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Decarbonising the EU Buildings | Model-Based Insights from European Countries

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Abstract: The European Union faces the pressing challenge of decarbonising the buildings sector to meet its climate neutrality goal by 2050. Buildings are significant contributors to greenhouse gas emissions, primarily through energy consumption for heating and cooling. This study uses the advanced PRIMES-BuiMo model to develop state-of-the-art innovative pathways and strategies to decarbonise the EU buildings sector, providing insights into energy consumption patterns, renovation rates and equipment replacement dynamics in the EU and in two representative Member States, Sweden and Greece. The model-based analysis shows that the EU's transition towards climate neutrality requires significant investment in energy efficiency of buildings combined with decarbonisation of the fuel mix, mostly through the uptake of electric heat pumps replacing the use of fossil fuels. The Use Case also demonstrates that targeted policy interventions considering the national context and specificities are required to ensure an efficient and sustainable transition to zero-emission buildings. The analysis of transformational strategies in Greece and Sweden provides an improved understanding of the role of country-specific characteristics on policy effectiveness so as to inform more targeted and contextually appropriate approaches to decarbonise the buildings sector across the EU.

Keywords: decarbonisation; energy efficiency; EU buildings; policy effectiveness; PRIMES-Buimo

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1. Introduction

The European Union's commitment to achieving climate neutrality by 2050 [1] has propelled a series of legislative measures aimed at decarbonising various sectors, with buildings emerging as a critical focus area. Under the Energy Performance of Building Directive 2010/31/EU (EPBD) [2], Member States are mandated to establish cost-optimal levels of minimum energy performance requirements for both new and existing buildings. These provisions, coupled with financial incentives and relative policies that promote energy renovations, constitute key strategies for improving the energy efficiency of the EU building stock. The revised Energy Performance of Buildings Directive (EPBD) [3] sets forth ambitious targets to transform the building stock into zero emission buildings (ZEBs) [4]. ZEBs are characterised by their very low energy demand, which is fully met by energy from renewable sources. The directive mandates that all new public buildings must be ZEBs by 2027, followed by all new (public and private) buildings by 2030 [5]. Moreover, existing buildings are required to undergo extensive renovations to meet ZEB standards by 2050 [4].

As part of the EU's broader decarbonisation agenda, the ZEB initiative can act as a complement to the European emission trading system (EU ETS), which prices carbon emissions and incentivises emission reductions across various sectors [6]. The integration of the buildings sector into the EU ETS framework (as the so-called ETS2) presents an opportunity to further accelerate the transition to a low-carbon built environment by incentivising energy-efficient building practices and renewable energy adoption.

The decarbonisation of buildings is a crucial component of the European Union's strategy to meet its climate targets and fulfil its commitments under the Paris Agreement.

However, recent literature suggests that the EU may fail to deliver on these commitments, risking a global temperature increase beyond 1.5 or 2 °C above pre-industrial levels [7]. While some reductions in greenhouse gas (GHG) emissions can be achieved by replacing old fossil-fuelled heating and cooling systems with higher-efficiency alternatives, deeper renovations of the building envelope and decarbonisation of energy supplies are essential if the EU decarbonisation targets are to be met effectively [8]. Without these measures, there is a risk of creating stranded assets (e.g., by adding more gas boilers) and falling short of EU's emission reduction goals.

Although the EPBD aimed to regulate and improve the energy efficiency of buildings across the EU, the implementation of requirements for nearly zero-energy buildings (NZEBs) has varied significantly among EU Member States [9]. While NZEBs were introduced to address the need for improved energy efficiency in buildings primarily using fossil-based energy sources, the definition and requirements have become increasingly outdated as renewable energy adoption increases [10]. Therefore, there is a growing recognition of the need to shift the focus from energy consumptions to GHG emissions by redefining NZEBs as 'nearly zero' emissions buildings.

Moreover, variations in heating and cooling demands throughout the year, coupled with fluctuations in renewable energy supplies, present challenges for achieving decarbonisation goals. As fossil fuels are phased out and are replaced by electric heat pumps, a proper management of the overall and peak power demand is required, through deep building renovations (to reduce total energy needs) and utilising electricity and heat storage. The uptake of sustainable energy supplies, particularly from renewable electricity generation and district heating, is crucial [11].

