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EqualHouse

Energy Efficient Renovation Measures Review

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Executive Summary

Energy efficient renovations are being promoted across the EU to help reach climate goals, alleviate energy poverty, strengthen energy security and improve the quality of an ageing building stock. As newer trends in energy efficient measures emerge, knowledge regarding the resultant unintended socio-economic or environmental consequences is yet to be fully established. Therefore, drawing from existing literature, this report presents a broad overview of trends in renovation measures, barriers, and strategies, in addition to their socio-economic and environmental consequences.

The review shows that passive renovation measures set a strong basis for improving energy efficiency and indoor air quality though climate change can introduce trade-offs between these goals, particularly as heatwaves become more frequent. Active systems can address these risks but involve additional costs and operational complexity that disproportionately affect households with limited resources or capacity to manage technical systems. In line with EU programs like the Renovation Wave, the combination of renovation measures either in a single, deep renovation project or in stages over time are recommended to maximize benefits and avoid lock-in effects.

High costs associated with deep renovation are meant to be offset by energy bill savings but these are dependent on pricing strategies and usage patterns which are highly influenced by occupant needs, behavior and cultural norms. Pricing strategies intended to reduce or optimize energy consumption like time-of-use tariffs and individually metered billing can unfairly burden households that have higher and less flexible energy needs.

Widespread uptake of renovation measures is dependent on reliable, long-term policies and funding. Community-based initiatives are especially effective in integrating the multiple objectives of renovations. They also help renovate dwellings at a larger scale, incorporating resident engagement, awareness-raising, and planning support services needed for long-term effectiveness.

At the same time, improved mechanisms such as smart meters and digital twins improve the quality of energy performance certificates and building



renovation passports help to standardize energy efficiency assessment. Trust in energy efficiency measures increases as a result, reducing the perceived risk of renovations and ultimately mobilizing investment from a broader group of actors.

Across tenure types, barriers and consequences differ markedly. Owner-occupiers with sufficient savings and administrative capacity are better positioned to benefit from subsidy schemes that reimburse costs after renovation completion, while lower-income owners are frequently excluded. In cooperative housing, collective decision-making processes and uneven distribution of benefits complicate renovation uptake. In the private rental sector, split incentives between landlords and tenants are a key obstacle, and stricter renovation requirements risk rent increases, displacement, or withdrawal of dwellings from the market. Social and public housing providers are more likely to engage in renovation programs, but smaller providers often lack access to funding mechanisms designed for large portfolios.

Geographic context further shapes outcomes. Rural areas face limited access to service providers, lower property values, and highly heterogeneous building types, reducing the feasibility of standardized renovation approaches. Urban areas, while better suited to large-scale renovation, face heightened risks of displacement and increased pressure on already constrained social housing systems. These patterns indicate that renovation policy must be sensitive to both tenure and spatial context.

The report concludes by reiterating that both the environmental and socio-economic performance of renovations hinges on a fair distribution of obligations and costs throughout the renovation process from funding and planning of the measures to pricing and technical maintenance strategies after the renovation.



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1. Introduction

The European building stock is ageing and in need of renovation. 85% of the building stock was built before 2000, and 75% have poor energy performance (EC, 2025). The existing building stock contributed to around 40% of the EU's energy use and 33% of energy-related greenhouse gas emissions (EEA, 2023a). 15.5% of the EU population had a leaking roof, damp walls, floors or foundation, or rot in window frames or floor in 2023 (Eurostat, 2024). The poor state of the housing stock poses issues to indoor comfort and health of occupants in addition to making them vulnerable to high energy bills. Therefore, the energy renovation of residential buildings across Europe is a key strategy to both tackle operational emissions from the building stock and improve living conditions.

However, regulations that impose energy efficient requirements on households regardless of their ability to invest in the measures place an unfair burden on vulnerable households, especially since these households tend to occupy buildings with poor energy performance (Von Platten et al., 2022). Ill-targeted renovation support schemes also tend to exclude the most vulnerable households who lack the administrative and financial capacity to be eligible or apply for them in time (EEB 2024). Moreover, effective programs to improve energy efficiency of homes involve payouts or tax returns upon completion of renovation and proof of improvement in energy performance. This automatically excludes households which do not have the required savings or loan eligibility to pay for the upfront costs of implementing renovation measures (Tzani et al., 2022).

The recent revisions to the Energy Efficiency Directive (EED) (European Parliament and Council 2023) and the Energy Performance Buildings Directive (EPBD) (European Parliament and Council 2024) include stronger provisions to protect vulnerable households, particularly those experiencing energy

Energy Efficiency Directive (EU) 2023/1791

Article 8(3)

This article requires Member States to establish and achieve a share of the required amount of cumulative end-use energy savings among specific target groups, i.e. people affected by energy poverty, vulnerable customers, people in low-income households and, where applicable, people living in social housing.

Article 24

Requires Member States to implement energy efficiency improvement measures and related consumer protection or information measures as a priority among people affected by energy poverty, vulnerable customers, people in low-income households and, where applicable, people living in social housing to alleviate energy poverty.



poverty. The EED stipulates that the share of end-use energy savings among the target groups is to be at least equal to the average of the four commonly used energy poverty indicators. Article 8(3) of the EED also highlights three types of adverse effects that may result from energy efficiency measures. The first type of effect is the increase of energy prices that are not offset by cost-reducing energy efficiency improvements, compromising cost-neutrality. The second type of effect identified is on the health and comfort of occupants because of renovations which do not, for instance, appropriately address ventilation. The third type of effect is a broader impact on socio-economic conditions such as an increase in the price of energy efficient solutions due to an increased demand triggered by regulations. The potential negative impacts energy renovations can have on housing affordability and quality emphasize the need for the holistic planning of renovation measures.

The need to renovate the European building stock while safeguarding socio-economic concerns has become increasingly relevant in recent years with the outbreak of the Covid-19 pandemic and subsequent Russian war on Ukraine. Recognizing this need, interdisciplinary and transdisciplinary efforts have been made in recent years to both improve the performance of technical renovation measures and to understand the impact of renovation measures on households.

A spectrum of barriers including economic, technical, institutional, social and legal barriers need to be addressed to achieve the systemic change necessary for decarbonizing the building stock and alleviating energy poverty. There is a trend towards more integrated solutions utilizing emerging digital capabilities in combination with community-based solutions. The social and environmental consequences of energy-efficient renovations are also documented but how recent measures and strategies influence these outcomes remain unclear.

Next Generation EU

Next Generation EU (NGEU), which allocates funding through the Recovery and Resilience Facility (RRF), the Recovery assistance for cohesion and the territories of Europe (REACT-EU), to help member states meet climate goals and recover post-pandemic.

Affordable Housing Initiative

This is a program part which aims to make housing energy-efficient and inclusive through pilot renovation projects directly addressing energy poverty.

New European Bauhaus (NEB)

NEB is an initiative which promotes sustainable, aesthetic, inclusive buildings.

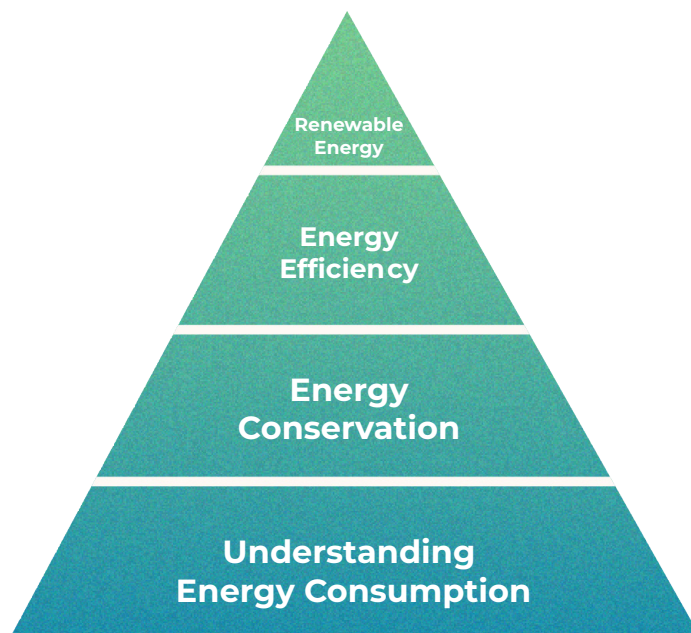
European Pillar of Social Rights

Principle 19 on housing and assistance for the homeless, and supports the EU's cohesion policy for 2021-2027.



This report, therefore, aims to provide a comprehensive overview of both the latest trends in renovation measures, barriers in implementing them, the tools and strategies developed to address them, as well as summarize current knowledge of their impact on households based on academic and grey literature. Where possible, we highlight how vulnerable households in different segments of the residential building stock such as tenants, owner-occupiers, cooperative owners, and those living in rural or urban areas are affected by the renovation measures.

Following a background chapter on housing and energy conditions in the EU, the first half of the report examines measures from each category of the energy pyramid that are commonly implemented in the EU alongside emerging trends. The second half covers the broader implications renovation measures have on households and the tools developed to implement them. Relevant regulations and examples from around the EU are highlighted throughout the report.



The energy efficiency pyramid

(Fig. 1) offers a comprehensive categorization of the different types of measures needed to improve the environmental performance of a building.

Often, a combination of these measures is required to achieve adequate improvements in energy efficiency.

Figure 1 Energy Efficiency Pyramid. Source: Buffington, D. E. (2010, May). The energy pyramid. *Mushroom News*, 58(5). Retrieved from https://www.americanmushroom.org/clientuploads/directory/mushroom_news/2010/2010_05.pdf



2. Background

The past five years have been shaped by economic slowdown caused by the pandemic and an energy crisis triggered by the Russian war on Ukraine in 2022. These events also contributed to a persistent housing affordability crisis, changing energy poverty levels as well as energy consumption patterns as a result.

Energy poverty levels which are typically monitored on the EU level through the “inability to keep home adequately warm” indicator of the EU statistics on income and living conditions (EU-SILC) survey had been steadily decreasing from 9.6% in 2015 to 6.9% in 2019. However, the outbreak of the covid-19 pandemic in 2020 brought about a reversal in this trend with energy poverty increasing to 7.5% in 2020, increasing even further to 10.6% in 2023 as the Russian war on Ukraine increased energy prices, eventually showing a slight decrease to 9.2% in 2024 (Eurostat, 2025).

Shifting Energy Use Patterns

Although it is still the leading energy source for households space heating in the EU, the share of natural gas has been decreasing since 2021.

The share of electricity and heat have remained relatively stable, with oil in the process of being phased out.

On the other hand, the share of renewables has progressed from 16% in 2000 to 28% in 2023) (Fig. 2).

This can be partially attributed to the price hikes and overall volatility induced by the Russian war which led to significant household measures, including fuel switching (Rosenow et al., 2022), and government incentives and policies (Mišík & Nosko, 2023).

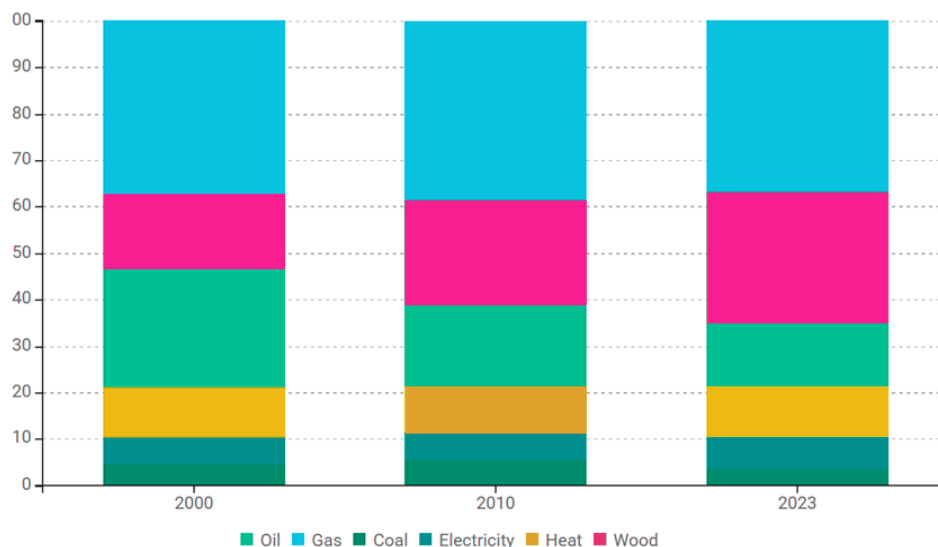


Figure 2 Household energy consumption for heating by energy source. Source: Odyssee-MURE URL: <https://www.odyssee-mure.eu/publications/efficiency-by-sector/households/energy-consumption-eu.html#:~:text=Natural%20gas%20is%20the%20most,Electricity%20in%20residential%20Heat%20Renewables>



The effects of the multiple crises of the past few years are experienced to varying degrees across the EU (Ata et al., 2025). Energy poverty and the unintended consequences of energy efficiency measures tend to affect households differently depending on a wide range of factors including, degree of urbanisation, type of tenure and demographic qualities.

Households in rural areas face specific issues such as physical isolation, high poverty rates, and older, inefficient building stocks which place them at greater risk of facing energy poverty. Rural housing in many countries have poorer indoor thermal comfort and energy performance (see Fig. 4). It is also more common for these households to use fossil-fuelled, or wood heating systems which greatly reduce indoor environment quality and pose health risks to occupants. The ageing population often found in rural areas is more vulnerable to such health risks. The lower real-estate value of these areas makes it less lucrative for large investments like renovations to be made and the unique characteristics of single-family houses prevalent in rural areas make it a difficult sector to implement systematic or large-scale renovations in (Apostoliotis et al., 2024).

In urban areas, households in the rental sector are often more vulnerable to the unintended consequences of renovations. It is easier to scale up renovations in urban areas due to the more standardized nature of urban residential buildings and their proximity to each other. However, the risk of “green gentrification” or “renoviction” is also higher. Low-income households who are unable to afford higher rents after major renovations are forced to move out (FEANTSA, 2022). Both the barriers to implementing renovations and the risks of unintended consequences are especially higher in the less-regulated private rental sector. For instance, the issue of split incentives is one of the main barriers experienced by

ODYSSEY-MURE

The ODYSSEY-MURE project provides comprehensive monitoring of energy efficiency trends in different sectors including households by combining data from two databases -ODYSSEY and MURE.

Energy Poverty Advisory Hub (EPAH)

This initiative monitors energy poverty levels in different segments of the residential sector through a comprehensive set of indicators in addition to providing training and advice to alleviate energy poverty.

Building Stock Observatory (BSO)

This observatory provides monitors building stock conditions and renovation efforts



stakeholders in this sector. Split incentives occur when the stakeholder who is responsible for financing renovation (e.g. the owner of rental properties) measures does not reap the benefits of reduced energy bills and improved indoor air quality (McCabe et al., 2018).

Public housing providers, especially larger organisations with more resources and access to funding, have been actively participating in renovation programmes (Cauvain & Karvonen, 2018). Despite these efforts, energy poverty is still prevalent among public housing tenants, who are often excluded from the traditional housing market and face greater socio-economic challenges (Croon et al., 2024).

Similarly, in cooperative housing sectors, split incentives arise from the differing needs of apartment owners. For instance, occupants who live on the top floor of a building or in a corner apartment will have a higher need for thermal insulation than apartments who have less contact with external walls. The legal and organizational barriers of building consensus on renovation measures amongst owner-occupants who in some cases have differing means and needs is also a barrier to vulnerable households accessing energy renovations.

Knowledge about the needs and capacities of households with different demographic qualities such as age, can be essential in implementing appropriate renovation measures (Greene & Fahy, 2020). For example, older people are particularly vulnerable to energy poverty as they generally have lower incomes and live in houses or apartments that are less energy-efficient (Willand & Horne, 2018). They are also perceived to be generally averse to new technologies (Charef et al., 2019) although this is not always the case as elderly people have also been found to be pioneers in this area (Caird et al., 2008). People that are already marginalized, such as disabled people, immigrants, or people with underlying mental health or



substance abuse issues, are also left behind when it comes to energy improvements. There is often an assumption that they lack the knowledge, awareness or literacy to reduce energy or for energy initiatives to have a high impact. Income level, being over 65 and educational level were also identified by Lara-García et al as factors that made people vulnerable to heatwaves (Lara-García et al., 2024).



3. Understanding Energy Consumption

Understanding energy consumption is a key precondition to changing energy usage behavior. Appropriate design of renovation measures requires detailed input and the lack of accurate information on building and household energy profiles is a barrier to successfully carrying out energy renovations (D'Oca et al., 2018). The EU has identified the installation of smart meters as an essential measure to help overcome this barrier among other things. Used in conjunction with digital tools like Building Information Modelling (BIM), digital twins and machine learning, the data collected through smart meters creates opportunities to better identify areas for improvement and to more accurately characterize the consumption needs of different households at a large scale.

