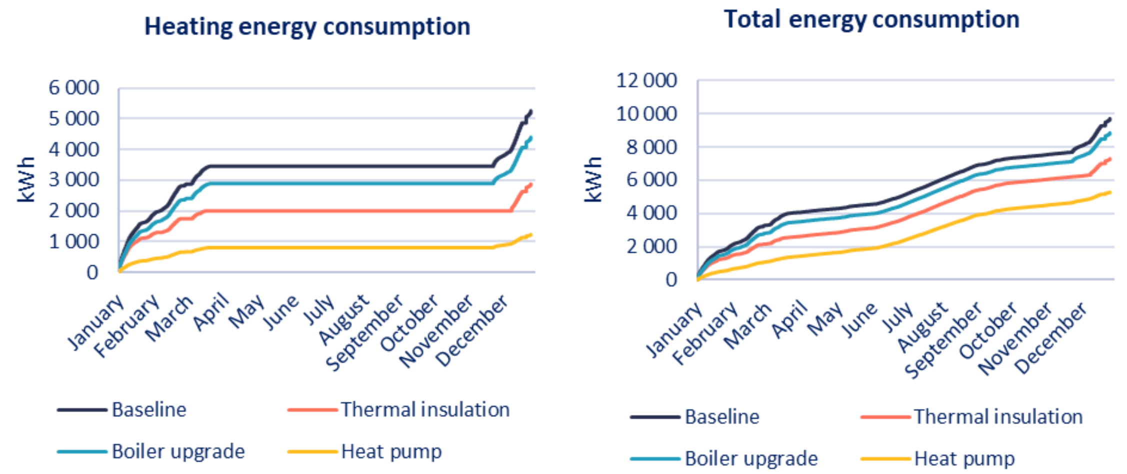


Figure 71. Cumulative total (right) and space heating (left) annual energy consumption per different renovation scenario in the typology "GR_4".

Figure 72 presents the annual carbon emissions produced and averted (in $kgCO_2$) under the baseline ("current" situation) and the renovation scenarios. Under the baseline scenario, the dwelling produces approximately 2,812 $kgCO_2$ per year, while emissions decrease to approximately 2,165.5 $kgCO_2$ with thermal insulation (646.5 $kgCO_2$ averted), 2,296.5 $kgCO_2$ following boiler upgrade (515.5 $kgCO_2$ averted), and 1,671 $kgCO_2$ after heat pump installation (1,141 $kgCO_2$ averted).

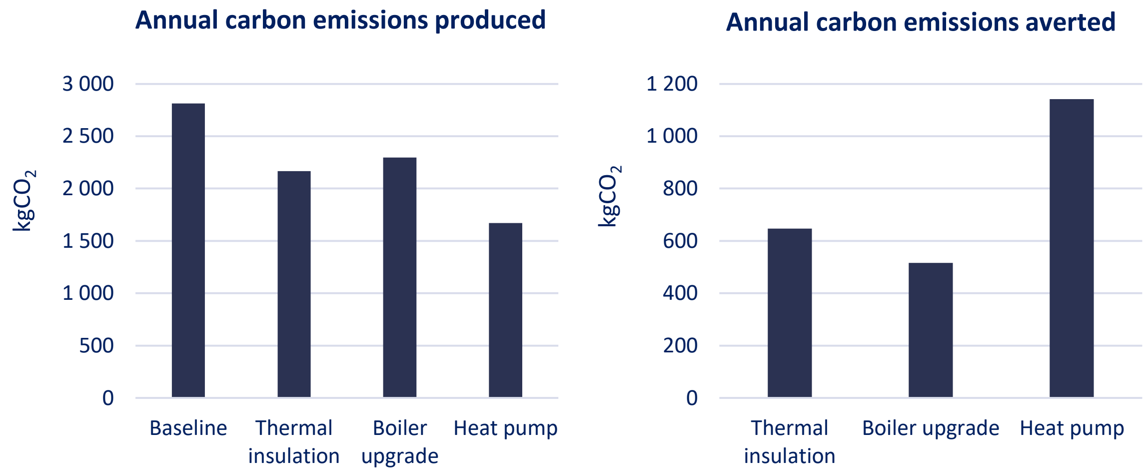


Figure 72. Annual CO_2 emissions (kg) produced and averted in the baseline ("current" situation) and in the renovation scenarios ("future" situations) in typology "GR_4".

4.3.2.2 Typology GR_5

Typology "**GR_5**" corresponds to a residential unit classified as EPC class C with a non-condensing gas boiler (COP = 0.92) as the primary heating source. This typology includes a cooling system. Thermal insulation, heat pump installation, and boiler upgrade to a higher-efficiency condensing gas boiler are examined as energy efficiency measures for this typology.

Baseline ("current" situation)

Under the baseline scenario, modelling results indicate annual energy consumption at **9,142 kWh** (approximately **114.39 kWh/m²**) for typology "**GR_5**". Of this total, **4,690 kWh** correspond to space heating needs, while **4,452 kWh** are associated with cooling and appliances (**Figure 73**).

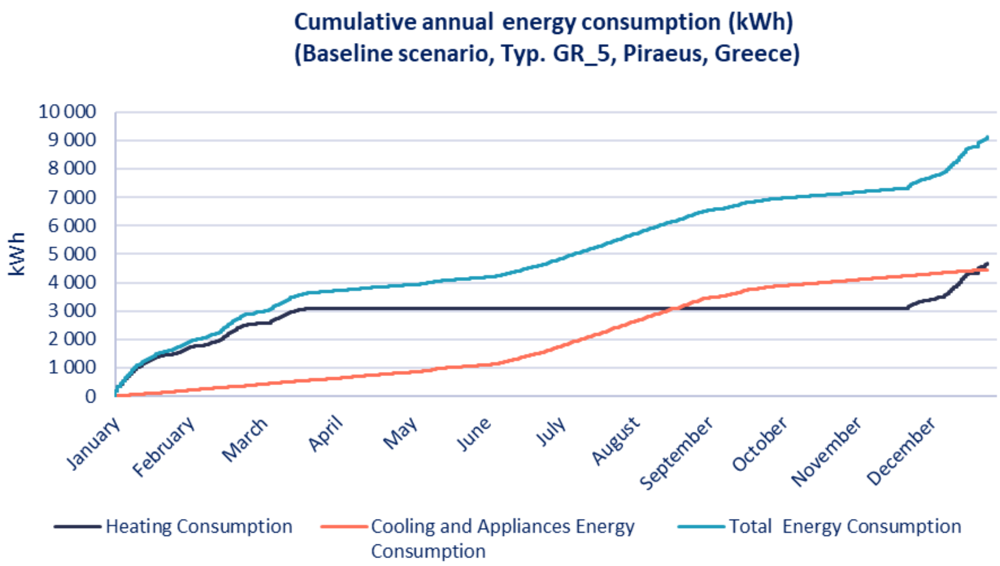


Figure 73. Cumulative annual energy consumption for the typology "GR_5" (baseline scenario).

Renovation scenarios

Figure 74 illustrates the annual heating and total consumption for the "**GR_5**" dwelling typology across the three renovation scenarios. Among the examined measures, heat pump installation achieves the greatest reduction, lowering annual heating demand to **1,233 kWh** (**73.7% reduction**). Thermal insulation also leads to a substantial decrease, reducing heating demand **to 2,568 kWh** (**45.3% reduction**), while upgrading from a non-condensing gas boiler to a high-efficiency condensing natural gas boiler lowers consumption to **4,407 kWh** (**6.0% reduction**).

For cooling and appliances consumption, similarly to the "**GR_5**" typology, the differences between renovation scenarios are relatively limited, with heat pump installation resulting in the lowest annual consumption, estimated at **4,054 kWh**, while thermal insulation and boiler upgrade result in **4,418 kWh** and **4,452 kWh**, respectively. Heat pump installation provides the lowest total energy consumption, estimated at **5,287 kWh** per year, for a reduction of approximately **3,854.5 kWh** saved annually. Thermal insulation appears to have a considerable impact on the final energy consumption, since it results in **6,986 kWh**, while boiler upgrade showcases the smaller impact on the final energy consumption of this dwelling typology, since it results in around **8,855.5 kWh**, very close to baseline total energy consumption. They lead respectively to an energy saving of approximately **2,156 kWh** and **286 kWh** annually.

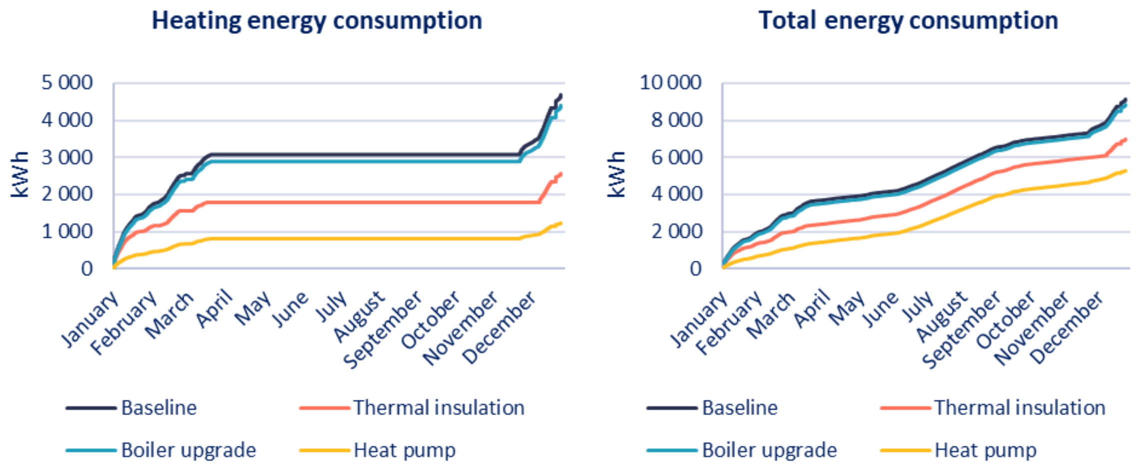


Figure 74. Cumulative total (right) and space heating (left) annual energy consumption per different renovation scenario in the typology "GR_5".

Figure 75 presents the annual carbon emissions produced and averted (in $kgCO_2$) under the baseline ("current" situation) and the renovation scenarios. Under the baseline scenario, the dwelling produces approximately **2,354 $kgCO_2$ per year**, while emissions decrease to approximately **1,915 $kgCO_2$** with thermal insulation (**439.5 $kgCO_2$ averted**), **2,296.5 $kgCO_2$** following boiler upgrade (only **58 $kgCO_2$ averted**), and **1,671 $kgCO_2$** after heat pump installation (**683.5 $kgCO_2$ averted**).

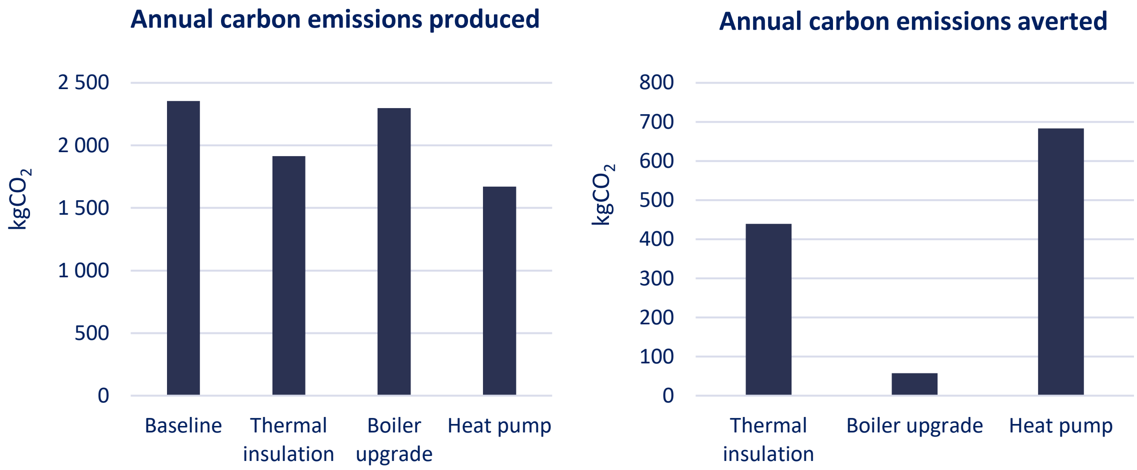


Figure 75. Annual CO_2 emissions (kg) produced and averted in the baseline ("current" situation) and in the renovation scenarios ("future" situations) in typology "GR_5".