Understanding the effectiveness and impacts of EU targets and policies for decarbonising buildings and identifying challenges in their implementation is essential for guiding policy decisions and strategies at both the EU and member state levels. Several studies have examined the implications of EU decarbonisation efforts in buildings to identify the challenges and complexities in achieving ambitious decarbonisation goals. For instance, ref. [12] analysed the impact of strong energy efficient strategies and policies within the context of long-term deep decarbonisation. The study provided insights into the necessity for fast and extensive renovation of existing buildings underscoring the importance of robust policies to accelerate renovation and electrification in buildings. The critical role of decarbonising heating and cooling systems in meeting energy and climate targets was examined by [13] which identified the key challenges in decarbonising space and water heating through heat pump technologies across the EU. Similarly, in [14], it is revealed that the electrification of the EU heating sector though heat pumps is a cost-effective measure used to decarbonise the energy system that can also be supported by the EU power system. The acceleration of buildings renovation has also been identified as an effective measure towards the decarbonisation of EU buildings in [15]. This is also in line with the EU's renovation wave [16,17]. However, in recent years, the investments towards the upgrade of the performance of EU buildings is too low to be in line with the EU's climate objectives [18], because these are capital intensive decisions that may involve many decision makers who lack concrete or sufficient knowledge on the matters, factors that have been identified as the main reasons for this low engagement [19,20].

The effectiveness of the current EU climate policy framework in facilitating a cost-effective low-carbon transition was examined by [21], which identified the main sectoral challenges for the underperformance of residential buildings relative to climate targets coupled with a lack of instrumental credibility and long-term clarity. Another study [22] revealed that reference scenarios integrating currently implemented climate policies across 32 countries globally are inadequate for achieving substantial decarbonisation and to meet the 1.5 °C Paris goals. Based also on [23], the most effective strategy to decarbonise buildings to the extent required to be in line with the 1.5 °C Paris goals would be to focus on fuel switching practices in the buildings sector. Based also on [23] the most effective strategy to decarbonize buildings to the extent required to be in line with the 1.5 °C Paris goals would be to focus on fuel switching practices in the buildings sector.

Energy efficiency and decarbonisation of the European building stock are considered as key drivers of Europe's transition to climate neutrality by the mid-century, as part of the EU Green Deal and the Fit for 55 policy package. However, most analyses on emission reduction in buildings are based on large-scale models that do not model the specificities of different building types and do not include a granular representation of the load profiles of energy consumers. To overcome these challenges, in this study we soft-link the PRIMES-BuiMo buildings model (one of the most widely used and well-established models at EU level [12]) with the WHY Toolkit (details can be found in [24]). PRIMES-BuiMo has been used to provide quantitative model-based assessment of major EU energy and climate policies (Energy Efficiency directive, Fit for 55 package, "Clean Planet for All" strategy, 2030 and 2040 Climate Target). The WHY Toolkit has been developed in the context of the WHY Project (a H2020 research project [25]) and utilises advanced algorithms to estimate household energy consumption with high spatial and temporal granularity. More precisely, the WHY Toolkit uses technical information of the building, behavioural data of the inhabitants and intervention scenarios to create load profiles for electrical and thermal consumption and water usage.

The current study offers quantitative evidence on different pathways to decarbonise the EU buildings sector by 2050, based on accelerated efficiency improvements, electrification, fuel switch, net-zero energy buildings and deep renovations, smart appliances and demand-side management, to achieve climate neutrality by 2050. Based on detailed consumer representation, the study assesses energy and climate policy instruments consistent with the revised Energy Efficiency Directive, the Fit for 55 package and the EU's commitment to turn climate-neutral by 2050. This study provides an improved understanding of the role of energy consumers towards the systemic transformations required to reach the EU Green Deal goals by exploring the effects and feasibility of climate neutrality in the buildings sector with unprecedented temporal and spatial granularity, while capturing system interlinkages between energy demand, supply, prices, grids, fuel mix and storage.