3.1 Smart Meters

Smart meters are digital energy meters that automatically relay energy usage information to suppliers without the need for manual readings. They may be deployed to measure the consumption of utilities including domestic hot water (DHW), electricity and gas. There are also opportunities to use an “open metering system” which combines data from all three utilities. Although it is more common to have a metering device which relays an entire household’s consumption data, there are also sub-metering systems which disaggregate the usage data for different appliances, providing better support for demand-response and flexibility in energy usage (see Chapter 9). The installation of smart meters, sub-meters and a shift towards an internet of things (IoT) system provides better data on energy consumption that can be communicated to multiple stakeholders including households, energy providers, landlords, and governmental organizations designing policies.

The European Union Agency for Energy Regulators (ACER) reported that as of 2023, fifteen countries have a smart meter roll-out rate above 80 % (Denmark, Estonia, Spain, France, Italy,

[Electricity Directive 2019/944](#)

The directive requires member states to reach at least 80% smart meter penetration by 2024, assuming cost-effectiveness.

[The Clean Energy for All Europeans package \(2019\)](#)

The package strengthened requirements for full deployments of smart meters where cost benefit analyses are positive.



Latvia, Luxembourg, Malta, the Netherlands, Austria, Portugal, Slovenia, Finland and Sweden). Belgium, Ireland, Lithuania and Great Britain have a roll-out rate of between 30% and 80%. On the other end of the spectrum, ten countries have a very limited rate of roll-out of smart meters to household consumers (below 30 %), specifically, Bulgaria, Czechia, Germany, Greece, Croatia, Cyprus, Hungary, Poland, Romania and Slovakia (ACER, 2024). According to Berg Insight, 63% of electricity consumers in the EU had smart meters. Meanwhile, 44% of gas consumers had a smart meter installed as of 2023. The main barriers to installing smart meters are investment costs, data and privacy risks, and lack of awareness (Berg Insight AB, 2024).

Installing smart meters as a standalone measure has not demonstrated significant reductions in household electricity consumption. Sub-meters measuring energy consumption at the appliance level have shown slightly better results but the main issue limiting the effectiveness of smart meters in energy reduction is the short-lived nature of behavioural changes when households are presented with their consumption data (Samancioglu et al., 2026).

Although the installation of smart meters has little direct effect on housing affordability, its benefits lies in enabling new services and pricing strategies. They facilitate more dynamic or individualized utility payment models resulting in different distributional effects on households depending on their ability to shift consumption patterns (see Chapter 5). For instance, Sweden now requires individual metering and billing of heating energy in the worst-performing multifamily buildings in the Norrbotten region. Given that a correlation between poor energy performance and low-income have been established in several studies, the individual metering and billing of heating raises concerns of low-income households in multi-family houses being unfairly burdened (J. Von Platten et al., 2020).



Meanwhile in the UK, Ofgem, Great Britain's electricity regulator, has a statutory obligation to protect and support vulnerable consumers. They recommend that energy suppliers to prioritize vulnerable households using prepayment meters and recognize the potential of smart meters to help them identify consumers that are self-disconnecting (Ofgem, 2025). This supports more automated and proactive targeting of vulnerable consumers for support while placing “minimal burden in notifying and updating energy companies of their circumstances.” Currently in practice, the Warm Homes Discount program matches property register data, income, modelled energy costs, and benefits data to identify households facing energy poverty and require energy providers to automatically give a discount to these households. (Ofgem, 2025). Harnessing granular and longitudinal energy consumption data from smart data could facilitate this automated and targeted support for households (HouseInc, 2025). The data measured by smart meters, aggregated at a larger scale can even be used to train machine-learning algorithms to better identify households at risk of energy poverty.

Another benefit of smart meters is that they help bridge the gap between modelled or calculated energy consumption and measured or actual energy consumption. This means that they help reduce prebound effects (Van Der Leer et al., 2026). Prebound effect refers to overestimation of energy use in energy models which results in less energy and financial savings than predicted, especially for buildings with lower energy efficiency. In these buildings, households tend to be more frugal with their energy usage (Sunikka-Blank & Galvin, 2012).

Mitigating the negative impacts of smart meters while leveraging on their potential to support vulnerable



households involves policy safeguards and embedding them in broader initiatives to support vulnerable households. This can be achieved through measures like placing functional requirements to ensure a minimum quality of service for all households as is the case in Sweden and placing obligations on service providers to use consumption data for targeted support as is the case in the UK. Coupled with fair pricing strategies, such measures ensure that the deployment of smart meters supports a just transition in the residential building sector.

3.2 Digital Twins

While smart meters monitor energy consumption, digital twins combine multiple aspects of building performance, enabling multi-objective (including affordability aspects) planning in renovations and maintenance. A digital twin provides real-time digital representation of the physical building and its operation through sensors which continuously monitor changes. It supports real-time building monitoring of parameters like energy consumption, indoor comfort, and safety and can also support decision-making on future measures. It can even be linked to building renovation passports to provide a comprehensive overview of a building or neighborhood's condition.

In the residential sector, they are more applicable to multi-family housing or housing at a larger scale such as a neighborhood or district. Digital Twins support more rigorous maintenance, repair works and staged renovations which require less upfront costs and cause disruption to tenants. This tool is still being tested in research and pilot projects (BPIE, 2025). This is part of a wider push for better quality and more comprehensive data on the building stock in the EU.

Open Data Policy

In France, the open data policy requires open data by default and proactive provision of data from all government authorities including building stock and its energy performance

LEdEx (Existing Building Logbook)

In Spain, the LEdEx is a specific national instrument for existing buildings, particularly those built before 2000. It assesses the current condition of the building and its potential for improvement and includes a renovation action plan.

iBRoad2EPC

Is an EU project which integrates building renovation passports into energy performance certification schemes for a decarbonised building stock. It tested this tool in Bulgaria, Greece, Poland, Portugal, Romania, and Spain.



4. Conserving Energy

Absolute energy demand can be reduced through changes in behavior guided by a sufficiency approach which aims to achieve “a state in which people’s basic needs for energy services are met equitably and ecological limits are respected” (Darby & Fawcett 2018). A sufficiency approach becomes especially pertinent when considering that the energy consumed per capita in housing occupied by lower income households which tend to live in more crowded dwellings, is lower than more affluent households which tend to live in underoccupied dwellings (J. von Platten et al., 2020; Savini et al., 2026).

Sufficiency in the building sector is an approach which aims to meet needs with a more careful use of material and energy resources. This approach can involve the reduction of living space, and more effective use of existing buildings. Such densification is a less discussed method of reducing final energy consumption compared to energy efficiency. However, a sole focus on efficiency ignores cultural trends around conspicuous consumption that increase energy and material use such as bigger homes, bigger cars and more and larger appliances (Sahakian, 2019).

At the same time, the political pressure to build more housing is increasing, especially amidst a lack of affordable options in the existing built environment. A sufficient approach to addressing the lack of affordable housing would be to redistribute built square footage amongst those in need of housing. Such an approach has been investigated in several studies including (Bagheri et al., 2025) which demonstrates that sufficiency policies like flat exchanges and moving advice can potentially reduce total floor area. (Arceo, Touchie, & O’Brien, 2025) highlight how freedom to swap housing while maintaining rent, mortgage and ownership structures can provide more appropriate housing choices. (Arceo, Touchie, &

Examples from the EU

The **German city of Göttingen** started developing two energy-efficient neighbourhood concepts (KfW programme) which include the analysis of the potential for densification.

France’s National Plan to Combat Vacancy includes a database of vacant buildings which includes energy performance information. Owners of buildings with a low performance are contacted and offered renovation incentives to align with Minimum Energy Performance Standards (MEPS).

In **Berlin, Hamburg, Potsdam and Munich** home swap meets were established in 2018, 2023, and 2020 respectively in collaboration with city-owned housing companies owned by the city (Die sechs landeseigenen ngsbaugesellschaften Berlin], 2018; SAGA 2023; Landeshauptstadt Potsdam, 2020; Landeshauptstadt München – Sozialreferat Gesamtplanung Wohnen, 2021).



O'Brien, 2025) specifically highlights home swapping as having “enormous potential to reduce per capita housing space”. (Bohnenberger, 2021) provides strong theoretical backing, showing sufficiency could reconcile social and environmental housing goals if pursued collaboratively.

One of the key issues in adopting a sufficient approach in building occupation is the temporal nature of housing needs. A dwelling occupied by a family can go through multiple occupancy scenarios in its lifetime. (Arceo, Touchie, O'Brien, et al., 2025) propose “rightsizing” a unit to its occupancy level at any point during its life cycle through strategies like subdividing larger houses into smaller dwellings or converting non-residential building to housing units.

While sufficiency and efficiency measures applied in isolation result in only modest emission reductions, a strategically targeted combination of space demand reduction and renovation offers significant potential to lower both operational and embodied emissions, reduce reliance on the uncertain future technologies, and meet housing needs within planetary boundaries (Batra et al., 2026; Horn et al., 2025). The success of the combined measures also depends on social acceptance, new norms, and innovative business models, with current political and social frameworks not fully exploiting sufficiency measures' potential (Bagheri et al., 2025; Passoni et al., 2021)

*The home swapping offer in **Vienna** generally sets a limit of one room more than people living in the household (Wiener Wohnen, 2020)*



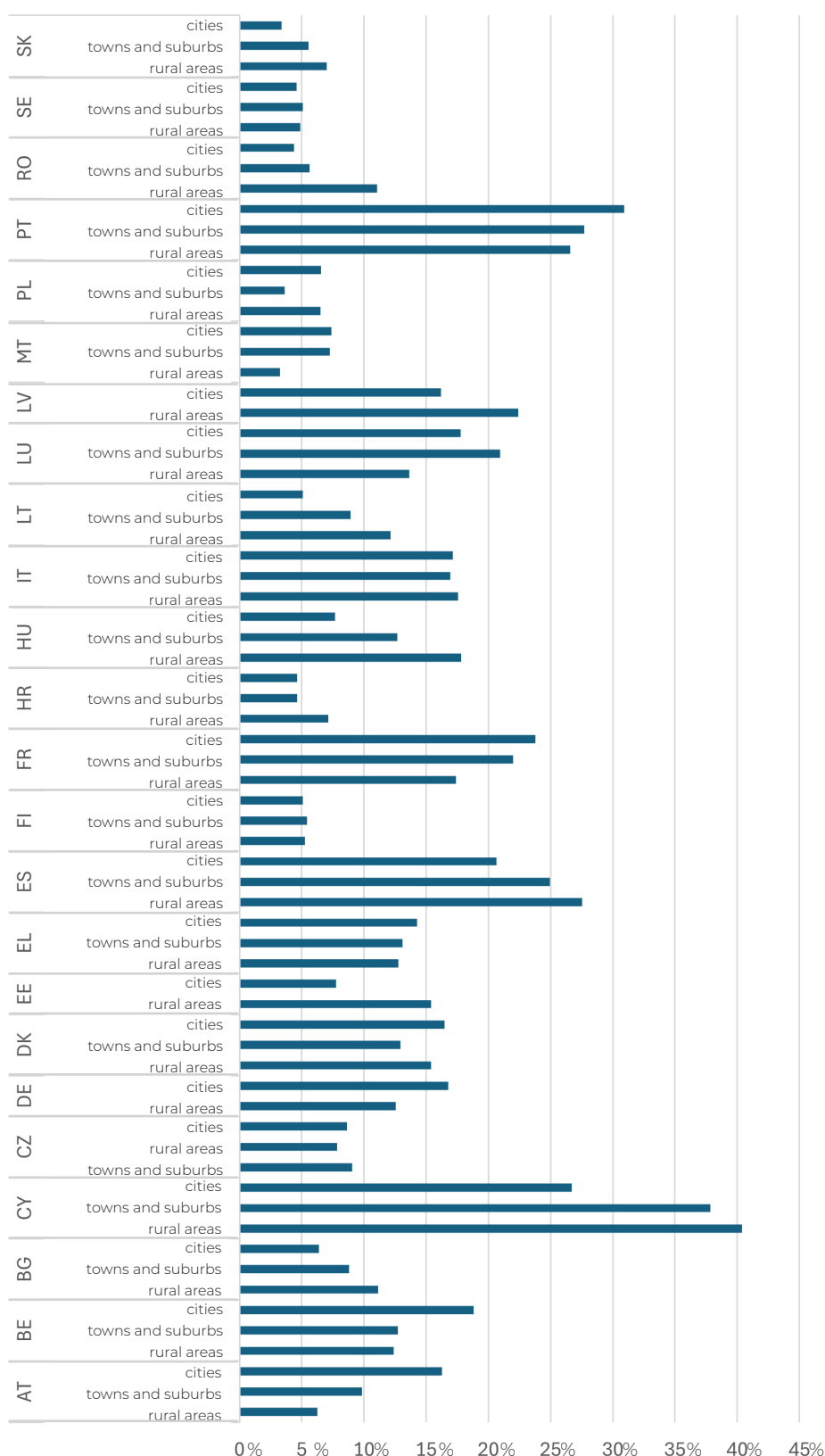
5. Improving Energy Efficiency

The EU has adopted an energy-efficiency first principle (EU 2021/1749) which prioritizes reducing energy consumption before investing in renewable energy supply (EC, 2021). Reducing energy demand through efficiency measures is also expected to put less pressure on infrastructure upgrades that are needed to switch to renewable sources of journey. Improving energy efficiency standards for buildings has been a priority in the EU since the 1970s oil crisis. Since 1990, it has generally increased in the EU. Households have seen the largest improvement of 31% or 1.6% each year (Odyssee-Mure, 2025). From 2018 to 2023, 29.4% of rural residents reported living in a dwelling with improved energy efficiency, compared with 25.4% in towns and 22.9% in cities (Eurostat, 2024). Typical energy renovation measures range from passive interventions such as replacing windows to active interventions like installing ventilation systems with heat recovery. ADEME, the French agency for energy transition, has summarized what the ideal order to carry out significant renovation works would be. They recommend starting with envelope insulation, followed by windows and doors, ventilation and finally the upgrade or replacement of heating and cooling systems (ADEME, 2021).

5.1 Passive Measures

Measures which improve the energy efficiency of the building envelope without the use of mechanical systems are referred to as passive measures. Insulating the building envelope, improving its airtightness and improving the u-value of windows are some of the main ways to improve the energy efficiency of the envelope. Across the EU, varying number of people live in a dwelling in need of measures to improve the building envelope. (see Fig. 3).

Insulating with (circular) bio-based materials is an increasingly popular strategy to mitigate the material emissions



Need for renovations

Among the EU27, the proportion of households affected by deficient building envelopes varies by degree of urbanization.

Countries with higher needs in rural areas

In Slovakia, Romania, Malta, Latvia, Lithuania, Italy, Hungary, Croatia, Spain, Estonia, Czechia, Bulgaria and Cyprus the problem is more significant in rural areas.

Countries with higher needs in urban areas

Meanwhile, in Portugal, France, Greece, Denmark, Germany, Belgium, and Austria the issue is more prevalent in cities.

Countries with higher needs in urban areas

Issues with the building envelope are only more prevalent in towns and suburbs for a few countries (Luxembourg, Sweden, and Finland).

Figure 3 The presence of damp, mold, leak. *Data for UK, Slovenia, Netherlands, towns and suburbs in Latvia, towns and suburbs in Estonia, Denmark, towns and suburbs in Germany, missing. Reference year: 2023. Source: EU-SILC



from conventional mineral-based. Conventional insulation materials such as glass wool, stone wool, expanded polystyrene (EPS), extruded polystyrene (XPS), and rock wool have a high global warming potential. Therefore, bio-based insulation materials are gaining traction as alternatives with a lower environmental impact (Zerari et al., 2024). Insulation made from hemp, flax, wood fibre, sheep's wool, and straw bales are some examples of bio-based alternatives. Although mineral-based insulation still dominates, sales of bio-based materials are expected to grow in Europe to more than €2.3 billion by 2032 especially as the poor fire-retardant qualities of mineral insulation is increasingly recognized (BPIE, 2025). Waste-derived bio-based materials from construction and industrial sources reduce the risk of dependence on unsustainably managed sources, thus improving the overall life-cycle impacts of renovations (Cintura et al., 2021).

Beyond the choice of insulation material, its placement within a building's facade is critical to avoiding unintended consequences such as mold growth, increased indoor pollutant levels, and overheating especially under a changing climate. Internal insulation is usually only preferred where buildings have facades with heritage status (Pagoni et al., 2023). However, it risks the growth of mold due to condensation that can occur within external walls, floors and roofs when warm, moist air passes through from the inside of the building and condenses at colder parts within it, particularly when there is a deficient vapour barrier or insulated attics (Hagentoft & Kalagasidis, 2016).