4.3.2.3 Typology GR_6

Typology "**GR_6**" corresponds to a residential unit classified as EPC class E with an oil boiler (COP = 0.82) as the primary heating source. This typology includes a cooling system. Thermal insulation, heat pump installation, and boiler upgrade to a higher-efficiency condensing gas boiler are examined as energy efficiency measures for this typology.

Baseline ("current" situation)

Under the baseline scenario, modelling results indicate annual energy consumption at **13,761 kWh** (approximately **196.31 kWh/m²**) for typology "**GR_6**". Of this total, **7,463.5 kWh** correspond to space heating needs, while **6,297.5 kWh** are associated with cooling and appliances (**Figure 76**), higher than in typologies “**GR_4**” and “**GR_5**”.

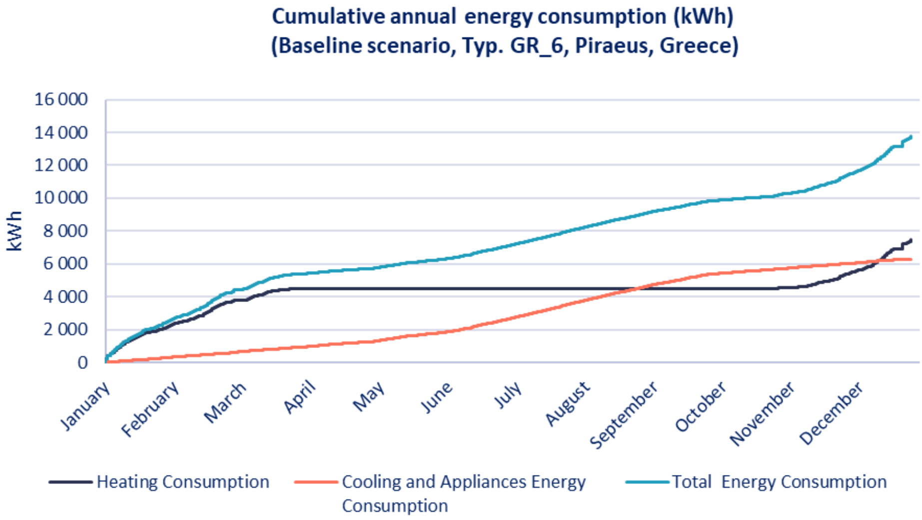


Figure 76. Cumulative annual energy consumption for the typology “GR_6” (baseline scenario).

Renovation scenarios

Figure 77 presents the annual heating consumption for dwelling typology “**GR_6**” for the three renovation scenarios under study. The results indicate that heat pump installation leads to the lowest heating energy consumption, reducing annual heating demand to **1,749 kWh** (**76.5%** reduction). Heating demand remains higher under the other measures, reaching **5,782 kWh** with thermal insulation (**22.5% reduction**) and **6,245 kWh** following the upgrade from an oil boiler to a high-efficiency condensing natural gas boiler (**16.3% reduction**).

For cooling and appliances consumption, the differences between renovation scenarios are meagre. Heat pump installation again results in the lowest annual consumption, estimated at **5,798 kWh**, while thermal insulation and boiler upgrade result in **6,262 kWh** and **6,298 kWh**, respectively. Heat pump installation provides the lowest total energy consumption, estimated at **7,546.5 kWh** per year. Thermal insulation and boiler upgrade show a similar overall effect, resulting in approximately **12,020 kWh** and **12,543.5 kWh** annually, respectively. Heat pump installation delivers the most significant reduction, with annual savings of approximately **6,215 kWh**. Thermal insulation achieves savings of around **1,741 kWh** per year, whereas the boiler upgrade results in more limited savings of approximately **1,218 kWh** annually.

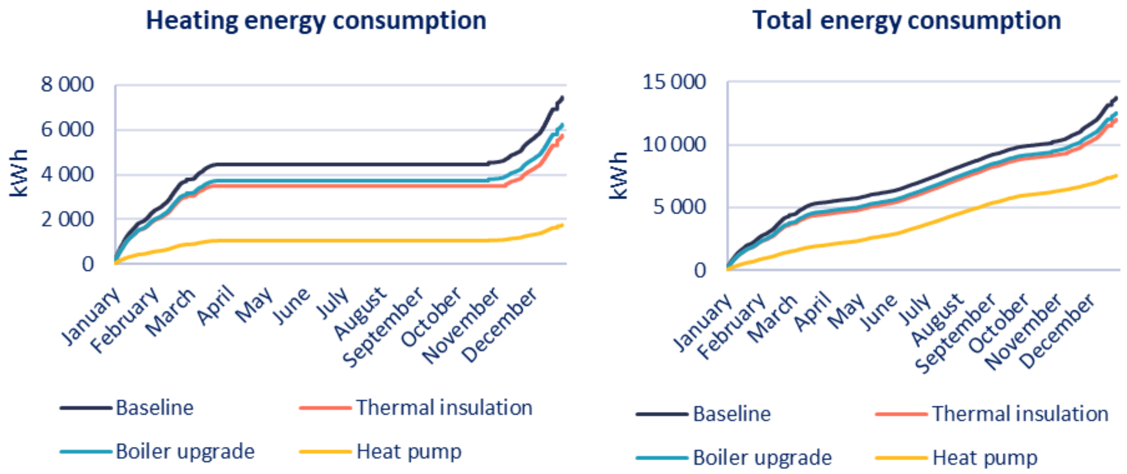


Figure 77. Cumulative total (right) and space heating (left) annual energy consumption per different renovation scenario in the typology "GR_6".

Figure 78 presents the annual carbon emissions produced and averted (in kgCO_2) under the baseline ("current" situation) and the renovation scenarios. Under the baseline scenario, the dwelling produces approximately **3,983 kgCO_2 per year**, while emissions decrease to approximately **3,525 kgCO_2** with thermal insulation (**458 kgCO_2 averted**), **3,252 kgCO_2** following boiler upgrade (**731 kgCO_2 averted**), and **2,385 kgCO_2** after heat pump installation (**1,598 kgCO_2 averted**).

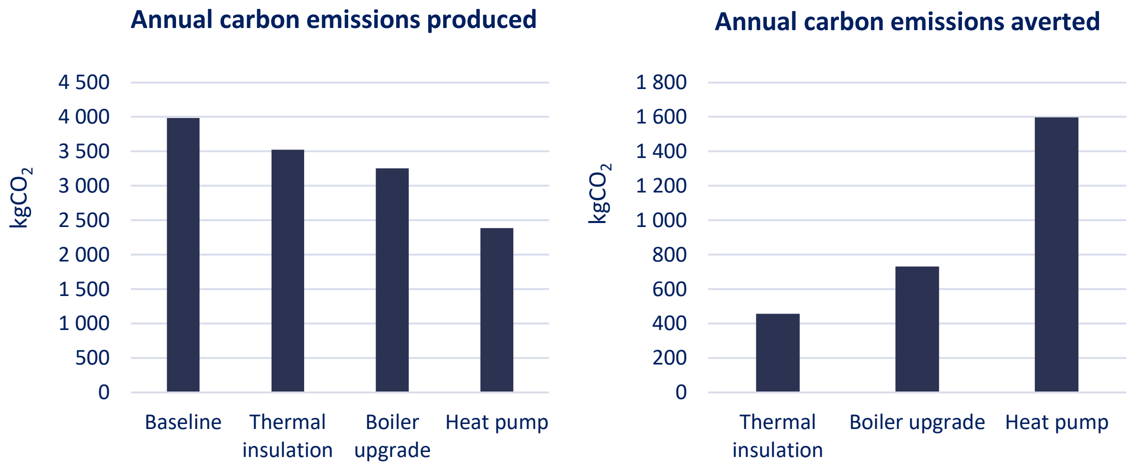


Figure 78. Annual CO_2 emissions (kg) produced and averted in the baseline ("current" situation) and in the renovation scenarios ("future" situations) in typology "GR_6".

4.3.2.4 Typology GR_7

Typology "**GR_7**" corresponds to a residential unit classified as EPC class G with an oil boiler (COP = 0.82) as the primary heating source. This typology includes a cooling system. Thermal insulation, heat pump installation, and boiler upgrade to a higher-efficiency condensing gas boiler are examined as energy efficiency measures for this typology.

Baseline ("current" situation)

Under the baseline scenario, modelling results indicate annual energy consumption at **24,266 kWh** (approximately **320.64 kWh/m^2**) for typology "**GR_7**". Of this total, **14,430 kWh** correspond to space heating needs, while **9,836 kWh** are associated with cooling and appliances (**Figure 79**), indicating the highest heating demand among the typologies constructed between 1981 and 2010.

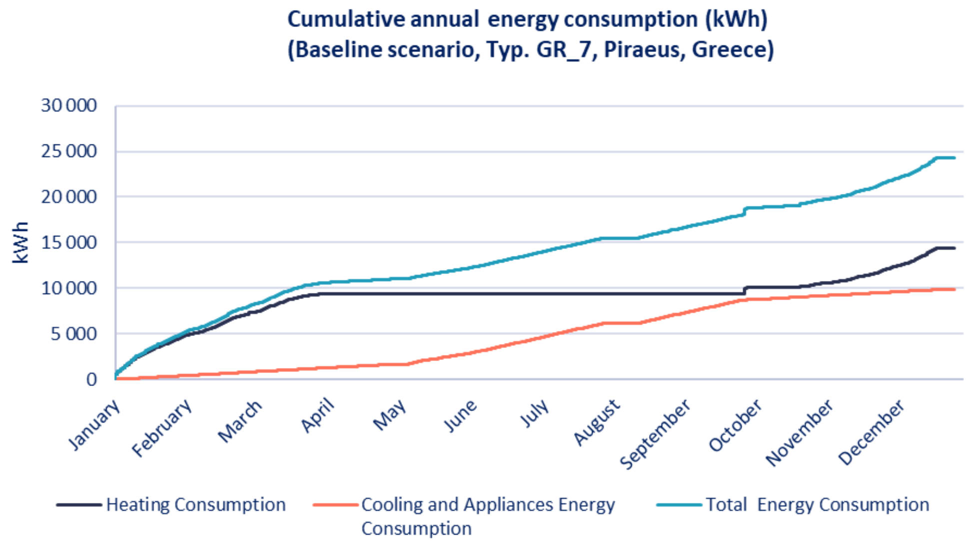


Figure 79. Cumulative annual energy consumption for the typology "GR_7" (baseline scenario).

Renovation scenarios

Figure 80 presents the annual heating consumption for dwelling typology "**GR_7**" for the three renovation scenarios under study. The results indicate that heat pump installation leads to the lowest heating energy consumption, reducing annual heating demand to **3,381 kWh** (**76.5%** decrease). By comparison, heating energy consumption remains higher under the other measures, reaching **5,279 kWh** with thermal insulation (**63.5%** reduction), and to **12,074 kWh** following the upgrade from an oil boiler to an improved-efficiency condensing natural gas boiler, leading to a **16.3%** decrease in heating consumption. For cooling and appliances consumption, heat pump installation again results in the lowest annual consumption, estimated at **8,784 kWh**, while thermal insulation and boiler upgrade result in **9,900 kWh** and **9,836 kWh**, respectively.

The heat pump scenario results in the lowest total energy consumption, estimated at **12,164.5 kWh** per year, for **12,101.5 kWh** saved annually. Thermal insulation also leads to a notable reduction, with total consumption reaching **15,179 kWh**, while the boiler upgrade has a more limited impact, resulting in approximately **21,909.5 kWh**. Both result in savings of **9,087 kWh** and **2,356.5 kWh** per year, respectively.