While previous studies have examined the decarbonisation of the building stock for the EU globally, a cross-country comparison on the effectiveness of different policy instruments on energy efficiency in buildings is rather scarce in the literature [26]. Schild et al. [27] compared the regulatory standards of new residential buildings. Filippini et al. [28] and Ó Broin et al. [29] analysed and compared the effectiveness of energy policies on energy efficiency in residential buildings across different countries. Our study distinguishes by focusing specifically on two EU Member States with different characteristics, Sweden and Greece, assessing their specific strategies towards decarbonising buildings, exploring in particular the renovation rates, energy consumption, replacement of dwellings and energy bill dynamics. These two countries were chosen due to their diverse climate conditions, economic, cultural and building stock characteristics, providing valuable insights into the challenges and opportunities for achieving EU decarbonisation goals across different contexts. The study analyses the different consumption patterns across these countries, the implications of ambitious energy efficiency and decarbonisation policies, and the variation in renovation and equipment replacement across different policy scenarios. By analysing these factors using the PRIMES-BuiMo model, this study aims to contribute to a better understanding of the effectiveness, impacts and feasibility of EU targets for decarbonising buildings and inform future policy development and implementation efforts.

This paper is structured as follows: Section 2 describes the model used and the scenario design used in the current study. In Section 3, we present the model results for the scenarios analysed. Finally, Section 4 discusses the main research findings, provides policy recommendations and suggests further expansion steps of the current study.

2. Materials and Methods

2.1. PRIMES-BuiMo Model and It's Intrelinkages with Other Tools

The PRIMES-BuiMo model simulates the future development of the buildings sector in the EU Member States, projecting energy consumption, fuel mix, equipment choice, renovation rates, investment and CO_2 emissions under alternative policy scenarios. It dynamically simulates renovation decisions, investment, technology and fuel choices considering market and non-market barriers [12]. The model represents diverse actors (energy consumers) with distinct behavioural patterns based on their income, preferences, weather, location and household composition. In this way, it addresses the drawbacks of the representative consumer assumption by differentiating discount rates, as well as specific modelling parameters that represent behavioural patterns and the market and non-market barriers that are relevant for each building type. The model dynamically estimates useful energy demand by building type, tracks technology vintages and determines fuel mix, CO_2 emissions, operating costs and investments. It incorporates policies such as energy labelling, regulatory instruments, taxes and subsidies. Notably, it addresses market and non-market barriers in the residential sector to bridge the "energy efficiency gap". PRIMES-BuiMo combines the detailed representation of economic behaviours with engineering aspects and technical constraints embedded in the integrated model-based decision framework (Figure 1). A detailed model description can be found in [12].