Without the provision of adequate ventilation, increased air tightness can also result in higher levels of indoor pollutants such as radon. Similarly, in certain circumstances thermal insulation has the potential to result in increased overheating (Collins & Dempsey, 2019). Internal insulation poses a higher risk of overheating as average summer temperatures and



heatwaves increase. For instance, Hungarian participants in the EU project, WELLBASED cited overheating as “the main problem” as they lived in apartments that had been externally insulated without consideration summer overheating risks a few years prior to the project. Adequate ventilation mechanisms are therefore required to remove both the moisture content of the air, pollutants and address increased cooling demands (Willand et al., 2015; Zukowska et al., 2021)

5.2 Active Measures

A changing climate and increasing energy efficiency are driving a shift to mechanical ventilation. Improving energy efficiency through the upgrade of technical systems (without necessarily switching to a renewable source) is a less common practice but used in colder climates where mechanical ventilation is more prevalent and more domestic hot water is required. However, as requirements for tightly insulated building envelopes increase, natural ventilation methods through window openings for instance do not provide sufficient fresh air to remove odor or contaminants and ensure good indoor air quality (Ferdyn-Grygierek & Grygierek, 2024; Zukowska et al., 2021). As more frequent heatwaves occur, the necessity for mechanical cooling is also growing. Therefore, mechanical systems even in countries that traditionally use natural ventilation in residential buildings are increasingly needed.

5.2.1 Mechanical Ventilation

Despite higher efficiency potential, cost, maintenance, and governance constraints shape the choice of system. The different types of mechanical ventilation typically installed in European housing are extract air ventilators in humid rooms and exhaust-only systems. Even though innovations such as phase change materials and mechanical ventilation with

Article 13(11)

This articles requires that, where technically, economically and functionally feasible, new and undergoing major renovation residential buildings are equipped as of 2026 with the following:
a) *the functionality of continuous electronic monitoring that measures systems' efficiency and informs building owners or managers in the case of a significant variation and when system servicing is necessary.*



heat recovery capabilities, that use 70 to 90% of exhaust heat are more efficient, they require strong financial incentives or obligations to be adopted (Zukowska et al., 2021).

Mechanical ventilation poses health risks if poorly designed or maintained, especially for vulnerable households. Substandard ventilation can cause extra health problems for vulnerable households. For instance, an improperly maintained filter or a filter with non-certified materials can cause infectious diseases (Giama, 2021). Therefore, the impact ventilation systems have on the indoor air quality is a crucial aspect of implementing this renovation measure alongside improving energy efficiency. Indoor air quality is primarily maintained by providing minimum levels of fresh air supplied from outdoors. Ventilation systems interact with climate change and can worsen overheating if not designed holistically. As the concentration of CO₂ in the atmosphere increases, more ventilation will be required to maintain an acceptable level of indoor CO₂ concentration (Adisorn & Vondung, 2019) (Dimchev et al., 2025). Overheating is another potential consequence of installing mechanical ventilation systems, especially when coupled with thermal insulation or improved airtightness. The building regulations in some countries such as the UK do not cover installation of summer bypass mode for mechanical ventilation with heat recovery which can lead to overheating.

Operational complexity and unclear responsibilities undermine real-world performance. Mechanical systems require more space and duct routing, which can be especially challenging in smaller housing units or dwellings. Similarly, decentralized systems where mechanical ventilation units with heat recovery are installed inside apartments can be difficult to access for regular maintenance. Running costs can also increase due to greater electricity consumption (Zukowska et al., 2021).



There is often a lack of clear instructions about system operation and maintenance requirements (e.g., MVHR filter replacement), in user manuals and during building handover. Follow-up service contracts and clear briefings to occupants about maintenance are therefore recommended to address these issues. One user-centred approach would be to incorporate the concept of Soft Landings which is a process that includes aftercare and regular system review at the early stages of post-occupancy (Behar, 2013).

However, the anticipation of respective risks and possible conflicts with tenants in turn may prevent landlords from investing in user sensitive technology. There may be less social acceptance of mechanical ventilation systems especially from occupants who need frequent cold air streams to perceive the indoor air as “fresh”. For landlords with high tenant turnover rates, providing adequate technical and behavioural instruction of new tenants can be particularly challenging. They may therefore prefer low-tech solutions such as window rebate valves/ventilators (in combination with or without exhaust systems), installing tilting locks or replacing window gaskets since these measures are cheaper, require less servicing and do not involve elaborate training for new tenants who move into dwellings.

Lower-cost alternatives may deliver acceptable outcomes when trade-offs are explicitly considered. A low-cost automatic window system, even without direct airflow control, can offer a feasible, energy-efficient alternative to mechanical systems in residential buildings, provided heating demand is also considered (Sarna & Ferdyn-Grygierek, 2025). Natural ventilation also remains effective in addressing certain needs such as cooling (Heracleous & Michael, 2018) and in reducing the spread of particulate matter from burning candles and cooking.



Therefore, the usage of natural ventilation in an adaptive approach (in which users have a broader and more dynamic comfort line depending on the outdoor temperature) would help reduce energy poverty risk in social dwellings (Levie et al.).

Governance frameworks must explicitly allow and manage trade-offs, not just promote technologies so that adaptive approaches can be adopted. Such policies enable a coordinated approach to energy efficiency and indoor air quality. Encouraging control mechanisms that ensure good implementation and operation is another key strategy to ensuring good indoor air quality standards. While subsidies for specific systems can increase their uptake, they need to be accompanied by outreach programs that educate occupants.

5.2.2 Domestic Hot Water Systems

DHW is emerging as a non-negligible energy end-use due to efficiency gains elsewhere. The share of domestic hot water (DHW) use in the total energy consumption of a building has historically been insignificant in comparison to space heating, ventilation or lighting and has therefore not been the focus of energy efficiency measures. However, as the efficiency of other end uses improve, more attention is needed for DHW. DHW systems can be either centralized (distributed to several apartments) or decentralized (heat exchanger or storage for individual apartments).

Proven DHW technologies exist, but uptake is uneven and often limited despite maturity. In countries like the UK, and the Netherlands, there is more activity in this field. In Cyprus, solar thermal collectors account for 82% of DHW systems. Waste water heat recovery systems are a particularly efficient method of heating water and have already recovered 300 GWh corresponding to the annual domestic hot water consumption of 17,000 households in the EU. Since the 1980s centralized systems in Germany, Switzerland and in the Scandinavian



countries make use of the heat in waste water, either in the sewage system or in the effluent of sewage treatment plants. Europe has the greatest technological lead in the world on this subject, with 326 patent applications since 2010, which is 70 percent of all patent applications in the world. However, this not the dominant water heating system.

Decentralized DHW systems offer efficiency advantages but face adoption barriers. Circulation losses are the primary inefficiency in many DHW systems. The three areas that DHW systems face energy losses are in end use, circulation, and storage with circulation losses being the dominant one. Therefore, there is growing research on decentralized/ localized systems without circulation for DHW production (Pomianowski et al., 2020). However, decentralized systems are not used as widely (REHVA, 2020).

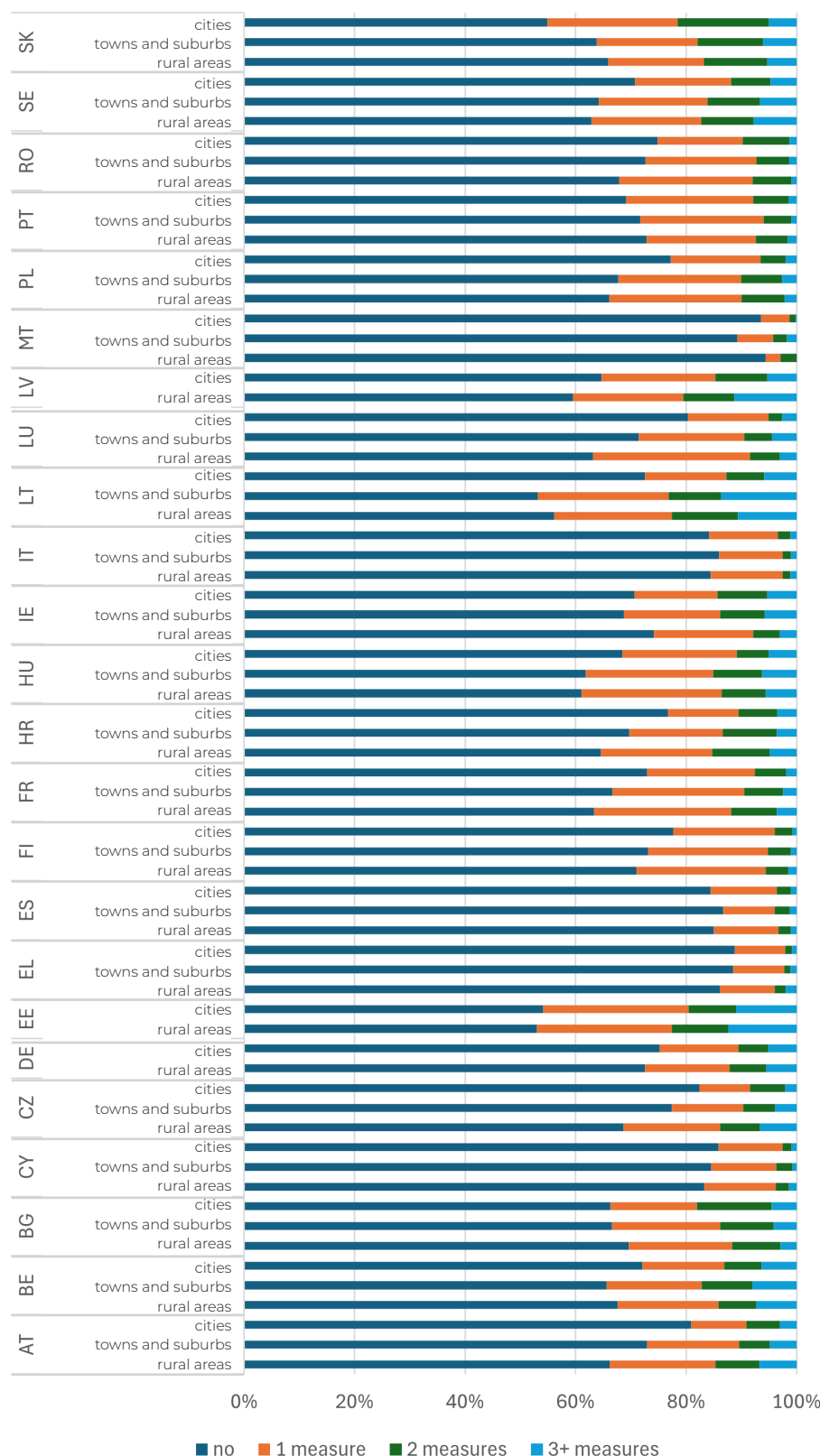
Decentralized systems are the most effective in improving energy efficiency in multi-family buildings. In multi-family houses, circulation loss would be responsible for 30–75% of the total DHW energy use, compared to up to 60% in single-family. Operation and investment in localized heaters at draw-off point should be considered in DHW installations where energy related costs to circulation and centralized DHW production are higher than operation of localized heaters (these are most often electric or gas). Cost efficiency increases for high wastewater volume flows and good insulation of piping (Pomianowski et al., 2020).

Meanwhile, DHW systems with heat recovery are more durable and offer maintenance free operation. Small local heat recovery systems from wastewater are more economically advantageous than a middle-scale district heating system, especially in colder climates, where they show a 2 to 2.6 times higher heat recovery capacity. Hence, under the right conditions, localized DHW and heat-recovery systems are

Renovation Wave

The Renovation Wave

aims for the doubling of the annual weighted energy-efficient renovation rate from the current EU level (with small national variations) of 1% to at least 2% by 2030. The average (or weighted) renovation rate describes the annual reduction of primary energy consumption achieved through the sum of energy renovations of all depths for the total building stock. As of 2016, only 0.2% of the residential floor area is renovated with an energy saving of more than 60% (ref). The BPfE estimates that this needs to increase to 3%.



Number of Energy Renovation Measures in the EU

Although rural renovations are considered harder to upscale, a higher number of renovation measures were undertaken in rural areas and towns in many countries. This indicates that rural home owners may have a higher capacity to renovate than perceived.

The EU-SILC survey does not, however, investigate how effective the implemented measures were in improving energy efficiency. Since there is a general lack of access to specialist services because due to a lack of expertise across the value chain on executing major energy renovations (McCabe et al., 2018). It is unclear how successfully the renovation works were executed.

Figure 4 Number of energy renovation measures from 2018-2023 by degree of urbanization. *Data for UK, Slovenia, Netherlands, towns and suburbs in Latvia, towns and suburbs in Estonia, Denmark, towns and suburbs in Germany, missing. Source: EU-SILC



economically and operationally advantageous (Pomianowski et al., 2020).

However, DHW efficiency gains must be embedded within broader, sequenced renovation strategies. While individual renovation measures such as insulating the envelope or installing a more efficient DHW system help to reduce certain aspects of energy consumption in buildings, a deep renovation rate of 3% is necessary to reach building decarbonization by 2050 (BPIE, 2021).

5.3 Deep Renovations

Deep renovation involves multiple measures which fully utilise a building's potential for energy efficiency improvement. It prevents lock-in effects from piecemeal measures such as window replacement which hinder subsequent investment in energy efficiency improvements by the building owner.

Aligning efficiency measures with the deployment of renewable heating technologies enables optimal solutions in terms of cost-effectiveness, reduced CO₂ emissions, low environmental impacts and energy security (BPIE, 2021). Conversely, renovation measures which only include renewable energy systems risk locking the building into higher energy consumption than is required if passive measures are not also implemented. For instance, heat pumps installed before envelope insulation is added could be over-dimensioned.

Deep renovations are complex undertakings which require large upfront payment and rigorous planning informed by expert knowledge. Despite the availability of several EU funding streams, there is still a lack of sufficient funding to scale renovations to reach targets (Bertoldi et al., 2021). Public funding schemes that are paid for post renovation exclude the poorest households who have debts or insufficient savings to pay the upfront costs. These groups are also not attractive candidates



for other loans. This is why public funding needs to be earmarked for the most vulnerable instead of being dispensed on a first come first serve basis. Intermediary organizations that provide the upfront costs on behalf of vulnerable households can get repaid when government funding has been dispensed. This type of revolving fund could be a way of resolving the issue of high upfront costs.

In rental housing, where tenants have primarily symbolic influence, large scale, rent increases can occur after major renovations, leading to eviction. This contributes to an increase in tenure inequality (FEANSTA. 2022). The disruption caused by major renovations can also cause displacement (Femenias et al. 2024). Fair rent negotiation processes and appropriate relocation plans could mitigate these issues .

FEANTSA also found a direct causal link between energy savings investments and increases in property prices. Expected increase in sale prices of properties after retrofitting ranges from at least 2% to 7%, making it unavailable for lower-income households (FEANSTA. 2022). In the rental housing, where tenants have primarily symbolic influence, large scale, rent-raising renovations usually ensue, causing “renoviction”, tenant evictions or indirect displacements (Pull, 2020).

Landsbyggefonden (LBF)

The Danish national revolving fund for uses payment from tenants' rents and savings from housing organisations to finance renovations in the non-profit housing sector.