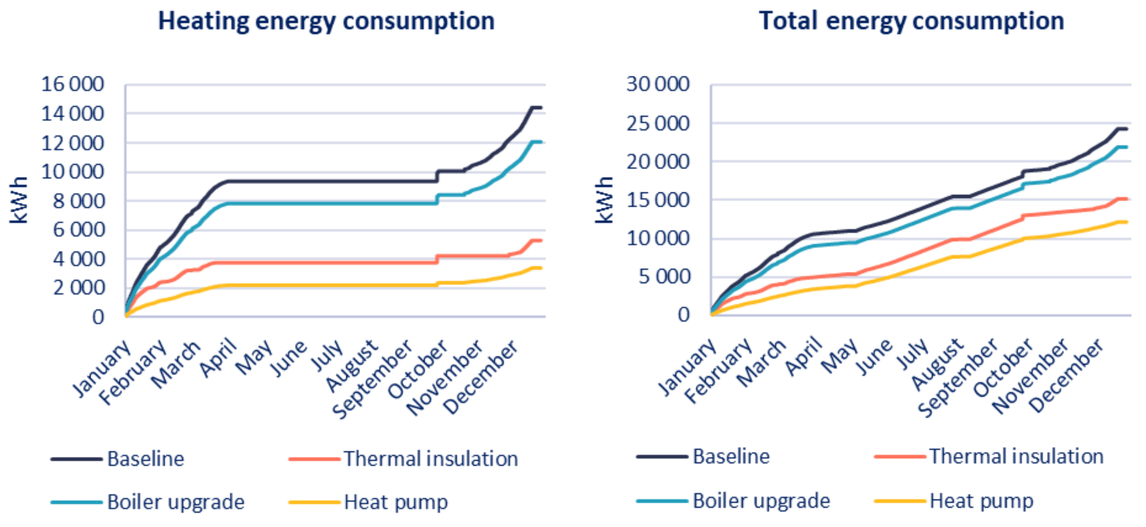


Figure 80. Cumulative total (right) and space heating (left) annual energy consumption per different renovation scenario in the typology "GR_7".

Figure 81 presents the annual carbon emissions produced and averted (in $kgCO_2$) under the baseline ("current" situation) and the renovation scenarios. Under the baseline scenario, the dwelling produces approximately **6,961 $kgCO_2$ per year**, while emissions decrease to approximately **4,538 $kgCO_2$** with thermal insulation (**2,423 $kgCO_2$ averted**), **5,547 $kgCO_2$** following boiler upgrade (**1,414 $kgCO_2$ averted**), and **3,844 $kgCO_2$** after heat pump installation (**3,117 $kgCO_2$ averted**).

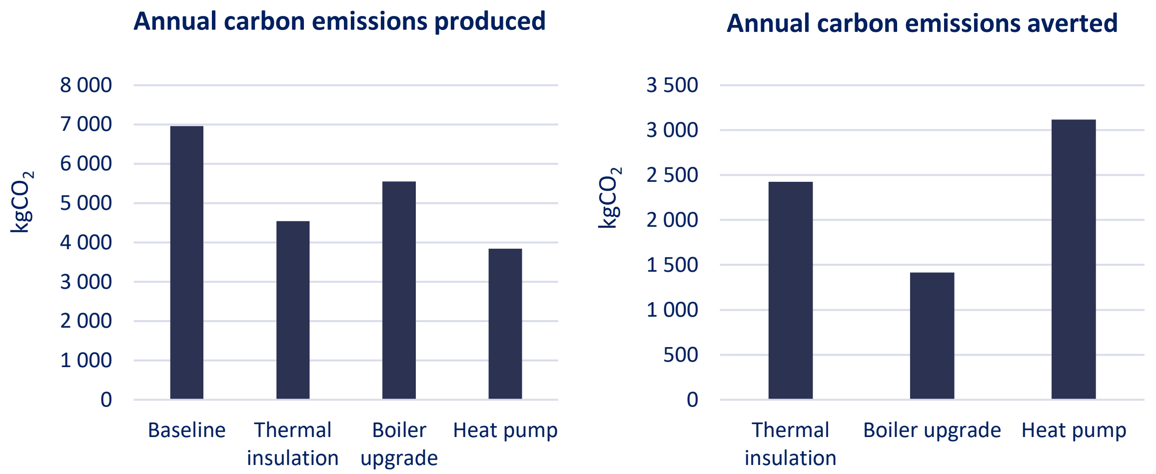


Figure 81. Annual CO_2 emissions (kg) produced and averted in the baseline ("current" situation) and in the renovation scenarios ("future" situations) in typology "GR_7".

4.3.2.5 Typology GR_8

Typology "**GR_8**" corresponds to a residential unit classified as EPC class G with electric heaters (COP = 1.00) as the primary heating source. It should be noted that, for typology "**GR_8**", only thermal insulation and heat pump installation are examined as energy efficiency measures, while boiler upgrade is not considered, as transitioning from electricity-based systems to fossil fuel-based systems is not a common practice.

Baseline ("current" situation)

Under the baseline scenario, modelling results indicate annual energy consumption at **16,951.5 kWh** (approximately **224 kWh/m²**) for typology "**GR_8**". Of this total, **7,584 kWh** correspond to space heating needs, while **9,367.5 kWh** are associated with cooling and appliances (**Figure 82**).

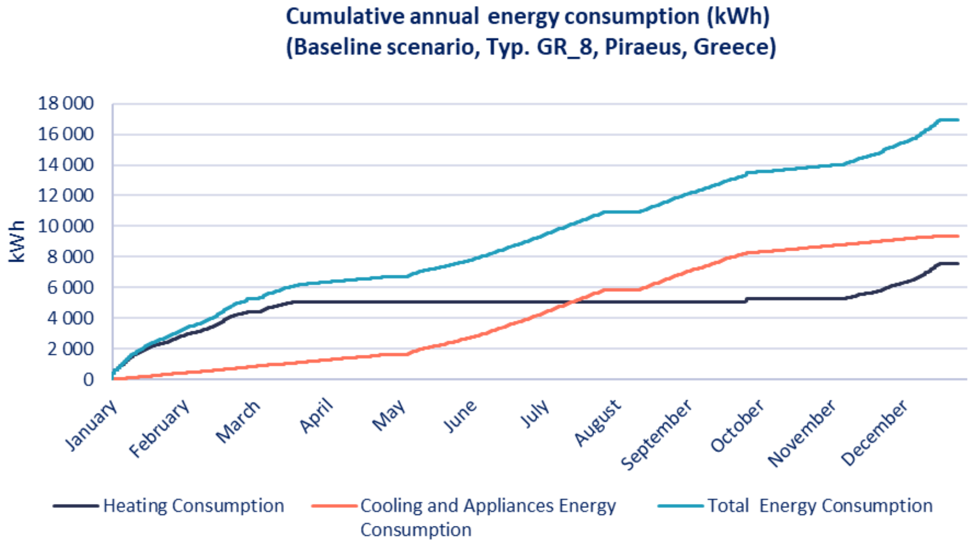


Figure 82. Cumulative annual energy consumption for the typology "GR_8" (baseline scenario).

Renovation scenarios

Figure 83 presents the annual heating consumption for dwelling typology "**GR_8**" for the two renovation scenarios under study. The results indicate that heat pump installation leads to the lowest heating energy consumption, reducing annual heating demand to **2,167 kWh** (**71.5%** reduction). By comparison, heating energy consumption remains higher under the other measure, reaching **2,817 kWh** with thermal insulation (**62.9%** reduction).

For cooling and appliances consumption, heat pump installation results in a limited reduction, decreasing consumption to **8,409 kWh**. As for the total annual energy consumption, heat pump installation provides the highest reduction. The resulting energy consumption level is estimated at **10,576 kWh** per year, while thermal insulation appears to have a significant impact on the final energy consumption, since it results in **12,523.5 kWh**. Energy savings are estimated at approximately **6,375.5 kWh** and **4,428 kWh** per year, respectively, showcasing high effectiveness for energy savings.

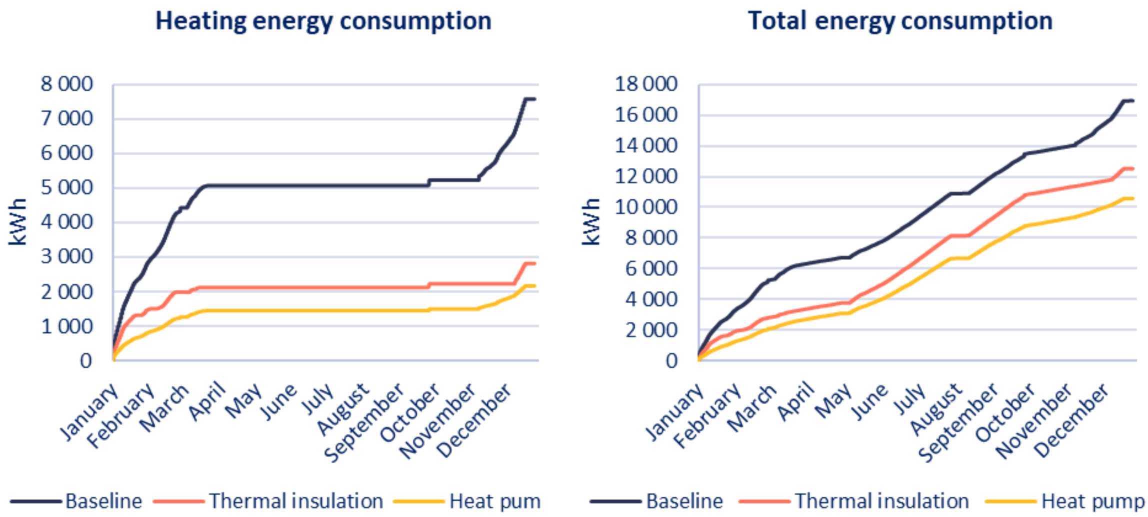


Figure 83. Cumulative total (right) and space heating (left) annual energy consumption per different renovation scenario in the typology "GR_8".

Figure 84 presents the annual carbon emissions produced and averted (in kgCO₂) under the baseline ("current" situation) and the two renovation scenarios for this dwelling typology. Compared to the baseline scenario, the dwelling produces approximately **5,356.5 kgCO₂ per year**, while emissions decrease to approximately **3,957.5 kgCO₂** with thermal insulation (**1,399.5 kgCO₂ averted**), and **3,342 kgCO₂** following heat pump installation (**2,015 kgCO₂ averted**).

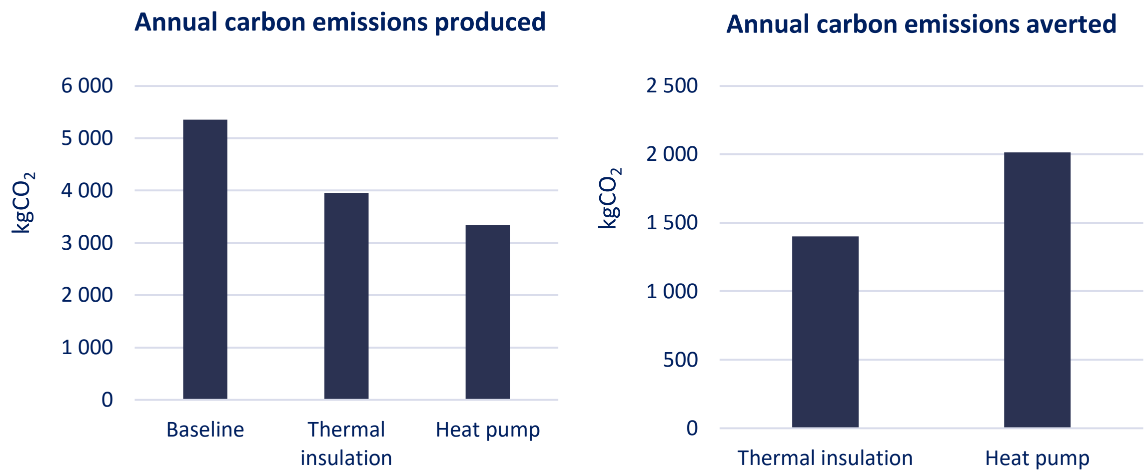


Figure 84. Annual CO_2 emissions (kg) produced and averted in the baseline ("current" situation) and in the renovation scenarios ("future" situations) in typology "GR_8".

4.3.3 Solar PV installation

The assessment of renewable energy generation systems evaluates their contribution to long-term energy savings, sustainability, potential risks, and return on investment, while also accounting for emerging aspects such as prosumer schemes, storage options, and grid interactions (e.g., rooftop solar panels, EV charging). In this context, the simulation of PV systems, a widely adopted and technically mature solution in Greece due to favourable solar potential and increasing deployment capacity, provides additional insights into their applicability across different residential typologies.