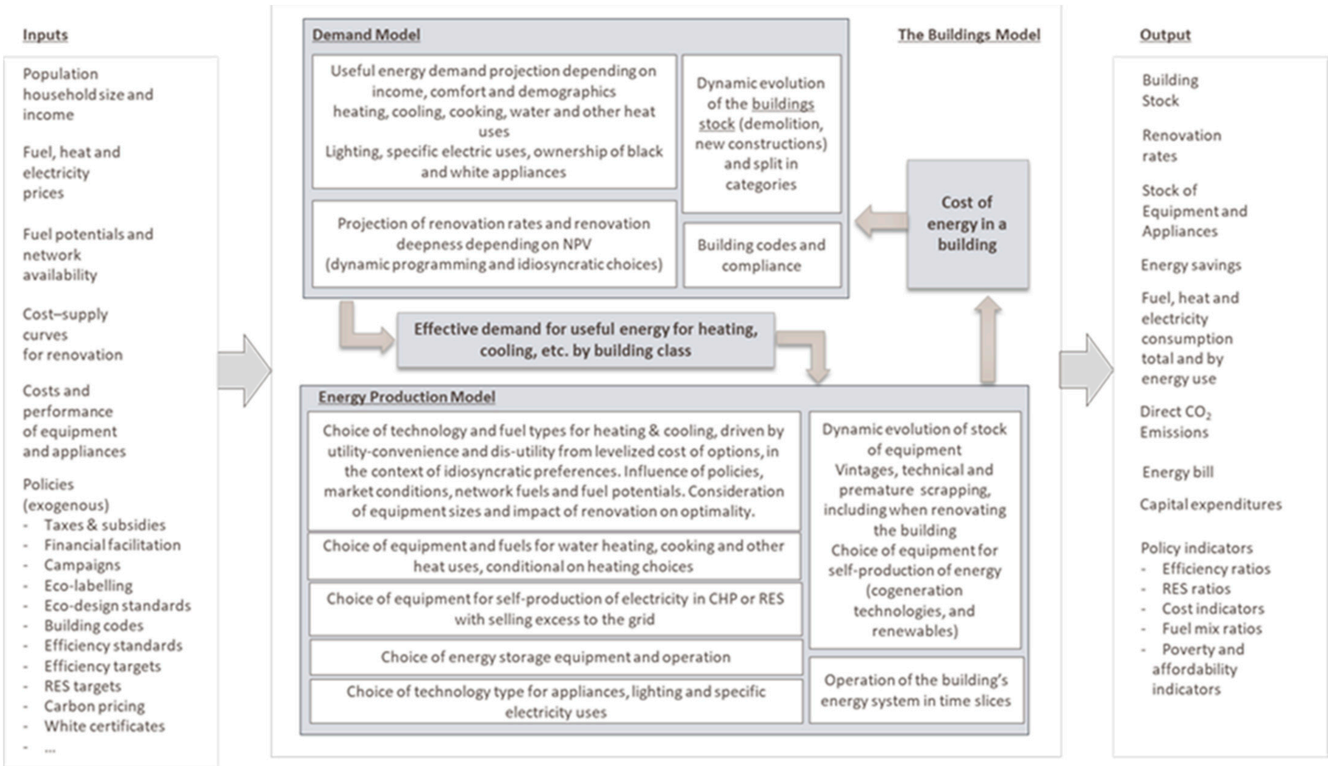


Figure 1. Flowchart of the PRIMES-BuiMo model.

The main strengths of PRIMES-BuiMo are as follows:

- The high-resolution segmentation of consumers into many classes considering key factors influencing the decisions of individuals, including income, geographic and other dimensions, as well as the classification of buildings by age and other criteria.
- The representation of market and non-market barriers hampering energy efficiency investment, through specific parameters; market barriers are related to "true" costs (that are actually paid by consumers), and issues related to the access to capital resources, whereas non-market barriers refer to elements that do not have a direct payable or "true" cost and are often termed as "perceived costs [12].

- The rich representation of policies to remove the various market and non-market barriers and facilitate energy efficiency investment. PRIMES-BuiMo can simulate a wide variety of policies and measures for the buildings sector, ranging from financial incentives (subsidies for building retrofits, loans) to institutional incentives that act as facilitators of investment, and even hard regulatory instruments (minimum efficiency standards, building codes).

PRIMES-BuiMo covers each of the EU28 MS individually. The model runs in 5-year time steps from 2005 to 2070; projections are from 2025 onwards, while the years 2005 to 2020 are calibrated to EUROSTAT statistics for energy consumption by fuel for the residential sector [30].

PRIMES-BuiMo includes a detailed database of many building classes and explicit energy-related technologies distinguished by type and vintage. The database for both sectors is integrated in the modelling framework and has been constructed using data from a variety of databases, reports and studies that had to be reconciled to construct a consistent dataset. In [30], there is an extended list of all the databases (and the respective references) that have been combined and elaborated to build the database for PRIMES-BuiMo.

The main external and internal variables included in PRIMES-BuiMo are presented in Table 1 and are instrumental in shaping the model-based scenario projections and insights that form the basis for informed decision-making and policy formulation.

Table 1. List of external and internal variables included in the study.