6. Installing Renewable Energy Systems

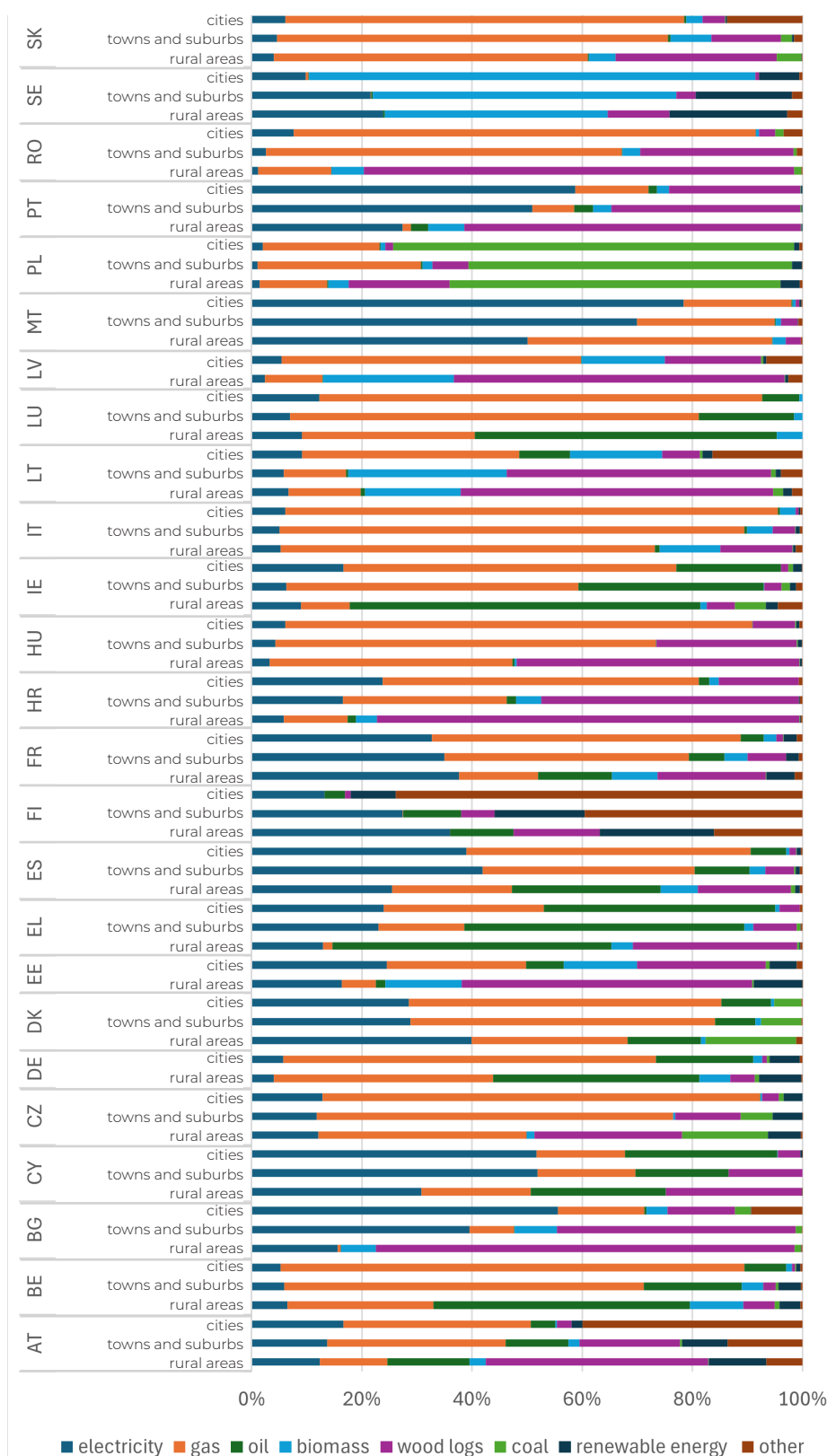
Decarbonizing household energy consumption by switching to renewable energy sources is an important step in meeting carbon emission reduction targets agreed by the EU (EC, 2020). Commonly installed renewable energy systems include solar energy systems, heat pumps, and biomass boilers which rely on electricity to function. The electrification of final energy consumption is therefore recommended (EEA, 2023). More than half of households in Malta, in Bulgarian cities, and in both towns and cities in Portugal and Cyprus used electricity as their main energy source in 2023 (see Fig. 6). However, as electrification efforts continue, the increase in electricity demand should be powered by renewable sources to avoid carbon leakage from the building sector to the electricity production sector.

The electrification that is required in the switch to renewable energy systems in turn necessitates improvements in grid capacity which is more challenging to implement in rural areas. As is the case when adopting most new technologies, installation of renewable energy systems in dwellings across the EU faces significant barriers including. (Jagarajan et al., 2017) state that the perceived risk or novelty factor around renovation measures like the installation of new renewable technology is a barrier to investments. It is costly to dimension systems that are entirely renewable energy-based. Moreover, overproduction in the sunny months would impose dimensioning of exceptionally large and not feasible storage solutions. The ratio between renewable and conventional energy production is usually a compromise between energy efficiency and investment cost. (Pomianowski et al., 2020). In Hungary for instance, the price disparity for buying versus selling energy further discourages decentralized production (ComActivate, 2024).

A significant number of households in Portugal, Spain, Malta, and to a lesser extent households in France and Italy do not

Emissions Trading Scheme (ETS) II

This new system will cover and address the CO₂ emissions from fuel combustion in buildings but the responsibility report emissions will be on energy providers.



Main Energy Source in Households (Fig. 4)

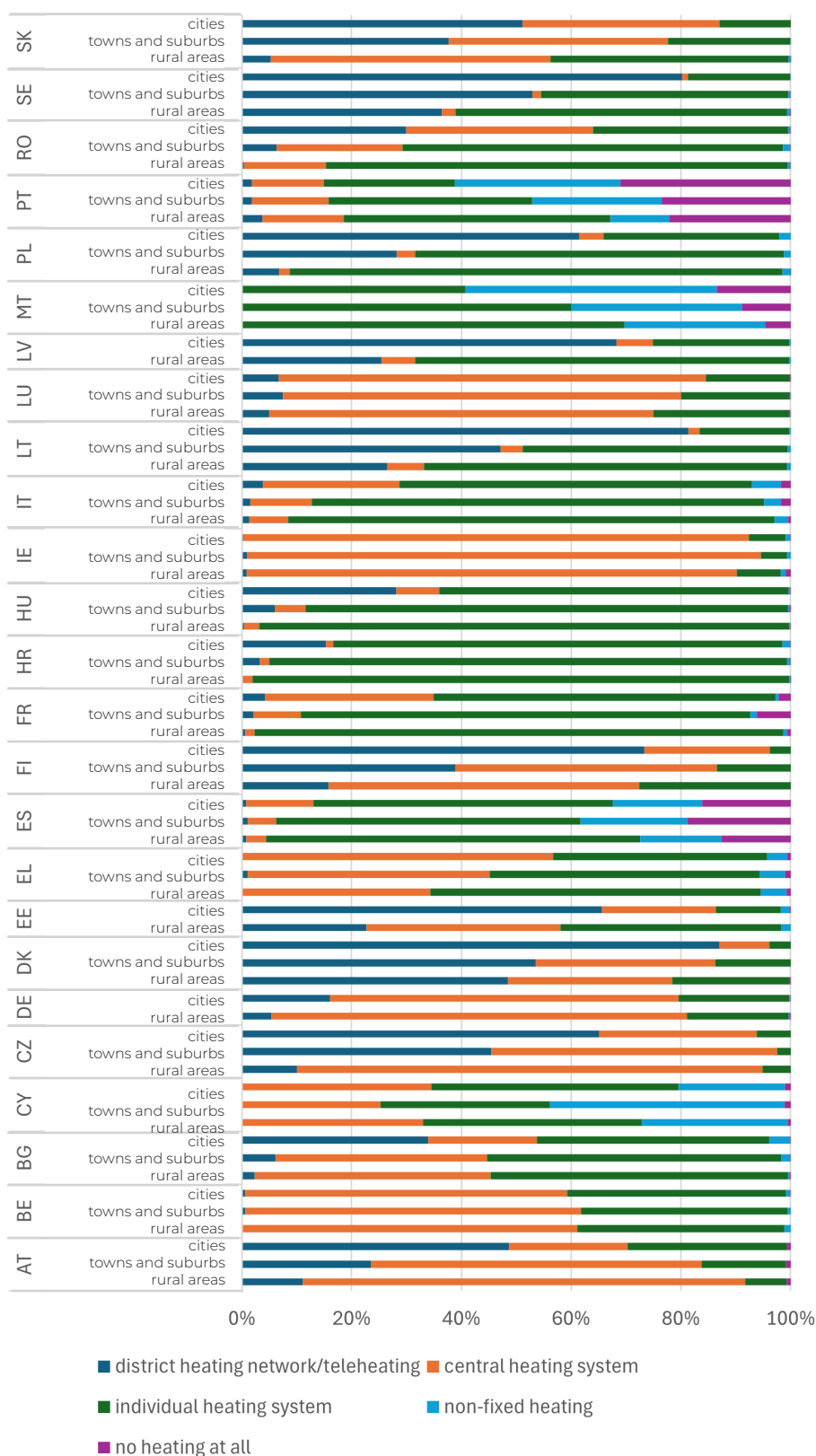
Gas is the predominant energy source in EU households. Wood logs account for a significant portion of many rural areas. In Poland, coal is still a widely used energy source across all areas. To a lesser extent, this is also the case for rural areas in Czechia and Denmark.

Figure 5 Main Energy Source by Degree of Urbanization. *Data for UK, Slovenia, Netherlands, towns and suburbs in Latvia, towns and suburbs in Estonia, towns and suburbs in Germany, missing. Reference year: 2023. Source: EU-SILC



have a heating system at all. Although these countries are in Southern Europe or have regions in Southern Europe with a warmer climate, heating systems may still be required for some of them; especially if they are not insulated well.

As with passive measures, renewable energy systems are often more effective when combined. The best available energy solution, focusing on technical and environmental criteria, is the combination of biomass and solar thermal systems for covering the heating processes in residential buildings. More specifically, the combined biomass–solar system has a lower overall environmental impact, due to the reduction in gaseous pollutant emissions, as well as the reduction in the amount of used fuel (Giama et al., 2023). Similarly, heat pumps integrated with PV have the highest potential for minimizing CO₂ emissions for a Danish household (Esmat et al., 2023).



Main Heating System in Households (Fig. 5)

Most households in the EU have some form of heating system. However, Estonia, Portugal, and Malta have a notable number of households across all areas who do not have any system installed at all. For the households who do have a system installed, central heating systems shared by a whole building and individual heating systems are common.

Figure 6 Main Heating System by Degree of Urbanization. *Data for UK, Slovenia, Netherlands, towns and suburbs in Latvia, Estonia, Germany, and Greece is missing. Reference year: 2023. Source: EU-SILC



6.1 Heat Pumps

Heat pumps are a central decarbonization technology for residential buildings. Heat pumps efficiently heat or cool buildings by harnessing heat from outdoor air or the ground. The installation of heat pumps is a commonly recommended method to replace fossil fuels with renewable energy sources to cover domestic hot water, heating, and cooling demands. A report from the European Climate Foundation (ECF) indicates that the installation of 60 million heat pumps across the EU by 2030 could facilitate a 40% decrease in gas consumption for buildings relative to 2022 levels, alongside reductions of 46% in carbon dioxide emissions and 40% in nitrogen emissions, respectively (ECF, 2023).

Similar to other more efficient or low-carbon technologies, technical potential for heat pump deployment is high, but uptake is slowing. Less than 5% of Belgian households were equipped with a heat pump in 2022 (Czock et al., 2025; Rosenow et al., 2022) and these are typically installed in homes with above-average insulation. Italy and Germany have the highest number of gas boilers in dwellings, followed by France, Spain, and the Netherlands. Together, these countries make up nearly 75% of the total 68 million gas boilers. As a result, Germany has the potential to achieve the greatest reduction in gas and oil usage, with a potential saving of 125 TWh. France follows with 50 TWh, Italy with 48 TWh, Spain with 22 TWh, and the Netherlands with 18 TWh. Around 41% of all EU dwellings currently heated by gas boilers are properly insulated allowing highly efficient functioning if heat pumps are installed in these buildings (Toleikyte et al., 2023).

Physical and regulatory constraints influence where heat pumps can be deployed successfully. The ability to accommodate a new heat pump system within the building's design, planning regulations in the area and especially the affordability of electricity prices to operate it are important

RePowerEU Plan

EU aims to install an additional 60 million heat pumps by 2030 as part of the RePowerEU Plan. There is a heat pump action plan

Danish Heat Pump Leasing Program

Denmark is rolling out "heat as service" programs to tackle the high upfront costs of installing heat pumps.



aspects of successfully installing heat pumps.

Operating costs and energy price strategies are a critical determinant of adoption and equity outcomes. The price ratio between electricity and gas is another persistent challenge. The ratio plays a crucial role in determining the competitiveness of heat pump operating costs. When the price ratio exceeds the seasonal performance factor of heat pumps, the fuel costs of heat pumps become higher than for gas boilers. A heat pump remains cost-effective as long as the price of electricity does not exceed three times the gas or oil price. In 2021, 19 Member States had an electricity to gas ratio exceeding three, whereas only six Member States had a ratio of three during the first half of 2023. However, the more favourable ratios during 2023 are primarily due to the high gas prices, which also means the energy prices have increased overall, worsening the situation for the energy poor. Achieving a favourable and stable electricity to gas ratio would allow heat pumps to maintain their efficiency advantage and ensure their economic viability compared to fossil-fuelled heating systems.

Current policy instruments inadequately address upfront cost barriers. The EU is currently planning to implement a new EU Emissions Trading System (ETS) that is expected to lead to an increase in the cost of operating fossil-based heating by including fuel combustion in buildings in the scope of the ETS. However, this does not address the large upfront costs involved in purchasing and installing heat pumps. The European Heat Pump Association is, therefore, advocating for 0% VAT on heat pumps and including heat pumps within ESG investment rules. Another mechanism to tackle upfront costs is to launch heat pump leasing programs which function as ongoing subscriptions rather than a single purchase. Maintenance and repair are also included in the contracts.

Decarbonization policies risk regressive impacts if equity and



system constraints are not considered. The International Energy Agency calls for implementing policies, such as banning the sale of gas boilers starting in 2025, to accelerate the adoption of this type of equipment (IEA, 2021). While a ban on fossil-based systems may be effective, it may be a burden for the over 16.8 million people who use LPG for heating (AEGPL, ND). Bottled gas is also seen as more reliable since it is not entirely dependent on the electrical grid and can be used during power outages. Czock et al. found that multifamily homes with single-story gas heating may face CO₂ costs up to 8,000 EUR per residential unit due to limited decarbonization options. Policymakers should consider these dynamics when prioritizing buildings for district heating or hydrogen in municipal heat planning or designing CO₂ price revenue recycling mechanisms (Czock et al., 2025).

Heat pumps also involve environmental trade-offs that require regulatory oversight. Although heat pumps emit less greenhouse gases than fossil-based systems, the industry norm is still to rely on fluorinated refrigerants, (i.e., F-gases) that are in most cases safer than other refrigerants, but which have very high global warming potential. In response, F-gas Regulation (EU) 2024/573, which came into effect in March 2024, requires the replacement of F-gases with low-global warming potential alternatives.

6.2 Biomass Boilers

Another alternative to fossil-based heating systems is biomass-based technologies. Biomass can contribute to decarbonization, but performance depends heavily on fuel type, sourcing, and emissions control. When designed and sourced efficiently and sustainably, they can play a significant role in decarbonizing the residential heating. Among the biomass fuels used in residential applications, the most common are wood logs, pellets (and briquettes), wood chips, straw, husks,



and shells. Unlike pellet boilers, which rely on standardized, densified fuel, wood chip boilers use locally sourced, less-processed biomass, often originating from forestry residues, thinning operations, or sawmill by-products. Efficiency typically ranges between 85% and 94%, but emissions remain highly dependent on fuel properties and operational settings. Therefore, emissions control remains a central challenge in adopting biomass boilers (Katerla & Sornek, 2025).

The use of biomass is a socially and culturally embedded energy practice. It is influenced by cultural traditions, accessibility, and economic factors. In rural regions, using firewood for space, water heating, and cooking is engrained in various cultures (see Chapter 8). Many families have free access to this resource due to their residence in rural areas where it can be easily sourced from their property, adjacent lands, or communal forests. Therefore, solid biomass is still an important energy source for many households across the EU.

Cleaner fuels like pellets involve affordability and price-stability trade-offs. Pellets are usually certified for quality, are more efficient in burning, emit less pollution, and therefore are less problematic. Ideally, they should also possess certifications verifying sustainable sourcing. While they are easy to manage and supply, pellets are pricier. They are more susceptible to fluctuations in the European market when compared to firewood, leading to increased expenses. Wood chips on the other hand, are significantly cheaper than pellets and more accessible, as they can be produced independently but emit more pollutants than pellets. They release gaseous pollutants and particulate matter into the atmosphere such as carbon monoxide and methane (Katerla & Sornek, 2025). Therefore, even modern biomass systems pose air quality risks that must be managed.

Biomass involves life-cycle and temporal carbon trade-



offs that complicate claims of carbon neutrality. For instance, if wood residues are not used for heating, the carbon they emitted may have been stored for a much longer time in standing forests. Thus, the use of woody biomass can only be truly considered carbon neutral if the burnt wood is rapidly replaced in its carbon storage function by newly planted biomass. The relatively shorter carbon life cycles of annual crops, for instance, could be preferable to wood residues from a life-cycle point of view since wood is part of a slower forest rotation and biomass decay (IEA 2017). This introduces a time element that is not always taken into consideration when assessing carbon savings benefits of bio-based solid fuels. Although solid biomass used in heat production is generally free from the indirect land use change caused by the displacement into the fuel market of biomass stock originally intended for food and feed use, farmers could receive an incentive to expand crops beyond necessary, ending up in unnecessary change of land use (Woltjer et al., 2017).

Fuel innovation and blending can reduce emissions without sacrificing performance. Technology improvements and efficient and integrated resource management would help mitigate the negative consequences of biomass boilers. Rabbat et al. found that pelletized biomass-based insulation materials mixed with certified wood could be considered an attractive alternative fuel for residential biomass boilers (Rabbat et al., 2023).