For this study, a representative residential PV system with a nominal capacity of **3 kW$_p$**, corresponding to an installation area of approximately **16 m^2**, was simulated for the Municipality of Piraeus. A cumulative annual energy production of the PV system is estimated at **5,886 kWh** annually, across all examined typologies. **Table 7** compares total electricity consumption under baseline and renovation conditions with the corresponding percentage of PV generation coverage.

The level of coverage ranges from **34.7% to 132.2%**, depending on the typology and scenario. In several cases (e.g., typologies "**GR_4**" and "**GR_5**"), particularly those associated with relatively higher energy performance classes (C), the electricity demand is fully covered by the PV system, highlighting the potential for surplus energy generation and its possible utilisation through grid export.

At the same time, the results show that solar PV coverage decreases in future scenarios that include heat pumps, due to increased electricity demand associated with electrified heating. This finding underlines the complementary nature of these interventions: while heat pumps increase electricity consumption, they also support the decarbonisation of heating. When combined with PV systems, they can contribute to a more integrated pathway towards building electrification, increased energy autonomy, and the alleviation of energy poverty in vulnerable households.

Table 7. Total electricity consumption and PV coverage across all dwelling typologies under baseline and renovation scenarios in the Municipality of Piraeus.

Typology	Scenario and heating source	Total electricity consumption (kWh)	Percentage of coverage
GR_1	Baseline (oil), Thermal Insulation (oil), Boiler Upgrade (gas)	6,109	96.4%
	Heat Pump (electricity)	7,076	83.2%
GR_2	Baseline (oil), Thermal Insulation (oil), Boiler Upgrade (gas)	6,575	89.5%
	Heat Pump (electricity)	7,977	73.8%
GR_3	Baseline (oil), Thermal Insulation (oil), Boiler Upgrade (gas)	8,650	68.0%
	Heat Pump (electricity)	11,337	51.9%
GR_4	Baseline (oil), Thermal Insulation (oil), Boiler Upgrade (gas)	4,451	132.2%
	Heat Pump (electricity)	5,287	111.3%
GR_5	Baseline (gas), Thermal Insulation (gas), Boiler Upgrade (gas)	4,452	132.2%
	Heat Pump (electricity)	5,287	111.3%
GR_6	Baseline (oil), Thermal Insulation (oil), Boiler Upgrade (gas)	6,298	93.5%
	Heat Pump (electricity)	7,546	78.0%
GR_7	Baseline (oil), Thermal Insulation (oil), Boiler Upgrade (gas)	9,836	59.8%
	Heat Pump (electricity)	12,164	48.4%

GR_8	**Baseline (electricity)**	16,951	34.7%
	Thermal Insulation (electricity)	12,523	47.0%
	Heat Pump (electricity)	10,576	55.7%

4.3.4 Cost-effectiveness analysis

Table 8 presents the investment costs, the cost-effectiveness for energy saving and carbon dioxide emissions savings for the most cost-effective measure, and the respective potential energy bill reduction.

Contrary to other pilot cases, older typologies register the highest costs for thermal insulation, namely typologies GR_1 and GR_3, despite the difference not being substantial, mainly due to differences in building elements' areas. Thermal insulation cost-effectiveness for energy savings among typologies ranges between **0.19 kWh/€** in typology GR_1 and **1.19 kWh/€** in typology GR_7. More recent typologies tend to perform better in the energy savings/investment cost ratio. Gas boiler upgrade registers higher values than thermal insulation, with its peak value for typology GR_3, at **1.70 kWh/€.** Heat pump installation continues to be the measure with higher cost-effectiveness, with values as high as **6.72 kWh/€** (for typology GR_3), outperforming the other measures by a large margin. This translates into more significant potential energy bill savings, ranging from **450 €/year** for typology GR_5 and **3215 €/year** for typology GR_7. Gas boiler upgrade yields greater potential energy bill savings for older typologies, but it is outperformed by thermal insulation, which registers very significant values for typologies GR_3 and GR_7 (**2,473 €/year** and **1,823 €/year, respectively**), due to significant absolute energy consumption reductions. Cost-effectiveness of thermal renovation for carbon emissions reduction is higher for heat pump installation, and it is, on average, higher for gas boiler upgrade than for thermal renovation, **0.40 kgCO_2/€** against **0.11 kgCO_2/€,** mostly due to the total energy consumption reduction, which is generally higher in absolute value. Considering total energy generation, polycrystalline PV panels with 3 kWp of power can yield **2.10 kWh/€** in Piraeus.

Table 8. Investment cost, cost-effectiveness for energy savings and carbon dioxide emissions reduction and potential energy bills reduction for each renovation scenario in the Municipality of Piraeus.

	GR_1	GR_2	GR_3	GR_4	GR_5	GR_6	GR_7	GR_8
Investment cost interval (€/per dwelling)								
Overall Thermal insulation	9,302-16,911	8,271-14,993	8,681-15,760	7,401-13,216	7,401-13,216	7,127-12759	7,620-13676	7,620-13,676
Walls	1,563-1,835	1,449-1,700	1,488-1,746	1,554-1,823	1,554-1,823	1,455-1,707	1,512-1,774	1,512-1,774
Window	7,738-15,077	6,822-13,293	7,193-14,014	5,847-11,393	5,847-11,393	5,672-11,051	6,108-11,902	6,108-11,902
Heat pump	2,033-2,948	2,033-2,948	2,033-2,948	2,033-2,948	2,033-2,948	2,033-2,948	2,033-2,948	2,033-2,948
Gas boiler	2,259-4,849	2,259-4,849	2,259-4,849	2,259-4,849	2,259-4,849	2,259-4,849	2,259-4,849	-
Polycrystalline PV panels	5,886	5,886	5,886	5,886	5,886	5,886	5,886	5886

Highest cost-effectiveness for energy saving (kWh/€ | kWh/€/m²)								
Thermal insulation	0.09	0.14	0.16	0.33	0.29	0.24	1.19	0.58
Heat pump	2.78	3.68	6.72	2.18	1.90	3.06	5.95	3.14
Gas boiler	0.69	0.92	1.70	0.38	0.13	0.54	1.04	-
Highest cost-effectiveness for carbon dioxide emissions' saving (kg/€)								
Thermal insulation	0.02	0.12	0.04	0.09	0.06	0.06	**0.32**	0.18
Heat pump	0.72	0.15	**1.76**	0.82	0.82	1.17	1.53	0.99
Gas boiler	0.33	0.44	**0.81**	0.23	0.03	0.32	0.63	-
Potential energy bill reduction (€/year)								
Thermal insulation	184	251	308	484	207	350	**1762**	1193
Heat pump	1460	1931	3532	1063	450	1493	**3215**	1810
Gas boiler	1000	1343	**2473**	664	53	943	1823	-

5 Discussion of the results

In this section results are analysed in three different lenses. Firstly, a cross-typology analysis is conducted for each pilot context, aiming to identify the typologies with the highest potential impact and understand the reasons behind the differential impact of energy efficiency upgrades. Secondly, a cross-pilot analysis is performed to contrast and compare the impact of similar reasons on dwelling stocks with different characteristics and in different climate conditions. Thirdly, the results are analysed in the light of the energy poverty mitigation goal, which guides the work developed in the project.

5.1 Cross-typology analysis within pilots

5.1.1 Rumia

Different measures and scenarios result in energy consumption reductions for different reasons. Thermal insulation lowers consumption by reducing energy demand for delivered heat, whereas heating system upgrade reduces consumption by increasing equipment efficiency, which increases the ratio between primary energy consumption and final energy consumption. This is an important note when analysing the results for the different renovation scenarios, summarised in **Table 9**.

Observing the results for all typologies, it is possible to pinpoint **PL_2** as the typology with the highest potential impact on energy consumption reduction from thermal insulation, heat pump installation, and condensing gas boiler upgrade. One of the reasons is the relatively low EPC class (lowest among the Rumia typologies), the older period of construction (before 1980), and the more inefficient heating equipment (gas boiler with 0.8 COP). This circumstance determines a relatively high energy demand, which is naturally linked to higher potential savings. As a consequence, this typology registers the highest cost-effectiveness values for energy savings for these three scenarios, per dwelling and per square meter. Lower absolute savings in more recent typologies like **PL_4**, compared with the older dwelling typologies, reflect the lower baseline heating demand which leaves less scope for further reduction through either envelope improvement or heating system replacement.

An important reason that distinguishes it from PL_1 (from the same age period) is also the higher energy performance standards for wall insulation, leading to higher energy demand reduction. Heat pump installation stands out as the most cost-effective measure, enabling the highest potential energy bill reduction, **26.2%** per year in this typology, also achieving a relevant reduction in typology **PL_1** and PL_3 (**20.2%** and **20.8%**). This bill reduction is a function of the level of energy reduced due to heat pump efficiency rather than energy price, as electricity price is the highest of all energy sources. The reduction of energy demand through thermal insulation (same heating systems) has a more significant effect on energy bills than upgrading a gas boiler and transitioning to district heating.

Thermal insulation also performs strongly across all dwelling types, delivering consistently positive reductions in both energy consumption (**20.6%** to **28.6%**), carbon emissions (**10.1%** to **24.7%**), and potential energy bill reduction (**9.3%-15.1%**), despite its higher cost-effectiveness, deriving from the need for higher investment, especially in typologies from after 1980. The more limited impact of gas boiler upgrades (**7.0%** to **10.8%**, energy reduction) suggests that replacing the boiler alone cannot address the broader structural sources of inefficiency to the same extent as measures targeting either the heating technology more fundamentally, as in the case of heat pumps, or the building envelope itself, as in the case of thermal insulation.

Carbon dioxide emissions averted are, on average, higher for heat pump installation than thermal insulation, but it differs from typology to typology. Due to lower costs associated with heat pump installation, the cost-effectiveness values are always higher for this solution, despite similar absolute values in emissions reduction. In the Polish context, both district heating and electricity remain relatively carbon intensive. As a result, both renovation measures lead to notable emissions reductions. The relatively high carbon intensity of electricity limits the extent to which the heat pump's energy advantage is translated into proportionally larger emissions reductions. This indicates that heat pumps provide the clearest overall gains in energy performance (reduction ranging from **26.3%** to **45.4%)**, while their climate benefit depends more strongly on the carbon intensity of the energy sources involved (reduction from **5.7%** to **29.0%**). In several typologies (e.g. **PL_2** and **PL_5**), insulation delivers carbon savings comparable to, or even greater than, those achieved by heat pumps, indicating that envelope improvements remain a highly effective measure in Rumia, particularly where lowering heat demand directly produces substantial emissions benefits. Gas boilers have limited impact on carbon emissions (**3.2%** to **6.0%**) since they still use high-emitting natural gas or LPG to produce heat, and the efficiency gain (from 0.8 to 0.98) is not sufficient to deliver greater reductions.

Although the transition to DH lowers final energy consumption more significantly (**6.5% to 14.6%)** in comparison with the existing gas boiler, it worsens emissions performance by **6.5%** to **32.2%** under the current Polish conditions. This is due to the higher emission factor associated with the existing district heating relative to natural gas, meaning that lower energy use does not translate into lower carbon emissions in this case. It also does not deliver a substantial energy bill reduction. However, new investments in RES DH are planned for the future years, which would lower the emission factor of this technology. Thus, the situation can change in line with the new low-carbon investments made by heating producers, anticipated in the new strategy of the DH network in Rumia (OPEC, 2023).

From an energy efficiency and cost-effectiveness perspective, heat pumps appear to be the strongest option across the analysed typologies. From an environmental perspective, however, the picture is more complex in the Polish context. Although heat pumps are aligned with long-term decarbonisation goals, their short-term emissions benefits depend not only on their technical efficiency, but also on the carbon intensity of the electricity used to operate them. This is particularly relevant in Poland, where coal remains the largest single source of electricity generation (Ember, 2026). Moreover, heat pumps are linked to the use of fluorinated gases, which have several-fold the global warming potential of carbon dioxide. Also, weather events such as strong winds can impact heat pump performance, and subsequently, the profitability of this technology can often not be as high as expected.