External Variables	• Socio-economic developments (including GDP and population projections, household income) • Technology cost assumptions • Evolution of international energy prices • Climate-related parameters (e.g., Heating Degree Days) • Energy and climate policies • Energy demand patterns, consumer habits etc • Energy resource potentials
Internal Variables	• Energy demand by sector • Energy efficiency improvements • Fuel mix by sector • Rate and depth of renovations • Adoption of efficient heating and appliances • Investment in energy efficiency and in heating equipment • Energy costs and prices • CO_2 emissions from fossil fuel combustion

A two-way interlinkage of the WHY Toolkit with the PRIMES-BuiMo model was implemented in the context of the WHY project, based on a data interface and the disaggregation of buildings in PRIMES-BuiMo. The aim of this interlinkage is to essentially update specific modelling parameters of PRIMES-BuiMo that represent consumer behaviours regarding energy consumption, based on the data on the energy consumption of the WHY Toolkit and taking into account that the latter stems from actual data on energy consumption. Essentially, the interlinkage is beneficial for PRIMES-BuiMo and the analyses that can be performed with it (like the one presented in this paper) because the model will more accurately reflect actual consumer behaviours.

The interlinkage has the form of a plug-in and is represented as data exchange tables in an MS Excel template. The tables provide the necessary dimensions for energy consumption by end use and energy carrier in different types of residential buildings. The interface requires the involvement of two operators: the toolkit operator and the operator of PRIMES-BuiMo. The toolkit operator translates the specifications into a query for the toolkit, generating the desired output. The modeller converts this output into the needed model input format.

In the context of the WHY project, the WHY toolkit was queried so as to provide separate estimates for 20 distinct European countries. The data provided from the WHY toolkit involved figures of energy consumption in different price schemes that resulted in changes in consumption patterns. The modeler translated this information into price elasticities of demand and by comparing these with the ones inferred by the original version of PRIMES-BuiMo, specific modelling parameters that represent consumers behaviour regarding energy consumption (or in other words the modelling parameters that represent non-market barriers related to energy consumption behaviour, like for example lack of knowledge, lack of information) were adjusted in such a way that the PRIMES-BuiMo could reproduce the price elasticities of demand (or their relative differentiation among the different building types) that have been calculated using the data from the WHY Toolkit. The model was then ready to be used for the preparation of policy scenarios, like the ones presented in this paper, and presented in the section below.

2.2. Scenario Design

The proper representation of the transition dynamics in the buildings sector concerns both the technical aspects of energy transition as well as behavioural elements of energy consumers and specific policy interventions, which will determine energy demand, fuel mix and clean technology uptake in the medium and long term. Given the large complexities and uncertainties related to the transformation of the EU buildings sector and the multitude of relevant policy instruments, a participatory online workshop was organised on "Improving Demand-side Modelling to Inform Ambitious Climate Policies in the European Union" in May 2022. Several stakeholders relevant to the EU's climate and energy policies were invited to investigate what issues should be considered when modelling the energy demand and what policy measures are the most important to drive the transition in the EU buildings sector. By engaging a diverse group of stakeholders, the aim was to learn about current trends and challenges from the practitioners' perspective, but also to increase the transparency and outreach of our research. The key findings from the workshop, based on the knowledge and expertise of the participating climate and energy experts, are presented in the WHY project report available online [31]. In this workshop, various energy and climate policies were identified as important for the transformation of EU buildings, building on recent regulations including the revised Energy Efficiency Directive, the Fit for 55 package and the EU's commitment to become climate-neutral by 2050 as part of the EU Green Deal (Figure 2).

The discussions at the workshop with the invited stakeholders provided valuable insights for the definition, prioritisation and development of the policy scenarios presented in the study. There are numerous political issues to be included in the energy demand modelling and prioritising them is a challenging task, where also the modelling capabilities should be considered. Through the stakeholder workshop and our research expertise, we identified the most relevant regulatory, economic and information-based interventions to be assessed in the study. Policy instruments such as subsidies or other financial incentives should be examined together with the enforcement of stringent building codes and energy performance certificates as well as measures to raise citizen awareness through informational campaigns and improved technical support.