Another possible strategy to reduce pollution, would be to use biomass in district heating instead of individual systems to avoid losses and to optimise combustion. Large district heating boilers are also suitable for the combined production of heat and power. More importantly, plants can be built to allow fuel flexibility and co-burning of different types of fuels which would avoid a fuel lock-ins when cleaner options are available.



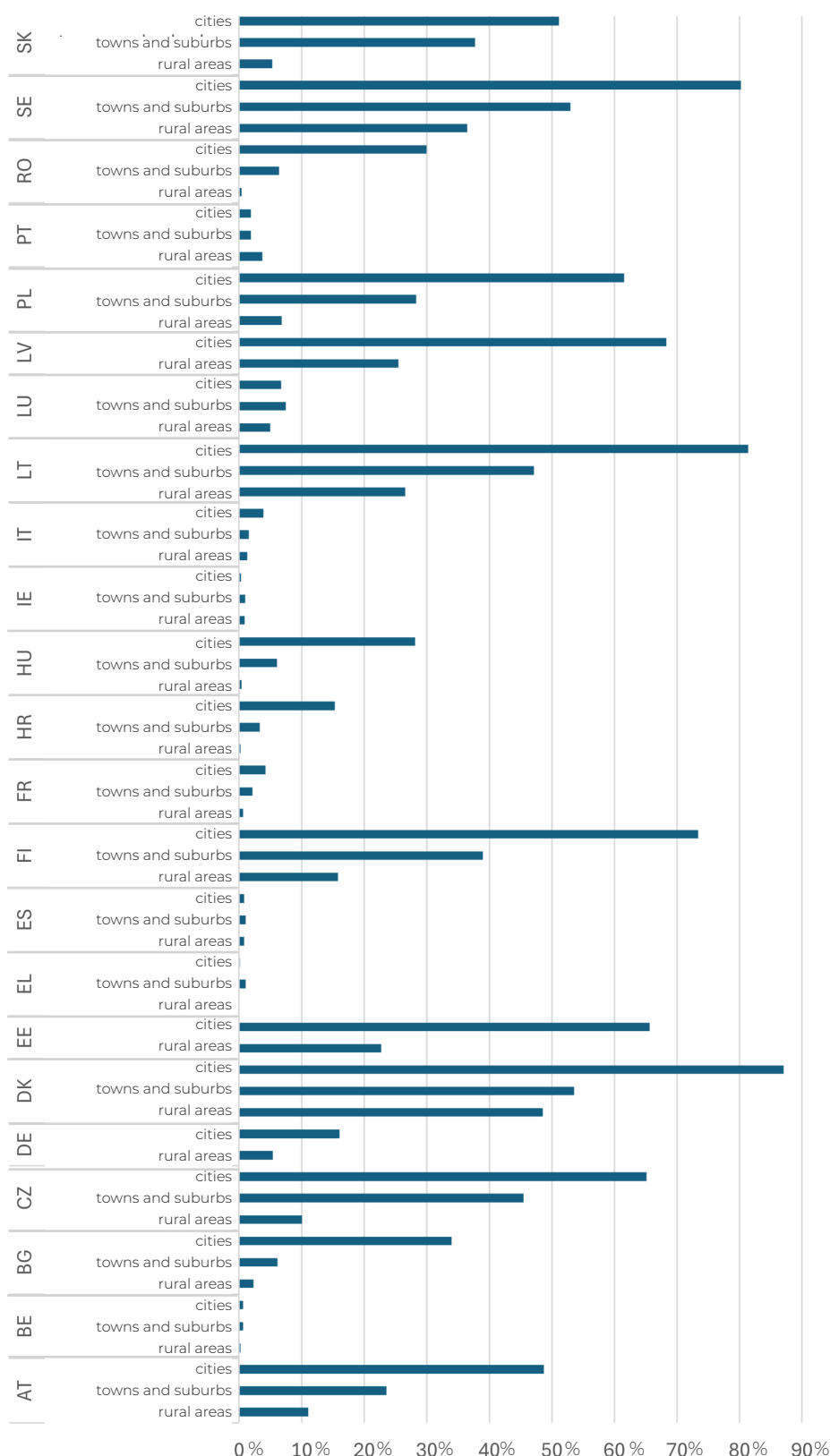
While biomass-based heating systems can contribute to residential decarbonization, their environmental, social, and economic impacts depend critically on feedstock choice, combustion scale, and governance frameworks.

6.3 Solar Panels

Residential solar is a more mature technology contributing to EU decarbonization strategies. Solar panels are a popular source of renewable energy in residential dwellings. By 2030, the EU aims for 600 GW of solar capacity, aligning with climate and energy security goals. However, according to SolarPower Europe, the EU association for solar power, residential solar installations have declined in 19 countries in 2025 (SolarPower Europe, 2025).

Solar deployment is increasingly uneven and shifting away from the residential sector. Solar Power Europe attributes the decline in sales to the phase-out of rooftop support schemes in several mature markets and the saturation of early-adopter households, while policy and electricity market settings in many countries remain insufficient to activate the broader mass-market segment. The exception to this trend is seen in the uptake of plug-in solar devices in Germany. Germany, Spain, and Italy dominate the EU solar market, contributing over 50% of total capacity. France, the Netherlands, and Poland are rapidly expanding, with grid and permitting reforms unlocking new capacity. Smaller nations like the Baltic states and Ireland are adopting community solar and storage for stability. It is also observed that uptake of solar technologies have shifted towards utility-level applications like solar farms.

Electricity market design and support schemes critically shape residential solar viability. The delayed liberalisation of the electricity market for residential consumers and the lack of net metering or other support measures for small-scale installations



District Heating as Main Energy System (Fig. 7)

District heating is most prevalent in urban areas since it is most efficient in dense settings. It is the main energy source in more than half of urban households in Slovakia, Sweden, Poland, Estonia, Denmark, Czechia, Finland, Latvia and Lithuania. On the other end of the spectrum, it is the main energy system in a negligible number of households in Belgium, Greece, Spain, Ireland, and Italy.

Figure 7 Households using district heating as main energy system.. *Data for Cyprus, Malta, UK, Slovenia, Netherlands, towns and suburbs in Latvia, towns and suburbs in Estonia, towns and suburbs in Germany, missing. Reference year: 2023. Source: EU-SILC



limit the market to self-consumption systems. The negative effects of the shift away from net metering to net billing can be seen in countries like Hungary, Netherlands and Greece. Similarly, the end of favourable legislation like the VAT waiver for private individuals in Austria installing PV systems up to 35 kW and PV subsidy programmes hinders more widespread adoption on solar panels in the residential sector. Double charges of electricity tariffs with double taxation of battery energy storage systems' charge/discharge and import/export connection charges are key still topics to be addressed.

Technical and regulatory system readiness determines the scalability of residential solar. The development of batteries for electricity storage, improvement of grid capacity and flexibility (see Chapter 10) are highlighted as crucial steps to provide affordable solar energy in Europe. Deregulation of the electricity market for residential consumers is seen as an important precondition as well (SolarPower Europe, 2023).

Aligning photovoltaic generation with real consumption patterns is essential for system efficiency. The overall strategy of load matching of photovoltaic electricity production and a building's energy consumption has been identified as an important strategy to maximise self-consumption, reduce reliance on the grid, and by extension, the risk of overloading the grid (Gergely et al., 2025). Research on load matching has shown in residential buildings, consumption patterns of households both over a day and over seasons are highly influential. (Fuster-Palop et al., 2023). Changing daily usage patterns or designing photovoltaic systems based on detailed usage patterns of households, especially at an aggregated at the energy community level are considered particularly effective (Gergely et al., 2025). For more on energy communities (see Chapter 11).

SMARTER TOGETHER

This project developed ICT tools for renovation and renewable energy consumption of urban residential areas.

ReDREAM

This project adopts a user-centric approach and co-creates platforms for renewable energy consumption and production.



6.4 District Heating and Cooling

District heating and cooling (DHC) systems offer a flexible, system-level pathway for decarbonizing heat supply. They provide centrally generated energy via insulated pipes to warm or cool individual buildings. One of the main advantages of district heating is that it can use many types of fuels, meaning that fossil fuels can be phased out in favour of renewable fuels or by heat recovery from many kinds of sources. Fossil fuels dominate as energy source for district heating in the EU, while biomass provides 22 % of the energy.

DHC systems are evolving technologically, but legacy infrastructure and fuel mixes still shape outcomes. Therefore, DHC deployment is geographically uneven and highly context-dependent. Biomass provides over 40 % of the district heating energy in the Nordic and Baltic countries, while for some countries, the biomass share is almost negligible. High temperature combined heat and power plants exist across Europe (mainly fuelled by gas), often shifted to biomass (seen in countries like France, Spain, Germany and former eastern European states) when refurbishing district heating systems (Goggins et al., 2022; Vilén et al., 2024). District heating covers around 12 % of the total heat demand of EU. The share of district heating and cooling is uneven within the EU Member States, with Sweden, Denmark, Lithuania, Slovakia, and Estonia being those EU countries with a higher district heating and cooling stock, whilst Southern and Mediterranean ones have the lowest district heating and cooling ratio (Vilén et al., 2024). Spain is an exception to this trend as high growth rates of new environmentally friendly district heating systems are observed (Zimakov, 2025).

More modern district heating and cooling systems adopt the concept of fourth generation district heating which includes aspects such as closer interaction between producer and



consumer, lower district heating distribution temperatures, and increased integration of exhaust heat from industries and other actors supporting the decarbonization of heat supply (Vilén et al., 2024)

DHC is not universally optimal; building stock characteristics determine suitability. More modern systems are typical in Scandinavian countries and involve the development of high-tech district heating systems based on renewable energy sources. This may not be appropriate in Southern European countries where the high proportion of old buildings with low energy efficiency and high heat losses make investments in district heating unattractive. Instead, it is suggested that energy renovation of buildings, combined with upgrading individual boiler equipment would be a more appropriate strategy to decarbonize heat supply and combat energy poverty in Southern European countries (Zimakov, 2025).

Since more advanced models systems that use low-temperature exhaust heat require equipment used by the end customer suited for the specific distribution temperature used, simply reducing the temperature of existing district heating grids could come with issues. This is one reason the utilization of low temperature exhaust heat is less common even though a decrease of district heating distribution temperatures has several benefits, such as decreasing the distribution losses, increasing the efficiency of heat pumps, allowing for new kinds of piping to be used for distribution as well as allowing for more efficient combined heat and power plants. Therefore, transitioning to low-temperature DHC involves technical coordination challenges across the whole system.

DHC pricing and billing structures can create inequities and weaken behavioural incentives. The inequality in district heating charges in apartment buildings is a concern raised in several studies. Rates that are charged according to built-



area of apartments do not incentivize reduction in energy consumption. They also do not consider the proportion of external walls an apartment is exposed to which makes indoor comfort conditions varied within a building. On the other hand, a study in London and Riga found that waste heat may reduce consumer energy bills, compared to replacing heating technologies, when energy poverty reduction is considered as an impact indicator. Although more research is needed to assess district heating and cooling schemes by conditions and structures, this collective infrastructure, with waste heat, could help alleviate energy poverty in urban areas (Lagoeiro et al., 2024).

DHC expansion depends heavily on public investment and coordinated planning. According to the European Association, which promotes sustainable district heating and cooling Euroheat & Power, public funding is key to fostering district heating and cooling networks across Europe. EU and state financing provide a valuable opportunity for stakeholders to access resources, boosting innovation and commissioning, especially in countries where systems are deteriorating in condition.



7. Renovation Support Services

7.1 Energy Audits & Coaching

Energy audits are a foundational tool for diagnosing and improving building energy performance. A systematic appraisal of a building's energy consumption is called an energy audit. It involves measuring or modelling energy consumption and identifying hot spots and potential areas for improvement in the energy performance of the building. Since energy audits are a time-consuming task, improving their quality and efficiency has been a focus of research and development initiatives.

Residential energy audits are driven by energy performance certification (EPC) requirements, especially when a building is rented or sold (Directive 2010/31/EU, p.11). However, these audits vary in the methods used. While some rely on operational ratings which assesses actual energy performance, others use asset valuations based on theoretical energy models (Ou et al., 2025). Therefore, the revised EPBD (EU/2024/1275) aims to improve comparability of EPCs across Member States, as well as making them more reliable and digitalized. The revision of the Directive in 2024 introduces a unified energy rating scale for all Member States, making it easier to compare buildings across borders (BUILD UP, 2025)

Energy coaching extends an audit's scope of technical diagnosis to include social intervention, providing tailored support for vulnerable households. Integrating health and social service support are more advisable since energy poverty is a multi-dimensional issue tied to general poverty, and demographic characteristics. These audits, which are also referred to as energy coaching, create the possibility to recommend targeted cost-effective measures which help the specific situation of vulnerable households and have a capacity building aspect which supports them in alleviating energy poverty in the long run (Van Der Wal et al., 2025). Energy coaching can have a higher impact on tenant-occupied homes

The European Committee for Standardization (CEN) (CEN)

The committee defines standards like BS EN 16247-1 for general energy audit requirements, providing a unified framework across the EU for these tiered approaches

Energy Coaching in the EU

*In **Austria**, the non-profit organisation, Caritas collaborates with the Austrian federal energy and climate fund to provide free energy advice and replacement of inefficient electrical appliances for vulnerable households*

*In **Amsterdam**, a recent study offering energy coaching services to houses in addition to smart devices monitoring their energy usage showed that interest in the devices was only sustained by visits from the energy coach, implying that households may need personalised support to improve their energy consumption habits.*



than on owner-occupied homes (Croon., 2024). It also becomes increasingly relevant as the population ages, especially in rural areas across the EU.

Post-renovation audits are underused but essential for learning, trust, and scale. Although it is more common to conduct energy audits before energy efficiency measures, audits conducted after renovations are more important to facilitate the scaling up of renovations. The research project, RENOVERTY found a lack of systematic monitoring and evaluation of implemented renovation measures (RENOVERTY, 2025). Accordingly, in other projects where inspections were carried out trust amongst local households in contractor services (Goggins et al., 2022). Audit-linked verification mechanisms strengthen accountability of renovation programs and increase their uptake.

7.2 One-stop-shops

One-stop-shops are particularly valuable for vulnerable households when embedded in local support ecosystems. The complexity of planning and executing deep energy renovations is known to be a barrier to households and one-stop-shops directly address this barrier by creating a single platform on which the investor is guided through the entire renovation process by certified professionals. They can range from basic awareness-raising models to ESCO type models whereby the service provider bears responsibility for energy savings. These platforms can be both online and in person. They are especially useful for vulnerable households who need customized engagement and support. One-stop-shops can also serve as a vital link to access financial support programs for vulnerable individuals.

However, process support alone is insufficient without reliable and accessible financing mechanisms. A survey conducted by EU Peers found that one-stop-shops in the EU rely heavily



on EU funds which poses a threat to this service being upscaled. Although they emphasize the importance of public involvement to ensure that these services remain accessible and neutral, they also found that private or hybrid models are more likely to specialise in deep renovations and offer more sustainable financing options.



8. Energy Flexibility

Demand-side flexibility is a key system-balancing mechanism in increasingly renewable and decentralized electricity systems. Buildings represent a major, underutilized source of future flexibility capacity. Flexibility of energy demand refers to the shift, reduction or increase in end-users' energy consumption in response to peaks in energy demand or supply. Electricity prices are adjusted dynamically to reflect these picks to encourage shifts in energy consumption (Han et al., 2024). It therefore helps to balance the supply and demand of electricity, enhances the efficiency of the power grid and reduces the likelihood of blackouts or significant reduction in voltage (Cabot & Villavicencio, 2024).

Estimates show that the EU's flexibility resources need to double between 2021 and 2030, reaching up to 362 TWh per year to keep up with the foreseen changes (EEA, 2023). SolarPower Europe estimates that by 2030, flexibility solutions from buildings have the potential to meet 52%, of daily, 35% of weekly, and 29% of annual flexibility needs (SolarPowerEurope, 2025). Devices that support demand flexibility include heat pumps, electric vehicles, and to a lesser extent, ventilation systems.

Flexibility in energy can be encouraged implicitly, through time-varying prices and tariffs or explicitly through direct compensation from third parties, such as aggregators or distribution system operators, for adjusting consumption to meet system or grid needs. The analysis of real-time smart meter data facilitates the strategic shifts in pricing (Han et al., 2024).