The results presented here, therefore, reflect current system conditions rather than a fixed long-term outcome. As the electricity mix gradually decarbonises, the share of renewable energy increases, and the role of coal declines, the carbon emissions savings associated with heat pumps are likely to become more significant. In this sense, the picture presented here should be understood as time-sensitive: it captures present conditions but is also likely to evolve progressively as Poland advances towards the broader 2050 climate neutrality pathway. Factors related to production, exportation, and life-cycle assessment should also be integrated towards a more comprehensive picture of the resources and impact associated with this solution. Comparing heating systems with PV electricity production using the same metric of cost-effectiveness (despite the fact that in this case it is electricity produced instead of saved), the value for PV generation surpasses the average heat pump cost-effectiveness, showing its potential relevance for these dwellings. It covers over **74%** of total consumption for every typology, showcasing its potential for energy autonomy.

Table 9. Summary of the energy saving and bill reduction potential, environmental impact, and cost-effectiveness of the different renovation scenarios in the dwelling typologies in Rumia.

Dwelling typologies	Renovation scenarios	Annual energy savings (kWh) and percentage reduction (%)	Annual carbon emissions averted ($kgCO_2$) and percentage reduction (%)	Cost-effectiveness for energy savings (kWh/€)	Cost-effectiveness for carbon emissions reduction (kWh/€)	Potential energy bills reduction (%)
"PL_1"	Thermal insulation	2,094 (-25.8%)	942.2 (-22.3%)	0.42	0.19	13.3
	Heat pump installation	2,934 (-36.9%)	1,200 (-28.4%)	1.76	0.71	20.2
"PL_2"	Thermal insulation	2,698 (-27.2%)	544.9 (-15.2%)	0.44	0.09	15.1
	Heat pump installation	4,499 (-45.4%)	389 (-10.8%)	2.65	0.23	26.2
	Boiler upgrade	1,072 (-10.8%)	216.4 (-6.0%)	0.57	0.11	10.9
	Transition to DH system	648 (-6.5%)	-1,154.8 (+32.2%)	0.43	-0.77	2.6
"PL_3"	Thermal insulation	2,360 (-28.6%)	1,061.9 (-24.7%)	0.26	0.12	14.9
	Heat pump installation	3,110 (-37.6%)	1,246.5 (-29.0%)	1.83	0.73	20.8
"PL_4"	Thermal insulation	1,299 (-20.6%)	584.3 (17.1%)	0.17	0.08	9.3
	Heat pump installation	1,661 (-26.3%)	665.6 (19.5%)	0.98	0.39	12.7
"PL_5"	Thermal insulation	1,460 (-22.2%)	294.8 (-10.1%)	0.19	0.04	10.0

Heat pump installation	1,939 (-29.4%)	167.6 (-5.7%)	1.14	0.10	13.9
Boiler upgrade	461 (-7.0%)	93.1 (-3.2%)	0.24	0.05	5.7
Transition to DH system	963 (-14.6%)	-190.3 (+6.5%)	0.64	-0.13	6.2

5.1.2 Torres Vedras

In Torres Vedras, the results show that heat pump installation is the measure with the strongest overall effect on reducing annual energy consumption across dwelling typologies, lowering it by **44.3% to 60.4%**. The significant efficiency gain resulting from heat pump installation in a dwelling stock where electricity use for space heating and electric heaters is common and other alternatives are considerably inefficient leads to consistently high reductions in absolute energy demand. This level of energy demand reduction, together with the lower investment of a multi-split heat pump compared to other options, yields the highest cost-effectiveness across all typologies. It is possible to pinpoint typologies **PT_6, PT_9 and PT_10**, with the highest cost-effectiveness for energy savings, respectively **4.51 kWh/€, 4.69 kWh/€,** and **5.36 kWh/€.** These typologies are fairly recent, especially the latter two (2001-2010), but they were classified with EPC classes E or F, reflecting their lower energy efficiency and higher energy demand, which increases their reduction potential. Heat pumps have the added benefit of reducing energy demand for space cooling, compared to older A/C installed in typologies **PT_3, PT_4, PT_7**, and **PT_8**.

The potential for energy bill reduction is also considerable when examining this solution, especially in typologies **PT_2** and **PT_5**, which are older typologies with an E or F EPC class and use an electric heater for space heating. Electric heaters are more efficient than gas or biomass boilers, but electricity prices are superior to these energy sources. Thus, the heat pump's efficiency gains help reduce a significant share of that demand, lowering energy bills. Its effect on carbon emissions is likewise the strongest among all the measures considered, with annual avoided emissions reductions of **44.3%** to **83.2%**. Overall, these results indicate that heat pump installation provides the clearest improvement in both energy and emissions performance across all construction periods examined.

Thermal insulation can also contribute positively across all typologies, although its effect is more moderate. Annual energy consumption reductions range from **4.4%** to **10.5%**, while annual carbon emissions reductions vary between **4.5%** to **12.4%**. The higher investment costs lead to low cost-effectiveness for both energy savings and carbon emissions reduction, indicating higher opportunity costs associated with this investment. The significant gap in emissions reduction relative to the heat pump installation is also linked to the low emission factor of electricity, due to the high share of renewable energy in electricity production in Portugal.

Conventional boiler upgrades show performance similar to thermal insulation in the typologies where they are assessed, for energy consumption reduction (**4.7**% to **12.6%**) and carbon emissions reduction (**5.3%** to **13.9%**). However, they register lower cost-effectiveness values for both goals linked to reduced necessary investments. Conventional boiler replacement has a more limited capacity to improve overall dwelling performance than a shift to heat pump-based heating.

A distinct intermediate pattern is observed for biomass heat recovery system upgrades, examined in typologies "**PT_3**", "**PT_6**", and "**PT_7**". This intervention achieves annual energy savings of **15.7%** to **20.9%** and carbon emissions reductions of **19.4%** to **24.8%**, outperforming, on average, thermal insulation and conventional boiler upgrades but remaining less effective than heat pump installation. However, a few considerations are worth noting. The emissions calculation uses an activity-based approach (Bastos et al., 2024) because it is unknown if the biomass was harvested sustainably. Thus, biomass has a higher carbon emission factor than gas, which might be an overestimation if the feedstock is sourced from forest residues rather than harvesting whole trees. Hence, the environmental benefit of this solution can be overestimated. Moreover, this fuel still has a central role in the context of energy poverty in Torres Vedras. On the one hand, it is most commonly used in low-efficiency systems and may contribute to indoor air quality in Torres Vedras homes. On the other hand, easy access at low or no cost can safeguard against situations of extreme vulnerability, especially given higher electricity costs. Thus, the results show that replacing old biomass boilers with more efficient ones can have a positive impact on energy savings, emissions reduction and energy bill reductions, especially in typology PT_6 (**32.3%)** at a reasonable cost-effectiveness value (**0.78 kWh/€)** compared to thermal insulation and gas boilers. In the Torres Vedras case, this measure can therefore be seen as an intermediate improvement option in the typologies where it is technically applicable and where heat pump installation is not suitable for any motive. Using the same metric of cost-effectiveness (despite the fact that in this case it is electricity produced instead of saved), PV electricity production outperforms thermal insulation and gas and biomass boilers per kWh, emerging as an important solution in a diverse strategy for decarbonisation and energy poverty reduction, due to its potential to cover significant percentages of consumption and subsequently reduce energy bills. Its energy consumption coverage ranges from 36% in more energy-consuming dwellings to over 100% in less energy-consuming and electricity-dependent dwellings.

The current national electricity mix, with a high share of renewable energy, pushes for the decarbonisation of homes, through the electrification of heating consumption. Though, municipalities such as Torres Vedras, with urban and rural contexts, should be mindful of specific territorial circumstances and socioeconomic groups that might require the consideration of different solutions. The summary of results is displayed in **Table 10**.

Table 10. Summary of the energy saving and bill reduction potential, environmental impact, and cost-effectiveness of the different renovation scenarios in the dwelling typologies in Torres Vedras.

Dwelling typologies	Renovation scenarios	Annual energy savings (kWh) and percentage reduction (%)	Annual carbon emissions averted ($kgCO_2$) and percentage reduction (%)	Cost-effectiveness for energy savings (kWh/€)	Cost-effectiveness for carbon emissions reduction (kWh/€)	Potential energy bills reduction (%)
		Dwellings constructed before 1981				
"PT_1"	Thermal insulation	875 (-8.8%)	112 (-8.8%)	0.11	0.01	8.8
	Heat pump installation	4,421 (-44.3%)	566 (-44.3%)	2.17	0.28	56.9

"PT_2"	Thermal insulation	1,485 (-10.0%)	190 (-10.0%)	0.18	0.01	10.0
	Heat pump installation	7,853 (-53.1%)	1,005.1 (-53.1%)	3.85	0.44	68.3
"PT_3"	Thermal insulation	780 (-6.3%)	292.1 (-8.4%)	0.08	0.03	5.3
	Heat pump installation	6,658 (-53.9%)	2,740.9 (-79.0%)	3.27	0.00	53.0
	Biomass heat recovery system upgrade	2,170 (-17.6%)	781.3 (-22.5%)	0.53	0.18	26.3
"PT_4"	Thermal insulation	623 (-5.8%)	129.5 (-7.0%)	0.06	0.01	4.1
	Heat pump installation	4,954 (-46.5%)	1,110.5 (-60.3%)	2.43	0.36	40.1
	Boiler upgrade	721 (-6.8%)	145.6 (-7.9%)	0.32	0.06	9.5
"PT_5"	Thermal insulation	1,143 (-9.1%)	146.3 (-9.1%)	0.11	0.01	9.1
	Heat pump installation	6,260 (-49.8%)	801.3 (-49.8%)	3.07	0.39	64.1
"PT_6"	Thermal insulation	1,592 (-10.5%)	573.1 (-12.4%)	0.15	0.05	9.4
	Heat pump installation	9,197 (-60.4%)	3,830.6 (-83.2%)	4.51	1.88	62.2
	Biomass heat recovery system upgrade	3,177 (-20.9%)	1,143.8 (-24.8%)	0.78	0.28	32.3
"PT_7"	Thermal insulation	731.0 (-4.8%)	272.1 (-6.1%)	0.06	0.02	4.0
	Heat pump installation	8,732 (-57.0%)	3,632 (-81.1%)	4.29	1.78	56.0
	Biomass heat recovery system upgrade	2,407 (-15.7%)	866.4 (19.4%)	0.59	0.21	24.0
"PT_8"	Thermal insulation	590.5 (-4.5%)	122.1 (-5.3%)	0.05	0.01	3.2
	Heat pump installation	6,544.2 (-49.8%)	1,477.8 (-63.6%)	3.21	0.41	43.5

	Boiler upgrade	614.9 (-4.7%)	124.2 (-5.3%)	0.26	0.05	6.6
"PT_9"	Thermal insulation	789.9 (-4.5%)	101.1 (-4.5%)	0.06	0.01	4.5
	Heat pump installation	9,557.1 (-54.7%)	1,223.3 (-54.7%)	4.69	0.60	70.4
"PT_10"	Thermal insulation	836 (-4.4%)	172.3 (-5.0%)	0.07	0.01	3.6
	Heat pump installation	10,912 (-57.9%)	2,415.6 (-70.4%)	5.36	1.19	55.9
	Boiler upgrade	2,368 (-12.6%)	478.3 (-13.9%)	1.05	0.21	19.3

5.1.3 Piraeus

In Piraeus, almost all typologies range from C to G EPC class, and less efficient dwelling typologies are also found for the most recent construction period (1981-2000). Almost every typology has an oil heater, except for GR_5 and GR_8, which have a natural gas boiler and an electric heater, respectively. Across all typologies, heat pump installation consistently delivers the strongest overall performance, achieving the highest annual energy savings (**37.6% to 54.7%**). It also results in the greatest carbon emissions reductions (**29.0% to 97.8% reduction**). This reflects both the high efficiency of heat pump systems and, in oil-based systems, the shift away from more carbon-intensive heating. Typologies **GR_3**, **GR_7** and **GR_2** have the highest cost-effectiveness values for energy savings. It is in these same typologies where greater shares of potential energy bill reduction are achieved (**56.1%** in **GR_2** to **63.6%** in **GR_3**), despite significant values being observed across all typologies. This is linked to a higher reduction in total energy consumption absolute values.