Regarding electrification, the focus is on the potential uptake of heat pumps to electrify heating demand, while regulatory interventions for the gradual phase out of combustion appliances, uptake of heat pumps and the further encouragement of efficiency standards are also important. The complementary nature of information-based policy instruments will be added to the interventions studied, while the transition impacts on the most vulnerable, low-income population groups will also be considered.

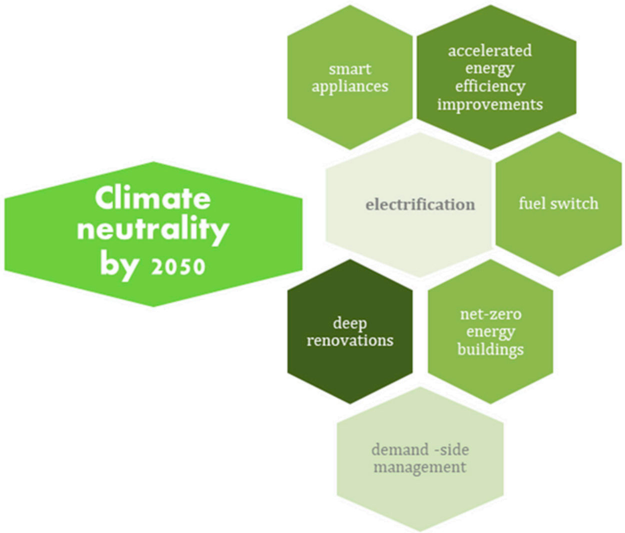


Figure 2. The foundation on achieving climate neutrality in the buildings sector. Source: elaboration by authors.

Based on the stakeholder feedback and interactions, we designed alternative policy scenarios to analyse the transformation of EU buildings towards climate neutrality. The designed scenarios are analysed to validate model behaviour under alternative policy and technology assumptions.

To explore PRIMES-BuiMo capabilities and assess its behaviour under changing exogenous assumptions, six scenarios have been designed and developed within the study. The scenarios aim to showcase the potential and demonstrate the added value of the soft-linkage of PRIMES-BuiMo model with the WHY Toolkit to enhance the modelling of the transformation dynamics of the EU Buildings sector. The main outcomes of this scenario exercise are a set of medium- and long-term projections of key energy–economy–emissions indicators that describe the future development of the EU buildings sector under alternative scenarios. These indicators include (among others) final energy consumption, energy mix in the EU buildings sector, CO_2 emissions, uptake of low-carbon technologies, renovation rates, energy and carbon prices, investment requirements and energy costs.

The study explores two different levels of climate policy ambition, namely the Existing Policy context and the Decarbonisation context. The former assumes that only existing EU and Member-State policies are implemented by 2030, but there is no intensification of climate policy beyond 2030. It includes low energy efficiency ambition reflecting the EU Reference scenario assumptions [32] aligning with the National Energy and Climate Plans (NECPs) of the EU Member States, as they were submitted in 2019. In contrast, the Decarbonisation scenario context ensures alignment with the Fit for 55 policy package and the EU Green Deal for the entire EU energy system achieving 55% emission reduction by 2030 from 1990 levels and climate neutrality by 2050. This scenario assumes also increased ambition of energy efficiency and renewable energy policies.

Within the policy contexts ('existing framework' and 'Decarbonisation') in the study, three scenarios are developed and presented in Table 2. These policy scenarios consider the stakeholder insights as gathered by the workshop and focus on different policy instruments to drive the EU's decarbonisation. In particular, the "Energy Efficiency and Electrification" scenario focuses on the potential uptake of heat pumps to electrify heating demand in EU buildings, combined with regulatory interventions targeting increased energy efficiency and the gradual phase-out of fossil fuel boilers. This scenario incorporates institutional and informational measures to remove the non-market barriers to investment in deep refurbishment of the building envelope and uptake of heat pumps. The measures tackle technical uncertainty, lack of information, inability to access funding and other institutional issues. Such measures may include education and information campaigns, adaptation of building regulations, certification, third party financing systems, the obligation of energy companies to assist energy saving investment, and others. The institutional and informational measures constitute conditions enabling consumers using reasonable discount rates in the investment decisions in energy efficiency while minimising hidden and perceived costs and can accelerate investment in the deep refurbishment of buildings.