Flexibility delivers system-wide economic and environmental benefits beyond individual households. As the supply of renewable energy (which is more intermittent than fossil-fuel supply) increases, flexibility services help make energy supply more reliable. Moreover, as more decentralized production



is promoted, more small units of electricity production connect to distribution grids, making flows more variable and unpredictable. Rewarding flexibility is recognized as a key variable for the EU to meet its renewable energy target (Nicolai & Münchmeyer, 2025). Reduced system consumption also offers the added benefit of lower need for costly, carbon-intensive peak power plants and fuel imports, while also decreasing the demand for reserve power plants and transmission capacity (Fischer & Madani, 2017).

Behavioural and cognitive constraints significantly limit households' ability to provide flexibility through manual action. The complexity or volume of available information about incentives can be too overwhelming for households to process whereas simple heuristics for adjusting electricity consumption patterns result in sub-optimal gains (Hobman et al., 2016). This tendency is amplified when the incentives to shift electricity consumption trigger frequent and repeated adjustments, leading to what is referred to as response fatigue (Kim & Shcherbakova, 2011). Automatic controllers can be designed to react to price changes resolve this issue to address this issue (Mokhtari et al., 2025).

Price-based flexibility alone produces limited and uneven behavioural responses. Automation and feedback technologies are critical enablers of effective demand-side flexibility. The effect of dynamic pricing has been shown to have limited effect in several studies (Rigaux et al., 2024). The relatively low reactions may be partly explained by a lack of awareness about incentives among the households involved (Enrich et al., 2024). This suggests a need for technologies that make price incentives more effective, such as in-home displays which can lead to stronger household responses (Canale et al., 2021).

Since households differ widely in their capacity to provide flexibility, flexibility pricing schemes can redistribute costs



regressively if not carefully designed. In moving to time-of-use tariffs, the cost burden shifts from users with flatter usage or non-coincident peaks to those with high coincident peaks, so that higher-income users may have lower bills even if they use a lot of electricity because relatively more electricity is consumed off-peak, whereas lower-income users may have higher unit costs because, despite lower total demand, they use relatively more peak electricity when it is expensive (Cabot & Villavicencio, 2024).

Households decisions are driven by multiple factors, including sickness and times of increased occupancy such as parties, which all influence the time-dependent and context-specific acceptability of flexibility (Rigaux et al., 2024). Stute et al., (2024) showed in their study that households with both a heat pump and electric vehicle experience the most cost-benefits and emphasize the need for a sufficient difference between dynamic and fixed prices to make demand flexibility worthwhile. Another study from rural Scotland found that the elderly population differs from the majority since they have lower incomes and face the risk of fuel poverty. Accordingly, their willingness and capacity to change time-use behaviours and reduce consumption is comparatively not as high. Low-income users may also have limited flexibility in changing the timing of their electricity use if their residences are poorly insulated and are unable to retain reasonable temperatures when heating or cooling systems are shut down (Bednar et al., 2017). However, Rigaux et al. contend that less-well-insulated homes may benefit from flexibility if high-temperature heat pumps are deployed with short but higher-powered interventions.

The delayed and potentially insignificant financial gains from adjusting consumption can serve as a deterrent to shifting energy consumption patterns (Rigaux et al., 2024). (Cabot &

Electricity Market Regulation

Flexibility is defined by the Electricity Market Regulation as 'the ability of an electricity system to adjust to the variability of generation and consumption patterns and to grid availability, across relevant market timeframes'.

Article 32 of the Electricity Directive (EU) 2019/944

mandates Member States to set incentives for DSOs to procure flexibility services and improve efficiencies in the operation and development of the distribution system.

Recognising the importance of occupant energy behaviour, Lithuanian energy supply companies have been providing consultation and running information campaigns consumers since 2017, expecting energy savings of up to 10% of energy (ComActivate, 2025).



Villavicencio, 2024) recommend that tariff design should consider periods of low renewables output and any prolonged period of high prices when designing tariffs. With the expected increase in carbon price, the costly natural gas used in peaking units, and the progressive phase-out of conventional thermal capacities (coal, lignite), the ratio between off-peak and on-peak hours is expected to increase gradually. Anticipatory and transparent tariff design is therefore essential for both efficiency and social acceptance.

Poorly designed flexibility control can also create rebound effects that undermine environmental benefits. From an environmental perspective, it is typical of systems to increase energy consumption beyond usual levels when resuming operation to return to the setpoint temperature; a phenomenon, known as a rebound peak. (Rigaux et al., 2024) find that rebound effects of flexibility events in a fleet of heat pumps are influenced by external temperatures as well. This should be taken into consideration, especially when designing automated controls for demand-response.



9. Attitudes & Norms

The effectiveness of energy efficient renovations is highly influenced by occupant behaviour. Households consuming less energy than is needed to ventilate the home, result in less savings and the presence of mold. Occupants can also cause a form of rebound effect by consuming more energy than before renovations as less energy is required for the same building services. Technology adoption depends on psychological, cultural, and societal factors

9.1 Attitudes

Attitudes, subjective norms, and perceived usefulness and ease of use are all consistently identified in academic literature as important factors with a direct impact on intention to use smart technology in homes, rendering groups either innovation prone or averse. The lack of trust is an especially important barrier to address when dealing with attitudes, especially since new technologies and calls for data sharing also raise security and privacy concerns (Adams et al., 2021). Consequently, trust in institutions and technology providers is a critical mediator of behavioral acceptance.

Housing tenure also shapes perceived agency, risk, and acceptance of energy technologies. The biggest differences are found between homeowners and those in social housing. Homeowners suspect much more strongly that an increased dependency on outside experts will result in a lack of control; moreover, they suspect that the technologies reveal sensitive data. These differences are easily explained by the fact that homeowners feel much more in charge of the technologies (Rau et al., 2020).

Automation can mitigate behavioural risks but raises questions about autonomy and acceptance. The pros and cons of occupant control versus automating building systems are debated in literature (Zukowska et al., 2021). However, while

Examples in the EU

*In **Hungary**, a historical attachment to gas and wood stoves in can be seen. Maintaining high indoor temperatures is another norm- presumably fuelled by the availability of subsidised, cheap energy (ComActivate, 2025).*

*Burning of coal or peat in open fireplaces is a key element of rural home heating in **Ireland** and **Bulgaria**. The economic and social transactions in harvesting and distributing fuel also contribute to maintaining community relations. However, the inconvenience of burning peat has motivated many households to switch fuels. (Fahy et al., 2019*

*In **Portugal, Slovakia, Hungary, Austria**, fuelwood is a central and multifunctional tool for coping with energy poverty because of its many favorable features, including enabling energy security and access, that outweigh its adverse environmental and health impacts.*



households prefer this feature, automated systems may relieve them of the cognitive overload of having to manually control heat pumps.

Beyond perception, energy consumption behaviour can be rather rigid even after energy efficient measures have been implemented. Family composition and preferences for comfort over energy savings have significant impacts on energy consumption. For instance, building energy performance can be particularly important for older or unemployed people who have high energy needs since they spend more time at home (Fleckinger et al., 2019). Goggins et al. categorised the behavioural tendencies of households after retrofits into three groups. The first is shifts in the use of different solid fuels (material) and associated meanings and skills. The second is immediate shifts in everyday practices and the third is rebound effects and a return to pre-retrofitting practices. Regarding shifts in fuel use, the location and geography of the area proved to be decisive (Goggins et al., 2022). These findings suggest that addressing post-renovation performance requires interventions that go beyond information provision and instead account for household composition, place-specific conditions, and the persistence of established practices.

9.2 Cultural Norms

Cultural norms also shape the success or failure of energy transitions. They may act as both an obstacle to successful implementation of energy-efficient measures and/or a driver of positive change. Some change initiatives are more successful when they ‘hit a cultural nerve’ and work with people’s daily practices, related skills, competences and meanings, as opposed to calling for changes in individual behavior (Fahy et al., 2019).

ENERGISE

This project sought to gain a deeper scientific understanding of social and cultural influences on energy consumption which then informed the development, testing, and assessment of bottom-up energy initiative in households and communities from 2016 to 2019.

ENCHANT

This project investigated the potential for large scale behaviour change across Europe in improving energy efficiency.



Culturally embedded informal heating practices and reinforced by local resource availability can even shape resistance to electrification. Stojilovska et al. theorise that the burning of wood for fuel often begins as a socio-cultural norm that justifies living with minimal energy needs before eventually evolving into a reliance on informal and individual heating solutions coupled with an aversion to seeking institutional support (Stojilovska et al., 2023)

Incremental, culturally compatible upgrades can reduce harm without forcing disruptive change. For households reliant on fireplaces, the prospect of incurring additional energy costs through electrification, even though they are more efficient, is often perceived unfavourably, even if it might enhance thermal comfort and indoor air quality. An alternative approach could involve upgrading less efficient biomass equipment to the most efficient, such as wood stove recirculating the heated air and securer options available in the market. These solutions may consider indoor air quality control by isolating the burning element from the indoor space and collecting ashes in a separate deposit.

Awareness and experiential learning can shift norms when embedded in everyday practices. Raising awareness through information campaigns, and support for affected groups to ensure an equitable and smooth transition therefore necessary. (Bahaj & James, 2007) suggest that renewable energy systems, such as photovoltaic panels, could even serve as educational tools, helping residents develop more efficient energy consumption habits, especially in public housing neighborhoods where a lack of knowledge amongst tenants is more prevalent (Jensen et al., 2018). Practice-related changes provide robust social-scientific evidence for culturally sensitive policy (Sahakian et al., 2021).



Identifying households for intervention requires culturally informed indicators. Goggins et al. suggest using alternative indicators such as participation in community networks, consumption standards and expectations, level of experience health and needs, cultural norms and practices instead of traditional demographic indicators (e.g. Age, income, level of formal education) when choosing candidates for energy-efficiency programmes. These indicators should be used in combination with collective or community-focused strategies rather than individualistic approaches.



frameworks, developing collective ownership models, and integrating technical systems, can achieve systemic changes and holistic benefits for multiple stakeholders.

The main advantage of these integrated models is that they help to distribute risks, costs, and benefits across multiple stakeholders. They provide the conceptual and regulatory framework for public and private partnerships -one of the main strategies often identified to overcome limited availability of public funds. However, finding optimal solutions that satisfy the conflicting goals of energy providers, households, and municipalities is challenging and the findings from pilot projects currently being tested need to be analysed to improve this process.

Solidarity mechanisms and energy justice principles need to be incorporated from the outset to adequately address the needs of vulnerable since their interests risk being neglected amidst the goals of the multiple stakeholders involved in such projects. This involves assessing how benefits and risks are distributed spatially and socially among actors (distributional justice), and the fairness of decision-making processes (procedural justice) (Lehmann et al., 2024).

The potential for renewable energy communities to be formed in different housing segments has only been recently explored in pilot projects. However, the potential of renewable energy communities in public housing is often overlooked, despite offering a dual opportunity of reducing the high energy consumption of this housing segment and fostering social inclusion (McCabe et al., 2018). Energy communities, which help to aggregate demand and resources, is also one potential solution promoted to counter the ad hoc nature of rural renovation. However, the administrative and organizational capacity it requires is a barrier for vulnerable households to participate in energy community projects without additional



10. Community-based Renovations

Recognizing the limitations of solely relying on individual household behavior changes to achieve energy efficiency, community-based initiatives are being promoted across the EU. They provide multiple benefits including stronger engagement of end-users for better outcomes and the creation of larger demand for energy renovations (Jensen et al., 2018). Collective engagement models that tap into local contextual conditions and shared understandings and practices include renewable energy communities, positive energy districts and neighborhood renovations.

PEDs, RECs, and District Renovations are distinct but interlinked models that support an integrated approach to energy efficient renovations and applied within the same project. Positive energy districts (PEDs) are urban areas that aim to achieve net-zero energy consumption, with a surplus of annual energy production through a comprehensive integration of renewable energy sources, high energy efficiency and energy flexibility strategies. They often integrate energy consumption and production from residential and non-residential buildings as well as electric vehicles, optimizing the local electricity system.

Meanwhile, renewable energy communities (RECs) are local groups of actors which collectively produces, shares, and consumes energy. The framework an REC provides a legal framework that allows stakeholders to produce and share electricity locally as well as with the electric grid. A renewable energy community can be formed within a Positive Energy District.

District renovations are the process of serial renovations at a neighbourhood scale that also integrate urban design elements such as greening and improvement of public spaces. District renovations are often necessary for a Positive Energy District to be formed. These models illustrate how aligning regulatory

Renewable Energy Directive 2018/2001/EU (RED II) (European Parliament and Council of the European Union, 2018) & Internal Market for Electricity Directive (IMED) 2019/944/EU (European Parliament and Council of the European Union, 2019),

These regulations provide legal status to RECs and recognize them as entities prioritizing environmental, social, or economic benefits over profit



support (Gouveia et al., 2025). It is therefore recommended that projects that involve vulnerable households have robust services to manage the investment, installation, and maintenance of renewable energy. This is especially true for multi-household buildings, where coordination may be difficult (Hoicka et al., 2021).

Longer term programmes with dedicated roles to facilitate the adoption of energy renovations have been identified as an important strategy. Owners of multi-family buildings, especially housing companies, are shifting towards serial renovations or renovation programs which can span two or more years (Meijer & Straub, 2022). These programs are implemented in strategic partnerships with maintenance contractors. Renovations that implement an ordered series of measures over a longer period can be less disruptive and less costly to execute. They are also often carried out together with scheduled facility maintenance operations (Passoni et al., 2009). The serial implementation of these renovations and the ambition to transfer lessons learnt has led to the rise of dedicated roles such as facilities managers, and local energy “champions” to effectively improve the uptake, increase trust and social acceptability of new technologies (Ebrahimigharehbaghi et al., 2022). By embedding renovation within longer-term programs and dedicated support roles, these approaches help address resistance, build trust, and improve social acceptance.

Technical renovation solutions that rely on prefabrication and standardized, modular connections offer a promising pathway to accelerate energy-efficient renovations while minimising disruption to occupants. By enabling components to be adapted or replaced with limited on-site work, and by allowing installation from outside the building envelope, these approaches reduce the need for resident relocation and interruptions to building functions (Passoni et al., 2021). In

SET Plan-PED, for Positive Energy Districts.

The SET Plan-PED initiative, part of Europe's Strategic Energy Technology Plan, aims to create 100 Positive Energy Districts (PEDs) by 2025.

The Affordable Housing Initiative Partnership

This initiative gathered examples of hundred neighbourhood renovations, which worked with inclusive and sustainable housing renovations.

oPEN Lab

This project facilitates the transition to Positive Energy Neighbourhoods (PENs) in Tartu (Estonia), Pamplona (Spain) and Genk (Belgium)



recognition of these benefits, policy instruments increasingly encourage plug-and-play solutions that can be deployed at neighbourhood scale to improve efficiency and reduce costs through replication (BPIE, 2025).

However, the effectiveness of prefabricated renovation techniques remains constrained by limited production scale, which keeps costs high, as demonstrated in early large-scale initiatives such as the Energiesprong project. Moreover, not all buildings are technically suitable for prefabrication due to architectural features such as balconies, structural nodes, or heritage constraints, while greater integration of building components can increase complexity in manufacturing processes (Femenias et al., 2023). These limitations underscore the importance of viewing prefabrication as a context-dependent strategy that is most effective when combined with differentiated renovation pathways rather than as a universal solution.

Community based approaches demonstrate that achieving scalable, equitable energy renovations requires combining place-based collective models, long-term facilitation, and context-sensitive technical solutions within governance frameworks that explicitly balance efficiency, affordability, and social justice. Without such integrated and supportive approaches, the risk remains that community-scale energy transitions will replicate existing inequalities rather than delivering the inclusive benefits they are often assumed to provide.



11. Conclusion

The review of energy efficient measures highlights trade-offs between the multiple objectives which energy renovations often aim to address (e.g. energy-efficiency, decarbonization, indoor air quality, tackling energy poverty). Deep renovations and high performance standards help achieve long-term energy efficiency but they also involve high upfront costs, disruption and increased complexity which can exclude low-income households, tenants and even small housing providers. Similarly, increased energy efficiency in a dwelling can also have a negative consequence on indoor air quality if appropriate ventilation strategies are not included. These trade-offs also exist in time-of-use pricing strategies seeking to optimise the electrical grid which can unfairly burden households who are unable to change their consumption patterns in response to dynamic tariffs.

Therefore, a comprehensive but cohesive policy mix integrating financial incentives with mechanisms to lower the upfront costs, including targeted low-interest loans, heating-as-a-service business models, and information campaigns are consistently recommended to achieve the systemic change of decarbonizing the built environment by 2050 (Brodnicke et al., 2025). Multiple EU initiatives under the Fit-for-55 Package aim to support a broad policy mix. In this report, we identify several general trends to address common barriers and upscale energy renovations. They include pooling energy demand through collective or community initiatives, diversifying production of energy with a mix of locally produced renewable energy sources, digitalized, standardized and large-scale data collection for customised energy solutions, to build trust, and ultimately distribute the risk of investing in energy efficient renovations amongst multiple stakeholders. To a lesser extent there is an adoption of automated production and construction processes and bio-based or reused building materials. Calls for tailored support as well as targeted long term funding alongside clear



and reliable regulations is reiterated across studies on different renovation measures.