Thermal insulation measures can also provide notable benefits across all typologies, with energy consumption reductions ranging from **5.6% to 37.4%** and carbon emissions savings between **5.8% to 34.8%**. This solution is more effective in typologies **GR_4** (**24.9%**), **GR_5** (**23.6%**), **GR_7** (**37.4%**), and **GR_8** (**26.1%**), which are the typologies where a more considerable improvement in window thermal transmittance is achieved, due to previous low-efficiency solutions. While insulation leads to significant improvements in these cases, its relative contribution is reduced in dwellings where inefficiencies are primarily associated with the heating system rather than the envelope. Cost-effectiveness for energy savings is higher in the same typologies, as the investment cost is the same for the window element, which completely replaces the previous solution instead of complementing the current one, as is the case for walls. This means a higher increase in thermal performance for the same cost. Cost-effectiveness for emissions reduction does not follow the same pattern, as the highest values are observed for GR_8, GR_2, and GR_7, which have the highest absolute emissions reduction. Moreover, heating in the latter two is provided with an oil boiler.

Boiler upgrades exhibit a more variable performance, with energy savings ranging **3.1% to 15.4%** and carbon emissions reductions between **2.5% to 34.9 %**. In dwellings constructed before 1981, boiler upgrades often outperform thermal insulation in terms of both energy and emissions savings. This is mainly due to the very low efficiency of existing oil boilers (COP ≈ 0.75), meaning that replacing them yields substantial gains. In contrast, in dwellings constructed between 1981 and 2010, heating systems are generally more efficient (COP ≈ 0.82), which limits the impact of boiler upgrades and increases the relative importance of envelope-related measures such as thermal insulation. Cost-effectiveness for energy and emissions reduction is superior for gas boiler installation in almost every typology, except for typologies **GR_5** (for both) and **GR_7** (for energy savings).

Comparing heating systems with PV electricity production using cost-effectiveness (even though in this case it is electricity produced instead of saved), a higher value is observed for PV generation than for thermal insulation and gas boilers, highlighting a potentially significant role in a strategy based on the complementarity of solutions that address demand and supply. The high share of heating oil used in Piraeus is a significant challenge that requires strategies that are mindful of consumers' circumstances and support them in the transition to a cleaner, sustainable energy system. The summary of results is displayed in **Table 11**.

Table 11. Summary of the energy saving and bill reduction potential, environmental impact, and cost-effectiveness of the different renovation scenarios in the dwelling typologies in Piraeus.

Dwelling typologies	"Future" renovation scenarios	Annual energy savings (kWh) and percentage reduction (%)	Annual carbon emissions averted ($kgCO_2$) and percentage reduction (%)	Cost-effectiveness for energy savings (kWh/€)	Cost-effectiveness for carbon emissions reduction (kWh/€)	Potential energy bills reduction (%)
Dwellings constructed before 1981						
"**GR_1**"	Thermal insulation	839 (-6.6%)	224.8 (-6.1%)	0.09	0.02	6.5
	Heat pump installation	5,660 (-44.4%)	1464.7 (-39.6%)	2.78	0.72	51.3
	Boiler upgrade	1,552 (-12.2%)	743.2 (-20.1%)	0.69	0.33	35.2
"**GR_2**"	Thermal insulation	1,148 (-7.4%)	308.8 (-7.5%)	0.14	0.12	7.3
	Heat pump installation	7,474 (-51.6%)	1,927 (-76.4%)	3.68	0.15	56.1
	Boiler upgrade	2,084 (-13.5%)	997.9 (-28.9%)	0.92	0.44	39.0
"**GR_3**"	Thermal insulation	1,407 (-5.6%)	376.6 (-5.8%)	0.16	0.04	5.5
	Heat pump installation	13,660 (-54.7%)	3,515.4 (--97.8%)	6.72	1.76	63.6

	Boiler upgrade	3,837 (-15.4%)	1,837.7 (-34.9%)	1.70	0.81	44.6
"GR_4"	Thermal insulation	2,415 (-24.9%)	646.6 (-22.9%)	0.33	0.09	23.4
	Heat pump installation	4,427 (-45.6%)	1,141 (-40.6%)	2.18	0.82	51.4
	Boiler upgrade	859 (-8.8%)	515.4 (-18.3%)	0.38	0.23	32.1
"GR_5"	Thermal insulation	2,156 (-23.6%)	439,4 (-18.7%)	0.29	0.06	14.2
	Heat pump installation	3,854 (-42.2%)	683.4 (-29.0%)	1.90	0.82	30.9
	Boiler upgrade	286 (-3.1%)	57.8 (-2.5%)	0.13	0.03	3.6
"GR_6"	Thermal insulation	1,741 (-12.7%)	457.7 (-11.5%)	0.24	0.06	11.9
	Heat pump installation	6,215 (-45.1%)	1,598.1 (-40.1%)	0.54	0.32	32.2
	Boiler upgrade	1,218 (-8.9%)	731.1 (-18.4%)	3.06	1.17	50.9
"GR_7"	Thermal insulation	9,087 (-37.4%)	2,423.1 (-34.8%)	1.19	0.32	34.3
	Heat pump installation	12,101 (-49.9%)	3,117 (-44.8%)	5.95	1.53	62.6
	Boiler upgrade	2,357 (-9.7%)	1,414 (-20.3%)	1.04	0.63	35.5
"GR_8"	Thermal insulation	4,428 (-26.1%)	1,399.3 (-26.1%)	0.58	0.18	30.8
	Heat pump installation	6,375 (-37.6%)	2,014.7 (-37.6%)	3.14	0.99	46.7

5.2 Renovation impact analysis across pilots

The cross-analysis of results between the pilots can also unveil interesting insights into the impact of similar renovation and energy efficiency scenarios in different contexts. **Figure 85** displays the average typology cost-effectiveness analysis for energy savings and carbon emission reduction. Heat pump installation was revealed to be the most cost-effective measure across typologies in the three case study pilots, though some relevant differences should be noted. The potential impact of this heating system is determined by some relevant factors, such as the existing building heating system. The energy efficiency of existing heating systems is a key factor, as low efficiency is associated with higher energy demand and with considerable potential for energy consumption reduction through efficiency gains, as in the case of the heat pump. The low cost of this solution across all locations provides a competitive advantage over other measures, strengthening its position as the most cost-effective. Despite higher electricity prices, the energy consumption offset from increased heat pump efficiency outperforms gas boilers, which benefit from more affordable fuel. Moreover, for Torres Vedras and Piraeus, this system also provides slight energy efficiency improvements in cooling energy consumption, yielding additional energy savings. Cost effectiveness for carbon emission reduction is not significant, as for energy savings for the heat pump. The national fuel mix for electricity production significantly influences the environmental benefit of this equipment. In fact, this is a crucial factor preventing higher values in Rumia. Gas boilers stand out in Piraeus compared to the other locations due to the existing stock of oil heaters, which are less efficient and more carbon intensive than new gas boilers.

Thermal insulation has limited cost-effectiveness in every pilot due to high investment costs, but it is particularly low in Torres Vedras compared to the other locations, mostly due to the fact that households of the respective typologies have bigger dimensions (window area, walls and pavement). Bigger dimensions require higher investments as prices are defined in square meter, in a context of already higher prices, which is the Portuguese. On the other hand, improving building elements with already lower thermal transmittance requires solutions that are generally costly, which is the case for Rumia. Conversely, in Piraeus, the more significant improvement of thermal transmittance of walls and windows from an inefficient baseline translates into greater potential for energy consumption reduction, contributing to higher cost-effectiveness values both for energy savings and carbon emission reduction. Different measures have distinct costs and effectiveness, highlighting the value of analysing the join and individual impact and cost-effectiveness of each measure, which may reveal unexpected opportunities and potential.

Solar PV electricity production has favourable cost-effectiveness for energy generated, outperforming thermal insulation and gas boiler upgrades in all locations and even heat pumps in Rumia. It is in Rumia

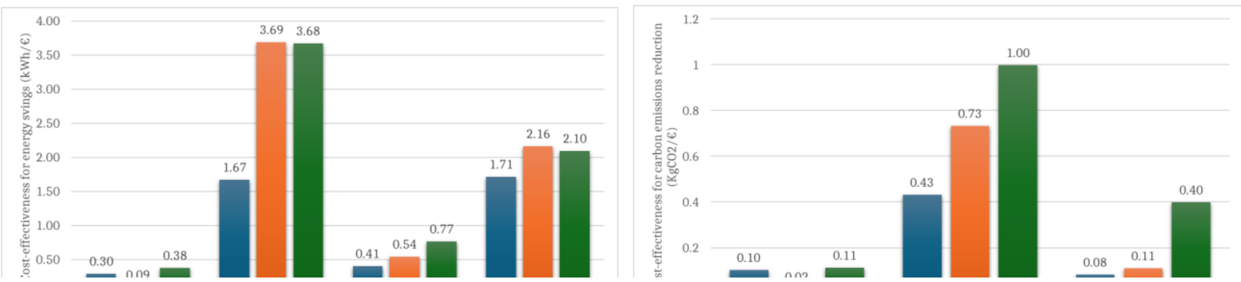


Figure 85. Average cost-effectiveness of renovation scenarios for energy savings (left) and carbon dioxide emissions reduction (right) in the three pilot regions

where this cost-effectiveness is lower, due to lower cumulative annual electricity production. This is directly connected to the lower sun exposure of Rumia compared to the more southern locations of Torres Vedras and Piraeus, which have similar values. Despite the smaller production, observing the coverage percentages, Rumia achieves a minimum coverage of 74% across scenarios, whereas Torres Vedras and Piraeus have a wider range, depending on the typology (from around 30 to 140%). This shows that PV can play an important role in every location, while coverage is more variable in Portuguese and Greek cities despite higher solar power potential, due to higher energy demands after renovation. It is important to consider that, despite progress in the capacity/area ratio, the tested power capacity (3 kWp) requires considerable roof or balcony space, which creates a relevant challenge for its implementation in apartments. On the other hand, higher energy consumption coverage from PV production is also associated with not electrifying heating consumption, which is not necessarily a positive trend, depending on the specific case.

The average potential energy bill reduction (**Figure 86**) follows a similar trend to the cost-effectiveness for energy savings. Torres Vedras dwellings use electricity more frequently for space heating, as individual electric heaters are a common solution. Additionally, electricity is the costliest energy source in the country, despite a decreasing trend with the rising share of renewable energy in the electricity production mix. Hence, replacement with a heat pump and its subsequent energy consumption reductions can have a considerable impact on energy bills for consumers if the same level of consumption is maintained. Thermal insulation is more effective in Greece for the same reasons mentioned for the cost-effectiveness analysis. As for the gas boiler upgrade, the higher potential energy bill reduction is also related to the higher price of oil in Greece compared to gas.

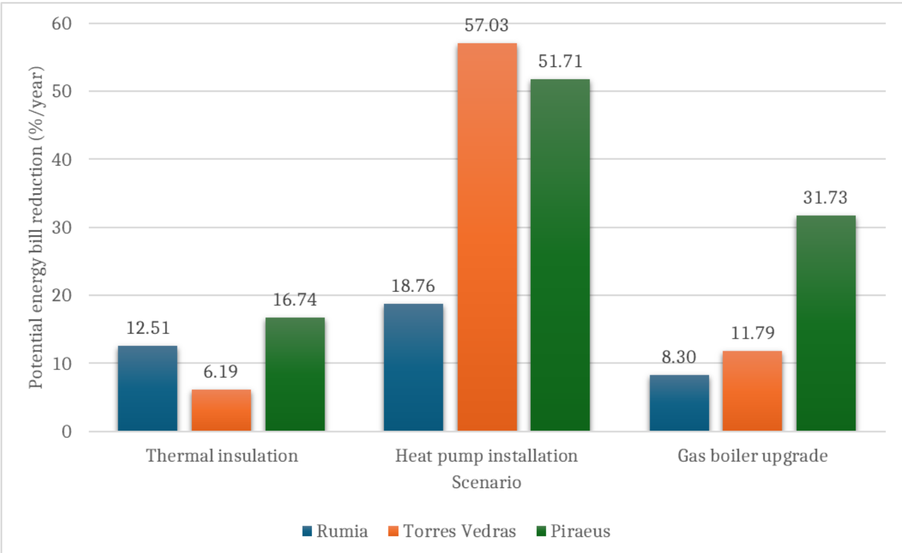


Figure 86. Average potential energy bill reduction (%) in the three pilot regions

5.3 Implications for Energy Poverty Mitigation

Beyond their relevance to renovation plans, these results can also be valuable to municipalities in their energy poverty mitigation strategies, as they provide an assessment of several energy efficiency measures in terms of investment, cost-effectiveness, impact on energy consumption, carbon emissions reduction, and energy bill curtailment. All these parameters can be useful to prioritise measures and typologies to address both energy efficiency, decarbonisation and energy poverty issues in an integrated way, in contexts of limited financial resources. These results should be crossed with the mapping analysis conducted in LOCATEE's report "Varieties of domestic energy deprivation in private multi-apartment buildings. Insights from Poland, Portugal and Greece" (Frankowski *et al.*, 2025) and future mapping developments, to identify where the analysed typologies match with social vulnerability and higher energy poverty levels. These two analyses complement each other and provide targeted inputs for policymaking, towards a more accurate targeting of vulnerable households to support.