The review shows that technical renovation measures need to be supported with process-based measures that support stakeholders in the administrative, and behavioral aspects of renovations, especially vulnerable groups for both environmental effectiveness for the wider society and socio-economic effectiveness for households.

Tailored supports can be incorporated into various community-based schemes as an effective means to reaching people that are otherwise difficult to engage for practical reasons, for example if households do not use the Internet or where people have disabilities that impede their participation (Gillard et al., 2017).

Article 8(3) of Directive (EU) 2023/1791 requires Member States to use of public funding and revenues from Emissions Trading System (ETS) allowances to compensate households that experience unfair distributional effects from energy efficiency policies like energy taxes or minimum energy performance requirements. Proactive identification of vulnerable households and provision of support to them is required for redistribution efforts to be effective.

To this end, how we understand vulnerable households may need to be expanded. Finding alternate ways to identify vulnerable households and provide tailored support measures could be as important as the actual implementation of renovation measures. (Fineman, 2012) argues that “designating only certain individuals and groups vulnerable transforms our shared vulnerability into a personal liability and renders the individuals so designated susceptible to alienation, stigma or demonization”. Therefore, different indicators could be considered when attempting to identify households for renovation programs such as those suggested by Goggins



et al. (i.e. participation in community networks, consumption standards and expectations, health and needs, cultural norms and practices). Moreover, more post-renovation audits are needed to assess the actual social and environmental impacts of renovation programmes.

While the EU has made substantial progress in improving and calculating energy efficiency, systematic approaches to decarbonization and comprehensive emissions accounting are still in their early stages. At the same time, material impacts from building renovation remain a significant contributor to emissions in the construction sector. Decarbonization is currently more abstract and less immediately perceptible to stakeholders than energy efficiency, which often delivers visible reductions in energy bills. Harmonized tools such as Life Cycle Assessment (LCA) and Environmental Product Declarations (EPDs) exist, but it is not yet the norm to use them in renovations (Bergman, 2018).

The review shows that the overall socio-economic and environmental effectiveness of energy efficient measures is not only dependent on the depth of the renovation but also a broader range of factors. The appropriate sequence of measures, the renovation's impact on a building's whole life cycle, integration with socially inclusive and place-based processes as well as real-world performance that is affected by occupant behaviour and pricing strategies. Integrating post-renovation audits into workflows would help gain insights into how these factors manifest in specific local contexts and apply them to subsequent projects.



12. References

Adams, J. N., Bélafi, Z. D., Horváth, M., Kocsis, J. B., & Csoknyai, T. (2021). How Smart Meter Data Analysis Can Support Understanding the Impact of Occupant Behavior on Building Energy Performance: A Comprehensive Review. *Energies*, 14(9), 2502. <https://doi.org/10.3390/en14092502>

Adisorn, T., & Vondung, F. (2019). Behind closed windows—An actor-centred analysis of barriers for the diffusion of energy. . . BUILDINGS.

Arceo, A., Touchie, M., & O'Brien, W. (2025). Beyond density: Examining overlooked drivers of housing and neighborhood greenhouse gas emissions. *Sustainable Cities and Society*, 120, 106131. <https://doi.org/10.1016/j.scs.2025.106131>

Agency for the Cooperation of Energy Regulators (ACER) & Council of European Energy Regulators (CEER). (2024). Market Monitoring Report 2024: Energy retail – Active consumer participation is key to driving the energy transition (Annual Report on the results of monitoring the internal electricity and natural gas markets in 2023). https://www.ceer.eu/wp-content/uploads/2024/09/ACER-CEER_2024_MMR_Retail-1.pdf

Agence de la transition écologique (ADEME). (2021). *La rénovation performante par étapes*. <https://librairie.ademe.fr/batiment/4636-la-renovation-performante-par-etapes.html>

Apostoliotis, A., Papantonis, D., & Flamos, A. (2024). Evaluation of energy efficiency measures addressing the needs of energy poor households in rural areas (Deliverable 4.1). RENOVERTY Project, University of Piraeus Research Center. <https://ieecp.org/projects/renoverty/>



Arceo, A., Touchie, M., O'Brien, W., Hong, T., Malik, J., Mayer, M., Peters, T., Saxe, S., Tamas, R., Villeneuve, H., & Schmaltz, B. (2025). Ten questions concerning housing sufficiency. *Building and Environment*, 277, 112941. <https://doi.org/10.1016/j.buildenv.2025.112941>

Ata, B., Péntzes, J., Pakrooh, P., Lotfata, A., & Mohammed, S. (2025). Comprehensive analysis of factors influencing EU-countries household energy consumption (2000–2022): Trends and vulnerability to COVID-19 and the Russia-Ukraine war. *Energy Strategy Reviews*, 59, 101728. <https://doi.org/10.1016/j.esr.2025.101728>

Bagheri, M., Pröpper, A., & Klein, G. (2025). Exploring residential space use patterns and potentials for change: Findings from a multi-country survey. *Energy Efficiency*, 18(6), 66. <https://doi.org/10.1007/s12053-025-10343-z>

Bahaj, A., & James, P. (2007). Urban energy generation: The added value of photovoltaics in social housing. *Renewable and Sustainable Energy Reviews*, 11(9), 2121–2136. <https://doi.org/10.1016/j.rser.2006.03.007>

Bankert, E., Düvier, C., & Diaconu, D. (2024). *EU and national level policy analysis and monitoring* (Deliverable D5.1, ComActivate—Enabling community action for energy sufficiency). Buildings Performance Institute Europe (BPIE). <https://www.bpie.eu/comactivate-enabling-community-action-for-energy-sufficiency/>

Batra, Z., Sommer, T., Jusselme, T., & Orehounig, K. (2026). Exploring the potential of Sufficiency scenarios to reach Net-Zero buildings in Swiss municipalities. *Energy and Buildings*, 351, 116727. <https://doi.org/10.1016/j.enbuild.2025.116727>

Bednar, D. J., Reames, T. G., & Keoleian, G. A. (2017). The intersection of energy and justice: Modeling the spatial, racial/ethnic and socioeconomic patterns of urban residential heating consumption and efficiency in Detroit, Michigan. *Energy and Buildings*, 143, 25–34. <https://doi.org/10.1016/j.enbuild.2017.03.028>



Berg Insight AB. (2024). Smart metering in Europe: 19th edition.
https://www.berginsight.com/contents/documents/reports/insights/berginsight_SM19.pdf

Behar, C. (2013). Ventilation in energy efficient UK homes: A user experience of innovative technologies.

Bertoldi, P., Economidou, M., Palermo, V., Boza-Kiss, B., & Todeschi, V. (2021). How to finance energy renovation of residential buildings: Review of current and emerging financing instruments in the EU. *Wiley Interdisciplinary Reviews: Energy and Environment*, 10(1). Scopus. <https://doi.org/10.1002/wene.384>

Bohnenberger, K. (2021). Can 'Sufficiency' reconcile social and environmental goals? A Q-methodological analysis of German housing policy. *Journal of Housing and the Built Environment*, 36(1), 171–189. <https://doi.org/10.1007/s10901-020-09762-4>

Buildings Performance Institute Europe (BPIE). (2025). Upscaling innovation in renovation: A call for a strategic approach for a competitive and sustainable construction sector. <https://www.bpie.eu/publication/upscaling-innovation-in-renovation/>

BUILD UP. (2024, November 5). *Energy Performance Certificates: boosting the market for energy efficient buildings*. European Climate, Infrastructure and Environment Executive Agency. <https://build-up.ec.europa.eu/en/resources-and-tools/articles/energy-performance-certificates-boosting-market-energy-efficient>

Buildings Performance Institute Europe (BPIE). (2021). *Deep renovation: Shifting from exception to standard practice in EU policy*. <https://www.bpie.eu/publication/deep-renovation-shifting-from-exception-to-standard-practice-in-eu-policy/>

Brodnicke, L., Rizzo, G., & Sansavini, G. (2025). Accelerating Heat Pump Adoption in Switzerland: An Agent-Based Policy Assessment. SSRN. <https://doi.org/10.2139/ssrn.5183936>



Cabot, C., & Villavicencio, M. (2024). Second-best electricity pricing in France: Effectiveness of existing rates in evolving power markets. *Energy Economics*, 136, 107673. <https://doi.org/10.1016/j.eneco.2024.107673>

Caird, J. K., Willness, C. R., Steel, P., & Scialfa, C. (2008). A meta-analysis of the effects of cell phones on driver performance. *Accident Analysis & Prevention*, 40(4), 1282–1293. <https://doi.org/10.1016/j.aap.2008.01.009>

Canale, L., Peulicke Slott, B., Finsdóttir, S., Kildemoes, L. R., & Andersen, R. K. (2021). Do in-home displays affect end-user consumptions? A mixed method analysis of electricity, heating and water use in Danish apartments. *Energy and Buildings*, 246, 111094. <https://doi.org/10.1016/j.enbuild.2021.111094>

Cauvain, J., & Karvonen, A. (2018). Social housing providers as unlikely low-carbon innovators. *Energy and Buildings*, 177, 394–401. <https://doi.org/10.1016/j.enbuild.2018.08.012>

Charef, R., Emmitt, S., Alaka, H., & Fouchal, F. (2019). Building Information Modelling adoption in the European Union: An overview. *Journal of Building Engineering*, 25, 100777. <https://doi.org/10.1016/j.jobbe.2019.100777>

Cintura, E., Nunes, L., Esteves, B., & Faria, P. (2021). Agro-industrial wastes as building insulation materials: A review and challenges for Euro-Mediterranean countries. *Industrial Crops and Products*, 171, 113833. <https://doi.org/10.1016/j.indcrop.2021.113833>

Collins, M., & Dempsey, S. (2019). Residential energy efficiency retrofits: Potential unintended consequences. *Journal of Environmental Planning and Management*, 62(12), 2010–2025. <https://doi.org/10.1080/09640568.2018.1509788>

ComActivate. (2024). EU and National Level Policy Analysis and Monitoring. Available at: <https://energy-poverty.ec.europa.eu/observatory/publications/analysis-eu-and-national-level-policies-related-renovation-and-alleviating>



Croon, T. M., Hoekstra, J. S. C. M., & Dubois, U. (2024). Energy poverty alleviation by social housing providers: A qualitative investigation of targeted interventions in France, England, and the Netherlands. *Energy Policy*, 192, 114247. <https://doi.org/10.1016/j.enpol.2024.114247>

Czock, B. H., Frings, C., & Arnold, F. (2025). Cost and cost distribution of policy-driven investments in decentralized heating systems in residential buildings in Germany. *Energy and Buildings*, 327, 115104. <https://doi.org/10.1016/j.enbuild.2024.115104>

Dimchev, I., Terziev, A., Ivanov, M., & Vassilev, M. (2025). Climate change impact on the energy performance of an air handling unit with two-stage heat recovery. *E3S Web of Conferences*, 608, 01009. <https://doi.org/10.1051/e3sconf/202560801009>

D'Oca, S., Hong, T., & Langevin, J. (2018). The human dimensions of energy use in buildings: A review. *Renewable and Sustainable Energy Reviews*, 81, 731–742. <https://doi.org/10.1016/j.rser.2017.08.019>

Ebrahimigharehbaghi, S., Qian, Q. K., De Vries, G., & Visscher, H. J. (2022). Municipal governance and energy retrofitting of owner-occupied homes in the Netherlands. *Energy and Buildings*, 274, 112423. <https://doi.org/10.1016/j.enbuild.2022.112423>

Enrich, J., Li, R., Mizrahi, A., & Reguant, M. (2024). Measuring the impact of time-of-use pricing on electricity consumption: Evidence from Spain. *Journal of Environmental Economics and Management*, 123, 102901. <https://doi.org/10.1016/j.jeem.2023.102901>

Esmat, A., Ghiassi-Farrokhfal, Y., Gunkel, P. A., & Bergaentzlé, C.-M. (2023). A decision support system for green and economical individual heating resource planning. *Applied Energy*, 347, 121442. <https://doi.org/10.1016/j.apenergy.2023.121442>



European Commission, Directorate-General for Energy. (2025, December). Energy Performance of Buildings Directive. Available at:
https://energy.ec.europa.eu/topics/energy-efficiency/energy-performance-buildings/energy-performance-buildings-directive_en#key-facts-on-energy-and-buildings-in-the-eu

European Commission. (2021). *Commission Recommendation (EU) 2021/1749 of 28 September 2021 on Energy Efficiency First: from principles to practice — Guidelines and examples for its implementation in decision-making in the energy sector and beyond* (Official Journal L 350, 4.10.2021, pp. 9–59). <https://eur-lex.europa.eu/eli/reco/2021/1749/oj>

European Environment Agency. (2023b). Addressing the energy crisis while delivering on EU's climate objectives: recommendations to policymakers. European Environment Agency. Available at: <https://climateadvisory-board.europa.eu/reports-and-publications/addressing-the-energy-crisis-while-delivering-oneus-climate-objectives-recommendations-to-policy-makers>

Eurostat (2024). Energy Consumption in Households. Available at:
<https://ec.europa.eu/eurostat/web/microdata/european-union-statistics-on-income-and-livingconditions/>

Eurostat (2025). Population unable to keep home adequately warm by poverty status (SDG_07_60). Eurostat Statistics Database. Retrieved January 15, 2026, from https://ec.europa.eu/eurostat/databrowser/view/sdg_07_60/default/table?lang=en

European Environment Agency. (2023b). Energy and Emissions in the Building Sector. Available at: <https://climate-energy.eea.europa.eu/topics/energy-1/energy-and-buildings/data>



European Environmental Bureau. (2024). How Renewables Can Help Vulnerable Households. Available at: <https://eeb.org/en/library/how-renewables-can-help-vulnerable-households/>

European Federation of National Organisations Working with the Homeless [FEANTSA]. (2022). How to avoid a Renoviction Wave: Report on the social impacts of the Renovation Wave (PDF).
https://www.feantsa.org/files/Themes/Energy/2022/reports/1_How_to_avoid_a_Renoviction_wave.pdf

Fahy, F., Goggins, G., & Jensen, C. (Eds.). (2019). Energy Demand Challenges in Europe: Implications for policy, planning and practice. Springer International Publishing.
<https://doi.org/10.1007/978-3-030-20339-9>

Femenias, P., Peter, S., & Legnér, M. (2023). Modern heritage and housing renovation: Policy development and practical experiences from Gothenburg, Sweden. Patrimoine contemporain et rénovation de logements: Élaboration de politiques et expériences pratiques à Göteborg (Suède). In Situ.