The microsimulation of energy poverty levels across districts and buildings is developed using an energy poverty indicator based on energy expenditures, and potential energy bill reductions can serve as direct inputs to the simulation to assess how energy poverty levels change with specific energy renovation measures. Lower energy bills are generally associated with reduced energy poverty vulnerability, except if the bills are abnormally low. However, it is important to note that the absolute values of this report reflect a theoretical analysis in which households maintain thermal comfort for a significant part of the day. In households suffering from energy poverty, this is unlikely to be the baseline situation. In fact, a considerable percentage of energy-deprived households are considered to be in hidden energy poverty, meaning they restrict their energy consumption to avoid high energy bills. Around 11.6% and 9.5% of households in Portugal and Greece, respectively, are said to be in hidden energy poverty (EPAH, 2026). Karpinska and Śmiech (2020) estimated 23.6% for Poland. This thermal comfort gap is reported in Palma et al. (2019) and Gouveia et al. (2019) for the Portuguese context. In cases like this, a reduction in energy bills in absolute terms would not achieve the magnitude described in this analysis. It is advisable to use the reduction percentages when estimating potential impacts for households in energy poverty, keeping in mind that, depending on the context, these still might not be verified in reality. On the other hand, increases in energy efficiency can influence behaviour and lead to increased energy consumption, in what is described by the rebound effect (Frondel, 2004; Özsoy, 2024). This would render estimates of energy savings and bill reductions less reliable.

Further considerations should be made about the analysed measures, aiming to further increase the degree of nuance that should be required when selecting them, as the analysis provided important outputs, but it is not able to address every relevant dimension of analysis. Heat pumps stand out as the most effective solution, but a full life-cycle assessment of their impacts, namely f-gas emissions over their lifespan, should be conducted. This technology is mostly imported from outside Europe, and international conflicts and energy crises deeply affect its availability and affordability. Moreover, digital and technological literacy issues may arise in certain groups of the population when dealing with a new heating system, requiring interpersonal support and additional investment in this process. The same can occur with other technologies, but it is less likely if the new equipment is similar to the existing one.

Maintaining certain heating systems may not contribute to full goals but may be linked to lower vulnerability. This can be the case of solid fuels, such as coal, and also biomass. Besides their potential cultural importance, the use of firewood and biomass boilers may be linked to cheaper heating due to low-cost or free access to local firewood. Switching to other systems and energy sources may bring additional difficulties in terms of adaptation and energy costs; thus, it requires additional support. On the other hand, biomass consumption can also be a form of coping with EP (Stojilovska *et al.*, 2023). It can have significant detrimental effects on indoor air quality. This highlights the importance of considering the different social and territorial contexts and circumstances when addressing energy poverty through technical solutions.

Solar PV production can be a relevant solution for increasing energy autonomy, but there are shortcomings to consider. The cost calculation did not consider batteries, which are needed to guarantee higher consumption levels and require a significant increase in investment cost, which reduces accessibility for vulnerable consumers. It is also considerably influenced by weather conditions. Production in winter is low, even though heating demand is normally higher. Moreover, installing this solution in multifamily buildings requires considerable roof space, considering the peak capacity, and approval from the majority of neighbours, which is a relevant challenge.

Thermal insulation (walls and windows) is not the most cost-effective measure, but it should be at the core of renovation strategies, as it delivers permanent, long-term energy demand reduction. This reduction is not dependent on energy prices, which are set in international markets where localities have no impact. It also improves indoor comfort and enables more stable indoor temperatures. Moreover, it can be commissioned using local materials and local labour, supporting the local economies, and it is less affected by international crises.

The development of an energy efficiency strategy to reduce energy poverty needs to address the usual barriers to renovation, such as split incentives, limited access to finance, lack of information, and administrative burdens, plus the lack of participation, inclusion, and difficulty in engagement, which is particular to citizens in energy poverty. Existing local support schemes can be revised in light of these results to better target these groups and more effectively address these known barriers, so that renovation measures reach those who most need them.

6 Conclusions

Buildings are a cornerstone sector for the economy's decarbonisation, climate change mitigation, energy access promotion, energy poverty reduction, and the improvement of the population's well-being. However, poor levels of conservation and low energy efficiency of its elements and equipment continue to hinder the achievement of these goals. Energy renovation is necessary, but several barriers slow its deployment, especially in private multifamily buildings, including a lack of financial resources, fragmented ownership, split incentives, and limited information on the most effective measures.

This report addresses the latter gap, aiming to assess the performance of different energy renovation solutions for upgrading the multifamily dwelling stock in the three pilot cities – Rumia, Torres Vedras, and Piraeus - each with distinct climatic, infrastructural, and political contexts, as well as varying energy poverty levels and expressions. It employs a dwelling-typology approach to represent each local dwelling stock and the dynamic energy simulation model DREEM to assess the impact of building-envelope insulation and heating-system upgrades on diverse output indicators, such as energy performance, carbon dioxide emissions, cost-effectiveness, and potential energy bill reductions. The selected group of indicators provides insights into the impact of measures to decarbonise, improve energy efficiency, promote renewable energy, and reduce energy poverty. It identifies the most cost-effective measures and the highest potential dwelling typologies for interventions.

This pilot detailed analysis can provide valuable inputs for municipalities to develop more tailored energy renovation strategies to achieve these goals, to enact local policy strategies, and to contribute to the achievement of national targets set in the National Building Renovation Plans and Social Climate Plans. The municipalities have limited authority to intervene in private multifamily buildings, but these results can inform the development of local support instruments to finance renovation while ensuring maximum resource efficiency in contexts of limited public funding. It is particularly timely, as the Social Climate Fund will soon become available for targeted building renovations, with potentially greater availability for local governments. The cross-analysis with the energy poverty vulnerability mapping is a key step towards a more socially just allocation of support. Through its integration in the Energy Poverty Monitoring System, a key component of the LOCATEE toolkit, it will enable the identification of buildings and districts at the nexus of social, energy, and structural vulnerabilities and will match the most cost-effective and impactful measures with the most vulnerable households and districts.

This analysis can be integrated into strategic planning, such as the SECAPs, building renovation plans, and regional or local Energy Poverty Mitigation plans, to enable more integrated and multidimensional action, or directly strengthen local instruments, such as renovation programs, during the design, deployment, and monitoring phases. The results can also inform advisory initiatives such as local support points and one-stop shops from the local governments, to directly help citizens identify the most effective measures to implement according to the typology of their home, and it can also be useful for supporting the initiatives of other key stakeholders, such as local associations which focus on the same goals.

Leveraging LOCATEE's network of stakeholders and joint workshops, this study will be disseminated and presented to the relevant local actors, aiming to increase its impact through integration into policy and local actions on the ground, dedicated to mitigating energy poverty mitigation via buildings' energy efficiency, renewable energy promotion, and decarbonisation.

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Annex A

Table A1. Dwelling specifications and characteristics per typology for the City of Rumia in Poland.

Pilot Area 1: Municipality of Rumia, Poland					
Parameters	PL_1	PL_2	PL_3	PL_4	PL_5
Dwelling characteristics					
EPC class	B	C	C	B	B
Construction period	1980 and before	1980 and before	1980 and before	After 1980	After 1980
Total (habitable) dwelling area [m²]	56.80	56.80	56.80	62.50	62.50
Total exterior walls area [m²]	75.37	75.37	75.37	79.06	79.06
Total floor area [m²]	56.80	56.80	56.80	62.50	62.50
Total roof area [m²]	56.80	56.80	56.80	62.50	62.50
Total windows area [m²]	12.22	12.22	17.18	15.72	15.72
Construction features					
U-value of exterior walls [W/(m²·K)]	1.3	1.3	1.3	0.19	0.19
U-value of floor [W/(m²·K)]	0.94	0.94	0.94	0.65	0.65
U-value of roof [W/(m²·K)]	0.6	0.6	0.33	0.5	0.5
U-value of windows [W/(m²·K)]	2.6	2.6	2.6	1.6	1.6

Sources: Ministry of Economic Development and Technology. (2025); TABULA. (2026)

Table A2. Dwelling systems specification and characteristics, energy demand, and occupancy profiles per typology for the City of Rumia in Poland.

Pilot Area 1: Municipality of Rumia, Poland					
Parameters	**PL_1**	**PL_2**	**PL_3**	**PL_4**	**PL_5**
Dwelling systems & energy demand					
Heating systems	District Heating	Natural Gas Boiler	District Heating	District Heating	Natural Gas Boiler
Nominal capacity of the heating systems [kW]	6.8	6.8	6.8	5	5
Coefficient of performance of the heating systems	0.90	0.80	0.90	0.90	0.80
Cooling systems	Non-existent	Non-existent	Non-existent	Non-existent	Non-existent
Nominal capacity of the cooling systems [kW]	-	-	-	-	-
Energy efficiency ratio of the cooling systems	-	-	-	-	-
Primary/final energy consumption [kWh/m²]	141.00	183.00	149.00	98.00	102.00
Other parameters (occupancy)					
Number of household members	3	3	3	3	3
Number of working household members	2	2	2	2	2
Working schedule of working household members	Weekdays 08:00 - 16:00	Weekdays 08:00 - 16:00	Weekdays 08:00 - 16:00	Weekdays 08:00 - 16:00	Weekdays 08:00 - 16:00

Sources: Statistics Poland (2022); General Office of Building Control (2025); TABULA (2026).

Table A3. Dwelling specifications and characteristics per typology for the City of Torres Vedras in Portugal.

Pilot Area 2: Municipality of Torres Vedras, Portugal										
Parameters	PT_1A	PT_1C	PT_2B	PT_2C	PT_2D	PT_2E	PT_3B	PT_3C	PT_3D	PT_3F
Dwelling characteristics										
EPC class	C or D	E or F	C or D	C or D	E or F	E or F	C or D	C or D	E or F	E or F
Construction period	Before 1981	Before 1981	1981-2000	1981-2000	1981-2000	1981-2000	2001-2010	2001-2010	2001-2010	2001-2010
Total (habitable) dwelling area [m²]	79.93	90.57	86.21	86.21	85.93	85.93	117.41	117.41	127.06	127.06
Total exterior walls area [m²]	89.40	95.17	92.85	92.85	92.70	92.70	108.36	108.36	112.72	112.72
Total floor area [m²]	79.93	90.57	86.21	86.21	85.93	85.93	117.41	117.41	127.06	127.06
Total roof area [m²]	79.93	90.57	86.21	86.21	85.93	85.93	117.41	117.41	127.06	127.06
Total windows area [m²]	20.56	21.89	28.78	28.78	28.74	28.74	32.51	32.51	33.82	33.82
Construction features										
U-value of exterior walls [W/(m²·K)]	1.29	1.66	1.14	1.14	1.19	1.19	1.02	1.02	1.13	1.13
U-value of floor [W/(m²·K)]	1.67	1.80	1.86	1.86	2.03	2.03	1.85	1.85	1.86	1.86
U-value of roof [W/(m²·K)]	2.31	2.81	2.26	2.26	2.71	2.71	2.28	2.28	2.89	2.89
U-value of windows [W/(m²·K)]	3.88	3.81	3.62	3.62	3.80	3.80	3.00	3.00	3.01	3.01

Sources: ADENE. (2026b); Monteiro (2018).

Table A4. Dwelling systems specification and characteristics, energy demand, and occupancy profiles per typology for the City of Torres Vedras in Portugal.

Pilot Area 2: Municipality of Torres Vedras, Portugal										
Parameters	**PT_1**	**PT_2**	**PT_3**	**PT_4**	**PT_5**	**PT_6**	**PT_7**	**PT_8**	**PT_9**	**PT_10**
Dwelling systems & energy demand										
Heating systems	None/Electric Heaters	None/Electric Heaters	Biomass Heat Recovery System	Natural Gas Boiler	None/Electric Heaters	Biomass Heat Recovery System	Biomass Heat Recovery System	Natural Gas Boiler	None/Electric Heaters	Natural Gas Boiler
Nominal capacity of the heating systems [kW]	10	10	9.20	23.27	10	6.51	10.04	23.50	10	22.29
Coefficient of performance of the heating systems	1.00	1.00	0.66	0.87	1.00	0.65	0.70	0.91	1.00	0.81
Cooling systems	Non-existent	Non-existent	Air Condition	Air Condition	Non-existent	Non-existent	Air Condition	Air Condition	Non-existent	Non-existent
Nominal capacity of the cooling systems [kW]	-	-	4.40	4.40	-	-	3.76	3.76	-	-
Energy efficiency ratio of the cooling systems	-	-	2.95	2.95	-	-	2.95	2.95	-	-
Primary/final energy consumption [kWh/m²]	111.75	154.71	122.51	97.83	132.50	161.04	114.31	99.35	126.80	132.24
Other parameters (occupancy)										
Number of household members	2	2	2	2	2	2	3	3	3	3
Number of working household members	1	1	1	1	1	1	1	1	1	1
Working schedule of working household members	Weekdays 09:00 - 17:00	Weekdays 09:00 - 17:00	Weekdays 09:00 - 17:00	Weekdays 09:00 - 17:00	Weekdays 09:00 - 17:00	Weekdays 09:00 - 17:00	Weekdays 09:00 - 17:00	Weekdays 09:00 - 17:00	Weekdays 09:00 - 17:00	Weekdays 09:00 - 17:00

Sources: ADENE. (2026b); INE (2021b); INE (2021c); Monteiro (2018).

Table A5. Dwelling specifications and characteristics per typology for the Municipality of Piraeus in Greece.

Pilot Area 3: Municipality of Piraeus, Greece								
Parameters	GR_1	GR_2	GR_3	GR_4	GR_5	GR_6	GR_7	GR_8
Dwelling characteristics								
EPC class	D	F	G	C	C	E	G	G
Construction period	Before 1981	Before 1981	Before 1981	1981-2010	1981-2010	1981-2010	1981-2010	1981-2010
Total (habitable) dwelling area [m^2]	80.93	69.51	73.30	79.92	79.92	70.10	75.68	75.68
Total exterior walls area [m^2]	89.96	83.37	85.62	89.40	89.40	83.73	86.99	86.99
Total floor area [m^2]	80.93	69.51	73.30	79.92	79.92	70.10	75.68	75.68
Total roof area [m^2]	80.93	69.51	73.30	79.92	79.92	70.10	75.68	75.68
Total windows area [m^2]	23.41	20.64	21.76	17.69	17.69	17.16	18.48	18.48
Construction features								
U-value of exterior walls [$W/(m^2 \cdot K)$]	2.20	2.20	2.20	2.20	2.20	2.20	2.20	2.20
U-value of floor [$W/(m^2 \cdot K)$]	3.10	3.10	3.10	2.75	2.75	2.75	3.10	3.10
U-value of roof [$W/(m^2 \cdot K)$]	3.05	3.05	3.05	3.05	3.05	3.05	3.05	3.05
U-value of windows [$W/(m^2 \cdot K)$]	4.70	4.70	4.70	6.10	6.10	4.10	4.70	4.70

Sources: Hellenic Republic (2017).

Table A6. Dwelling systems specification and characteristics, energy demand, and occupancy profiles per typology for the Municipality of Piraeus in Greece.

Pilot Area 3: Municipality of Piraeus, Greece								
Parameters	**GR_1**	**GR_2**	**GR_3**	**GR_4**	**GR_5**	**GR_6**	**GR_7**	**GR_8**
Dwelling systems & energy demand								
Heating systems	Oil Boiler	Oil Boiler	Oil Boiler	Oil Boiler	Natural Gas Boiler	Oil Boiler	Oil Boiler	Electric Heaters
Nominal capacity of the heating systems [kW]	24	24	24	24	24	24	24	12
Coefficient of performance of the heating systems	0.75	0.75	0.75	0.82	0.92	0.82	0.82	1.00
Cooling systems	Air Condition	Air Condition	Air Condition	Air Condition	Air Condition	Air Condition	Air Condition	Air Condition
Nominal capacity of the cooling systems [kW]	4.5	4.5	4.5	6	6	6	6	6
Energy efficiency ratio of the cooling systems	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Primary/final energy consumption [kWh/m²]	154.21	217.73	346.32	128.87	117.34	201.87	311.58	400.79
Other parameters (occupancy)								
Number of household members	2	3	4	2	2	2	4	4
Number of working household members	1	2	2	1	1	1	2	2
Working schedule of working household members	Weekdays 09:00 - 17:00	Weekdays 09:00 - 17:00	Weekdays 09:00 - 17:00	Weekdays 09:00 - 17:00	Weekdays 09:00 - 17:00	Weekdays 09:00 - 17:00	Weekdays 09:00 - 17:00	Weekdays 09:00 - 17:00

Sources: Greek Ministry of the Environment and Energy (2017); Greek Ministry of the Environment and Energy (2025b); ELSTAT (2026).

Annex B

Table B1. Acceptable ranges of the "Predicted Mean Vote (PMV)" and "Predicted Percentage of Dissatisfaction (PPD)" indices according to the current standards.

PPD (%)	PMV	Description
< 6	- 0.2 < PMV < + 0.2	Increased expectation level: recommended for spaces inhabited by highly vulnerable individuals with specific needs, like sick children, elderly people, etc.
< 10	- 0.5 < PMV < + 0.5	Standard expectation level: new and renovated buildings.
< 15	- 0.7 < PMV < + 0.7	Moderate expectation level (acceptable range): existing buildings.
< 20	- 1 < PMV < + 1	Minimum expectation levels: values acceptable only for limited parts of the day.
> 20	PMV < -1 or PMV > + 1	Unacceptable expectation levels: values deviating from acceptable criteria, deemed tolerable only for a very limited part of the year.

Source: Based on Stavrakas and Flamos (2020)

Table B2. Brief overview of the key components and modules of the DREEM model applied in this study.

Components	Modules	Description	Modelling/Programming Environments
C_1: Climate/ Weather data	-	This single-module component is responsible for generating climatic boundary conditions. It reads weather data from the respective files and then provides them to the other components, where and when necessary.	Modelica
C_2: Building envelope	-	This single-module component models different building typologies with the corresponding characteristics, properties, and heat conduction elements.	Modelica Python
C_3: Energy demand	*C_3M_1: Occupancy*	This module defines and sets the parameters for the behaviour and the activities of occupants by generating and storing default patterns.	Modelica
	C_3M_2: Appliances	This module is responsible for generating energy demand profiles from appliances, using statistics describing their mean total daily energy demand and associated power use characteristics, including steady-state consumption, or typical use cycles, based on occupancy patterns.	
	C_3M_3: HVAC	This module is responsible for heating, ventilation, and air conditioning inside the building.	
C_4: Thermal comfort	-	This single-module component is responsible for determining, based on international standards, appropriate conditions and temperature ranges that result in occupants' thermal satisfaction.	Modelica Python

Source: Based on Stavrakas and Flamos (2020)

Annex C

Table C1. Specifications of the renovation scenarios.

Renovation scenarios specifications							
Pilot areas	**Municipality of Rumia**		**Municipality of Torres Vedras**			**Municipality of Piraeus**	
Construction periods	**Before 1980**	**After 1980**	**Before 1981**	**1981-2000**	**2001-2010**	**Before 1981**	**1981-2010**
Thermal insulation - Applicable to all typologies							
U-value of exterior walls [W/(m²·K)]	0.50 0.21 0.19	0.11		0.50		0.41	0.41
U-value of windows [W/(m²·K)]	1.20 1.20 1.20	1.20		2.80		2.60	2.60
Boiler upgrade to a higher efficiency condensing gas boiler - Applicable to typologies: GR_1-7, PT_4, PT_8, PT_10, PL_2, PL_5							
Nominal capacity [kW]			24				
Coefficient of performance			0.98				
Heat pump installation - Applicable to all typologies							
Nominal capacity [kW]			10				
Coefficient of performance			3.50				
Biomass heating system upgrade - Applicable to typologies: PT_3, PT_6, PT_7							
Coefficient of performance			0.90				
Connection to the local DH system - Applicable to typologies: PL_2, PL_5							
Coefficient of performance			0.90				
PV installation - Applicable to all typologies							
Nominal power [KW_p]			3				

Sources: Hellenic Republic (2017); DGEG/ADENE (2021); Ministry of Development and Technology, 2022.

Table C2. Building envelope upgrade measures

Building element	Measure	Reference Price (Portugal) €/m2	Price (Poland) €/m2	Price (Greece) €/m2	Thickness (mm)	Thermal resistance (m²ºC/W)	Thermal conductivity (K·m⁻¹)
Wall	Extruded polystyrene (XPS)	19.8	19.75	16.51	80	19.8	19.75
	Extruded polystyrene (XPS)	13.57	13.54	11.32	50	13.57	13.54
	Extruded polystyrene (XPS)	11.52	11.49	9.61	40	11.52	11.49
	Expanded polystyrene (EPS)	33.5	33.42	27.94	130	33.5	33.42
	Expanded polystyrene (EPS)	19.67	19.62	16.40	120	19.67	19.62
	Expanded polystyrene (EPS)	29.76	29.69	24.82	110	29.76	29.69
		20.44	20.39	17.05	60	20.44	20.39
	Extruded polystyrene (XPS)	11.87	11.84	9.90	30	11.87	11.84
	Expanded polystyrene (EPS)	16.73	16.69	13.95	40	16.73	16.69
	Expanded polystyrene (EPS)	15.77	15.73	13.15	35	15.77	15.73
	Mineral wool	12.88	12.85	10.74	60	12.88	12.85
	Mineral wool	11.69	11.66	9.75	50	11.69	11.66
	Cotton wadding	11.85	11.82	9.88	40	11.85	11.82

	Cotton wadding	17.42	17.38	14.53	80	17.42	17.38
Window frame (average 1200x12000 mm)	PVC window frame "CORTIZO" +	660.29 (unit)	658.77 (unit)	550.62 (unit)	88	0.77	-
	Aluminium window frame "CORTIZO"	731.92 (unit)	730.23 (unit)	610.36 (unit)	70	0.77	-
	Wooden window frame "ROMÁN CLAVERO"	701.24 (unit)	699.62 (unit)	584.77 (unit)	78	0.77	-
	PVC window frame "KÖMMERLING"	405.97 (unit)	405.03 (unit)	338.54 (unit)	70	0.77	-
Glazing	Double glazing standard	49.27	49.16	41.09	14	0.36	-
	Low emissivity double glazing standard	136.92	136.60	114.18	16	0.40	-
	Low emissivity double glazing standard	140.52	140.20	117.18	26	0.71	-

Source: Based on CYPE (2026)

Table C3. Equipment upgrade measures

Type of measure	Measure	Reference Price (Portugal) €/unit	Price (Poland) €/unit	Price (Greece) €/unit	Nominal capacity (kW)	Coefficient of performance (COP)
Heating system	Condensing gas boiler - standing	4860.0	4848.8	4052.8	30	-
	Condensing gas boiler - standing	4693.0	4682.1	3913.5	22	-
	Condensing gas boiler - wall	2264.4	2259.2	1888.3	30	0.9
	Biomass Boiler (pellets)	6651.0	6635.6	5546.3	8	0.89
	Central heating Biomass boiler (firewood)	4083.2	4073.8	3405.0	16	0.82

	A/C multisplit 4 units	2954.3	2947.5	2463.6	8.6	3.50
	A/C multisplit 3 units	2037.4	2032.7	1699.0	6.8	3.50
	Transition to District heating	-	1500-4500	-	-	0.90
Renewable energy generation	Polycrystalline photovoltaic panels	2811.3	2804.8	2344.4	3	-

Source: Based on CYPE (2026)

Table C4. Energy prices

€/kWh	Natural gas	Electricity	District Heating	Heating oil	Biomass
Rumia	0.073	0.271	0.085	-	-
Torres Vedras	0.127	0.271	-	-	0.122
Piraeus	0.086	0.228	-	0.164	-

Source: Eurostat, 2026b; Eurostat, 2026c; Continente, 2026

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