Ferdyn-Crygierek, J., & Crygierek, K. (2024). Ventilation Methods for Improving the Indoor Air Quality and Energy Efficiency of Multi-Family Buildings in Central Europe. *Energies*, 17(9), 2232. <https://doi.org/10.3390/en17092232>

Fineman, M. A. (2012). "Elderly" as Vulnerable: Rethinking the Nature of Individual and Societal Responsibility. *SSRN Electronic Journal*. <https://doi.org/10.2139/ssrn.2088159>

Fischer, D., & Madani, H. (2017). On heat pumps in smart grids: A review. *Renewable and Sustainable Energy Reviews*, 70, 342–357. <https://doi.org/10.1016/j.rser.2016.11.182>

Fleckinger, P., Glachant, M., & Tamokoué Kamga, P.-H. (2019). Energy Performance Certificates and investments in building energy efficiency: A theoretical analysis. *Energy Economics*, 84, 104604. <https://doi.org/10.1016/j.eneco.2019.104604>

Fuster-Palop, E., Prades-Gil, C., Masip, X., Viana-Fons, J. D., & Payá, J. (2023). Techno-Economic Potential of Urban Photovoltaics: Comparison of Net Billing and Net Metering in a Mediterranean Municipality. *Energies*, 16(8), 3564. <https://doi.org/10.3390/en16083564>

Gergely, L. Z., Barancsik, L., & Horváth, M. (2025). Beyond net zero energy buildings: Load profile analysis and community aggregation for improved load matching. *Applied Energy*, 379, 124934. <https://doi.org/10.1016/j.apenergy.2024.124934>

Giama, E. (2021). Review on Ventilation Systems for Building Applications in Terms of Energy Efficiency and Environmental Impact Assessment. *Energies*, 15(1), 98. <https://doi.org/10.3390/en15010098>

Giama, E., Kyriaki, E., Papaevaggelou, A., & Papadopoulos, A. (2023). Energy and Environmental Analysis of Renewable Energy Systems Focused on Biomass Technologies for Residential Applications: The Life Cycle Energy Analysis Approach. *Energies*, 16(11), 4433. <https://doi.org/10.3390/en16114433>

Gillard, R., Snell, C., & Bevan, M. (2017). Advancing an energy justice perspective of fuel poverty: Household vulnerability and domestic retrofit policy in the United Kingdom. *Energy Research & Social Science*, 29, 53–61. <https://doi.org/10.1016/j.erss.2017.05.012>

Goggins, G., Rau, H., Moran, P., Fahy, F., & Goggins, J. (2022). The role of culture in advancing sustainable energy policy and practice. *Energy Policy*, 167, 113055. <https://doi.org/10.1016/j.enpol.2022.113055>

Gouveia, J. P., Cuervo, T., Caneva, S., Del Pero, C., Ricci, D., Elangovan, E., Mlecnik, E., Abdelhalim, E., Leonforte, F., & others. (2025). White paper on affordable, sustainable energy transition and building renovation. IWG5 Buildings. <https://research.tudelft.nl/>

Greene, M., & Fahy, F. (2020). Steering demand? Exploring the intersection of policy, practice and lives in energy systems change in Ireland. *Energy Research & Social Science*, 61, 101331. <https://doi.org/10.1016/j.erss.2019.101331>

Hagentoft, C.-E., & Kalagasidis, A. S. (2016). Drying Potential of Cold Attic Using Natural and Controlled Ventilation in Different Swedish Climates. *Procedia Engineering*, 146, 2–7. <https://doi.org/10.1016/j.proeng.2016.06.345>

Han, Y., Lam, J. C. K., Li, V. O. K., Newbery, D., Guo, P., & Chan, K. (2024). A deep learning approach for fairness-based time of use tariff design. *Energy Policy*, 192, 114230. <https://doi.org/10.1016/j.enpol.2024.114230>

Heracleous, C., & Michael, A. (2018). Assessment of overheating risk and the impact of natural ventilation in educational buildings of Southern Europe under current and future climatic conditions. *Energy*, 165, 1228–1239. <https://doi.org/10.1016/j.energy.2018.10.051>

Hobman, E. V., Frederiks, E. R., Stenner, K., & Meikle, S. (2016). Uptake and usage of cost-reflective electricity pricing: Insights from psychology and behavioural economics. *Renewable and Sustainable Energy Reviews*, 57, 455–467. <https://doi.org/10.1016/j.rser.2015.12.144>

Hoicka, C. E., Lowitzsch, J., Brisbois, M. C., Kumar, A., & Ramirez Camargo, L. (2021). Implementing a just renewable energy transition: Policy advice for transposing the new European rules for renewable energy communities. *Energy Policy*, 156, 112435. <https://doi.org/10.1016/j.enpol.2021.112435>

Horn, S., Gough, I., Rogers, C., & Tunstall, R. (2025). Meeting housing needs within planetary boundaries: A UK case study. *Ecological Economics*, 230, 108510. <https://doi.org/10.1016/j.ecolecon.2024.108510>



Jagarajan, R., Abdullah Mohd Asmoni, M. N., Mohammed, A. H., Jaafar, M. N., Lee Yim Mei, J., & Baba, M. (2017). Green retrofitting – A review of current status, implementations and challenges. *Renewable and Sustainable Energy Reviews*, 67, 1360–1368.
<https://doi.org/10.1016/j.rser.2016.09.091>

Jensen, P., Maslesa, E., & Brinkø Berg, J. (2018). Sustainable Building Renovation: Proposals for a Research Agenda. *Sustainability*, 10(12), 4677.
<https://doi.org/10.3390/su10124677>

Katerla, J., & Sornek, K. (2025). Biomass for Residential Heating: A Review of Technologies, Applications, and Sustainability Aspects. *Energies*, 18(22), 5875.
<https://doi.org/10.3390/en18225875>

Kim, J.-H., & Shcherbakova, A. (2011). Common failures of demand response. *Energy*, 36(2), 873–880. <https://doi.org/10.1016/j.energy.2010.12.027>

Lagoeiro, H., Maidment, G., & Ziemele, J. (2024). Potential of treated wastewater as an energy source for district heating: Incorporating social elements into a multi-factorial comparative assessment for cities. *Energy*, 304, 132190.
<https://doi.org/10.1016/j.energy.2024.132190>

Lapillonne, B., Payan, E., & Retailleau, K. (2025). *Energy efficiency in time of crisis at EU level* (Policy brief). ODYSSEE-MURE Project. <https://www.odyssee-mure.eu/>

Lara-García, Á., Rivera-Gómez, C., Núñez-Rivera, C., Galán-Marín, C., & Cruz-Mazo, E. C. (2024). Linking Vulnerability to Heatwaves and Public Health: Indicators for EU Policies on Energy Renovation of Residential Buildings. In E. Galende Sánchez, A. H. Sorman, V. Cabello, S. Heidenreich, & C. A. Klöckner (Eds.), *Strengthening European Climate Policy* (pp. 61–74). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-72055-0_6



Lehmann, P., Gawel, E., Meier, J.-N., Reda, M. J., Reutter, F., & Sommer, S. (2024). Spatial distributive justice has many faces: The case of siting renewable energy infrastructures. *Energy Research & Social Science*, 118, 103769. <https://doi.org/10.1016/j.erss.2024.103769>

McCabe, A., Pojani, D., & Van Groenou, A. B. (2018). The application of renewable energy to social housing: A systematic review. *Energy Policy*, 114, 549–557. <https://doi.org/10.1016/j.enpol.2017.12.031>

McGinley, O., Moran, P., & Goggins, J. (2022). An Assessment of the Key Performance Indicators (KPIs) of Energy Efficient Retrofits to Existing Residential Buildings. *Energies*, 15(1), 334. <https://doi.org/10.3390/en15010334>

McKenna, E., Zheng, L., & Huebner, G. (2025). *D4.2: Smart meter data for measurement and identification of energy poverty* (HouseInc project deliverable). HouseInc Consortium. <https://houseinc.eu>

Meijer, F. M., & Straub, A. (2022). Sustainable renovation of non-profit housing in the Netherlands: From projects to programs. *IOP Conference Series: Earth and Environmental Science*, 1085(1), 012051. <https://doi.org/10.1088/1755-1315/1085/1/012051>

Mišík, M., & Nosko, A. (2023). Post-pandemic lessons for EU energy and climate policy after the Russian invasion of Ukraine: Introduction to a special issue on EU green recovery in the post-Covid-19 period. *Energy Policy*, 177, 113546. <https://doi.org/10.1016/j.enpol.2023.113546>

Mokhtari, R., Madsen, H., & Li, R. (2025). Exploring the impacts of consumer reaction to dynamic heat prices in district heating. *Energy and Buildings*, 347, 116347. <https://doi.org/10.1016/j.enbuild.2025.116347>



Nicolai, S., & Münchmeyer, M. (2025). The EU Data Act and electricity consumer participation in demand response and flexibility services. *Journal of Energy & Natural Resources Law*, 1–25. <https://doi.org/10.1080/02646811.2025.2485725>

Odyssee-MURE. (2024, November). Household energy consumption by energy in the EU. <https://www.odyssee-mure.eu/publications/efficiency-by-sector/households/energy-consumption-eu.html>

Office of Gas and Electricity Markets (Ofgem). (2025). *Warm Home Discount (WHD): Eligibility*. <https://www.ofgem.gov.uk/environmental-and-social-schemes/warm-home-discount-whd/eligibility>

Ou, Y., Bailey, N., McArthur, D. P., & Zhao, Q. (2025). The price premium of residential energy performance certificates: A scoping review of the European literature. *Energy and Buildings*, 332, 115377. <https://doi.org/10.1016/j.enbuild.2025.115377>

Pagoni, P., Møller, E. B., & Hansen, T. K. (2023). Internal Insulation – four systems in one historic residential building. *Journal of Physics: Conference Series*, 2654(1), 012006. <https://doi.org/10.1088/1742-6596/2654/1/012006>

Passoni, C., Marini, A., Belleri, A., & Menna, C. (2021). Redefining the concept of sustainable renovation of buildings: State of the art and an LCT-based design framework. *Sustainable Cities and Society*, 64, 102519. <https://doi.org/10.1016/j.scs.2020.102519>

Platten, J. von., Mangold, M., & Mjörnell, K. (2020). Energy inequality as a risk in socio-technical energy transitions: The Swedish case of individual metering and billing of energy for heating. *IOP Conference Series: Earth and Environmental Science*, 588(3), 032015. <https://doi.org/10.1088/1755-1315/588/3/032015>

Platten, J. von, Mangold, M., & Mjörnell, K. (2020). A matter of metrics? How analysing per capita energy use changes the face of energy efficient housing in Sweden and reveals



injustices in the energy transition. *Energy Research & Social Science*, 70, 101807.
<https://doi.org/10.1016/j.erss.2020.101807>

Pomianowski, M. Z., Johra, H., Marszal-Pomianowska, A., & Zhang, C. (2020). Sustainable and energy-efficient domestic hot water systems: A review. *Renewable and Sustainable Energy Reviews*, 128, 109900. <https://doi.org/10.1016/j.rser.2020.109900>

Pull, E. (2020). Displacement: Structural Evictions and Alienation. *ACME: An International Journal for Critical Geographies*, 19(1), 364–373.
<https://doi.org/10.14288/acme.v19i1.1893>

Rabbat, C., Villot, A., Awad, S., & Andrès, Y. (2023). Gaseous and particulate matter emissions from the combustion of biomass-based insulation materials at end-of-life in a small-scale biomass heating boiler. *Fuel*, 338, 127182.
<https://doi.org/10.1016/j.fuel.2022.127182>

Rau, H., Moran, P., Manton, R., & Goggins, J. (2020). Changing energy cultures? Household energy use before and after a building energy efficiency retrofit. *Sustainable Cities and Society*, 54, 101983. <https://doi.org/10.1016/j.scs.2019.101983>

Rigaux, B., Hamels, S., & Ovaere, M. (2024). The Proof of the Pudding is in the Heating: A Field Experiment on Household Engagement with Heat Pump Flexibility. SSRN.
<https://doi.org/10.2139/ssrn.5068963>

Rosenow, J., Gibb, D., Nowak, T., & Lowes, R. (2022). Heating up the global heat pump market. *Nature Energy*, 7(10), 901–904. <https://doi.org/10.1038/s41560-022-01104-8>

Sahakian, M., Rau, H., Grealis, E., Godin, L., Wallenborn, G., Backhaus, J., Friis, F., Genus, A. T., Goggins, G., Heaslip, E., Heiskanen, E., Iskandarova, M., Louise Jensen, C., Laakso, S., Musch, A.-K., Scholl, C., Vadovics, E., Vadovics, K., Vasseur, V., & Fahy, F. (2021). Challenging social norms to recraft practices: A Living Lab approach to reducing household energy



use in eight European countries. *Energy Research & Social Science*, 72, 101881.
<https://doi.org/10.1016/j.erss.2020.101881>

Samancioglu, N., Castaño-Rosa, R., Väänänen, K., & Komal, M. (2026). The role of smart meter feedback in enhancing inhabitants' energy efficient behaviour in residential buildings. *Energy and Buildings*, 351, 116689. <https://doi.org/10.1016/j.enbuild.2025.116689>

Sarna, I., & Ferdyn-Grygierek, J. (2025). Natural ventilation for thermal comfort: A simulation-based comparison of manual and automated window control strategies in temperate climate housing. *Building and Environment*, 285, 113551.
<https://doi.org/10.1016/j.buildenv.2025.113551>

Savini, F., Kopp, M., Hochstenbach, C., Cohen, L., Berrill, P., & Merciai, S. (2026). Socio-ecological inequalities in housing consumption: How income, urban form, and tenure drive carbon footprints. *Ecological Economics*, 242, 108896.
<https://doi.org/10.1016/j.ecolecon.2025.108896>

Stojilovska, A., Dokupilová, D., Gouveia, J. P., Bajomi, A. Z., Tirado-Herrero, S., Feldmár, N., Kyprianou, I., & Feenstra, M. (2023). As essential as bread: Fuelwood use as a cultural practice to cope with energy poverty in Europe. *Energy Research & Social Science*, 97, 102987. <https://doi.org/10.1016/j.erss.2023.102987>

SolarPower Europe. (2025). *EU Solar Market Outlook 2025–2030*.
<https://www.solarpowereurope.org/market-outlook-2025-2030>

Stute, J., Pelka, S., Kühn bach, M., & Klobasa, M. (2024). Assessing the conditions for economic viability of dynamic electricity retail tariffs for households. *Advances in Applied Energy*, 14, 100174. <https://doi.org/10.1016/j.adapen.2024.100174>



Sunikka-Blank, M., & Galvin, R. (2012). Introducing the prebound effect: The gap between performance and actual energy consumption. *Building Research & Information*, 40(3), 260–273. <https://doi.org/10.1080/09613218.2012.690952>

Tzani, D., Stavrakas, V., Santini, M., Thomas, S., Rosenow, J., & Flamos, A. (2022). Pioneering a performance-based future for energy efficiency: Lessons learnt from a comparative review analysis of pay-for-performance programmes. *Renewable and Sustainable Energy Reviews*, 158, 112162. <https://doi.org/10.1016/j.rser.2022.112162>

Toleikyte, A., Roca Reina, J. C., Volt, J., Carlsson, J., Lyons, L., Gasparella, A., Koolen, D., De Felice, M., Tarvydas, D., Czako, V., Koukoufikis, G., Kuokkanen, A., & Letout, S. (2023). *The heat pump wave: Opportunities and challenges—Analysis of the large-scale deployment of heat pumps by 2030 following the REPowerEU plan* (JRC Science for Policy Report No. EUR 31565 EN). Publications Office of the European Union. <https://doi.org/10.2760/27877>

UNEP. 2021. Global Status Report for Buildings and Construction: Towards a Zero-Emission. Efficient and Resilient Buildings and Construction Sector. 2021; pp. 1–105. Available online: <https://www.unep.org/resources/report/2021-global-status-report-buildings-and-construction>

Van Der Leer, J., Femenias, P., & Granath, K. (2026). Implementing minimum energy performance requirements ‘from the middle’: Shifting levels of agency and capacity of housing developers in Sweden. *Energy Policy*, 208, 114901. <https://doi.org/10.1016/j.enpol.2025.114901>

Van Der Wal, A. J., Van Ooij, C., Straver, K., & Rietbergen, M. (2025). The Effects of Three Governmental Programmes—Energy Coaches, Home Renovations, and White Goods Schemes—On Energy Poverty-Related Issues in Dutch Households. *Sustainability*, 17(15), 6803. <https://doi.org/10.3390/su17156803>



Vilén, K., Lygnerud, K., & Ahlgren, E. O. (2024). Policy implications of challenges and opportunities for district heating – The case for a Nordic heating system. *Energy*, 308, 132831. <https://doi.org/10.1016/j.energy.2024.132831>

Von Platten, J., Mangold, M., Johansson, T., & Mjörnell, K. (2022). Energy efficiency at what cost? Unjust burden-sharing of rent increases in extensive energy retrofitting projects in Sweden. *Energy Research & Social Science*, 92, 102791. <https://doi.org/10.1016/j.erss.2022.102791>

Willand, N., & Horne, R. (2018). “They are grinding us into the ground” – The lived experience of (in)energy justice amongst low-income older households. *Applied Energy*, 226, 61–70. <https://doi.org/10.1016/j.apenergy.2018.05.079>

Willand, N., Ridley, I., & Maller, C. (2015). Towards explaining the health impacts of residential energy efficiency interventions – A realist review. Part 1: Pathways. *Social Science & Medicine*, 133, 191–201. <https://doi.org/10.1016/j.socscimed.2015.02.005>

Woltjer, G., Daioglou, V., Elbersen, B., Barberena Ibañez, G., Smeets, E., Sánchez González, D., & Gil Barnó, J. (2017). Study Report on Reporting Requirements on Biofuels and Bioliquids.

Zerari, S., Franchino, R., Pisacane, N., Llatas, C., & Soust-Verdaguer, B. (2024). Addressing the Difficulties and Opportunities to Bridge the Integration Gaps of Bio-Based Insulation Materials in the European Construction Sector: A Systematic Literature Review. *Sustainability*, 16(19), 8711. <https://doi.org/10.3390/su16198711>

Zimakov, A. V. (2025). Decarbonization of Heat Supply in Southern Europe: Strategy, Challenges, and Social Implications. *MGIMO Review of International Relations*, 18(1), 100–123. <https://doi.org/10.24833/2071-8160-2025-1-100-100-123>



Zukowska, D., Rojas, G., Burman, E., Guyot, G., Bocanegra-Yanez, M. D. C., Laverge, J., Cao, G., & Kolarik, J. (2021). Ventilation in low energy residences – a survey on code requirements, implementation barriers and operational challenges from seven European countries. *International Journal of Ventilation*, 20(2), 83–102.
<https://doi.org/10.1080/14733315.2020.1732056>