Table 2. Developed scenarios.

Energy Efficiency and Electrification Policies	• Focuses on specific policies for enhancing energy efficiency and electrification. • Includes institutional and informational measures to address non-market barriers, encouraging investment in deep refurbishment and heat pumps
Carbon Pricing Extension	• Assumes an extension of carbon pricing in non-ETS sectors (e.g., buildings) • A linear increase in carbon price to USD 450 by 2050 complementing bottom-up renewable energy and energy efficiency policies
Energy Crisis Impact	• Reflects the recent energy crisis, with a drastic reduction in Russian gas imports to the EU • International energy prices increase significantly in 2025 and moderately in 2030 relative to "existing framework" assumptions

The second scenario assumes an extension of carbon pricing in non-ETS sectors (i.e., buildings sector) that acts as an explicit policy instrument and complements the bottom-up renewables and energy efficiency policies, as well as the enabling conditions of the first scenarios. The carbon price is defined exogenously and increases linearly by USD 15 per year, reaching USD 300 in 2040, and USD 450 in 2050. Finally, driven by stakeholder preferences, the third scenario analyses the impacts of the recent energy supply crisis with a drastic reduction in Russian gas imports to the EU, leading to increased fossil fuel import prices in the EU in 2025 and to a smaller extent from 2030 onwards. The high energy prices act on top of the scenario assumptions described above, namely the enabling conditions for efficiency and electrification as well as on the carbon pricing in non-ETS sectors.

By combining the two climate contexts (termed as "Base" and "Decarb") with the above scenarios, we designed six scenarios (presented in Table 3) which are quantified with the PRIMES-BuiMo model.

Table 3. Scenarios analysed.

Base	Reflects the existing framework scenario based on 2019 NECPs and Reference scenario assumptions. Available at: https://energy.ec.europa.eu/data-and-analysis/energy-modelling/eu-reference-scenario-2020_en (accessed on 6 June 2024)
Base_CP	Builds on "Base" scenario, but extends EU ETS scope to include the buildings sector with a linearly increasing carbon price
Base_HP_CP	Builds on "Base_CP" scenario, but assumes increased energy import prices due to energy crisis
Decarb	Reflects the 'Decarbonisation' scenario with enhanced "Energy Efficiency and Electrification" policies, including regulatory and institutional measures that align with the Fit For 55 package and climate neutrality by 2050
Decarb_CP	Builds on "Decarb" scenario, but extends the EU ETS scope to include the buildings sector with a linearly increasing carbon price
Decarb_HP_CP	Builds on "Decarb_CP" scenario, but assumes increased energy import prices due to energy crisis

3. Results

3.1. EU Scenario Results

The analysis of policy scenarios provides insights into the medium- and long-term projections of key indicators for the EU buildings sector. Figure 3 shows the final energy projections for the EU residential sector in alternative scenarios. In all 'baseline' scenarios, the final energy demand remains consistently higher than in the 'decarbonisation' scenarios, with larger differences in 2050 due to the EU's climate neutrality ambition and the system inertia to changed energy and carbon prices in the first years of the simulation due to stock turnover dynamics. The emergence of carbon prices and the increased energy import prices contribute to further reductions in final energy consumption. The effects of high energy and carbon prices are larger in the "Decarbonisation" context compared to "Baseline", as high energy (and carbon) prices alone are not sufficient to induce deep energy savings in "Baseline", as the market and non-market barriers to energy efficiency do not allow for extensive efficiency investments. The regulatory and institutional measures of the decarbonisation scenarios that remove the market and non-market barriers enable accelerated uptake of energy efficiency investments for all consumer classes and building types that are necessary when energy (and carbon) prices increase. Energy efficiency indicators based on PRIMES-BuiMo modelling highlight a significant reduction in average energy consumption per household in the decarbonisation scenarios, reaching about 50% by 2050 compared to 2015 levels.

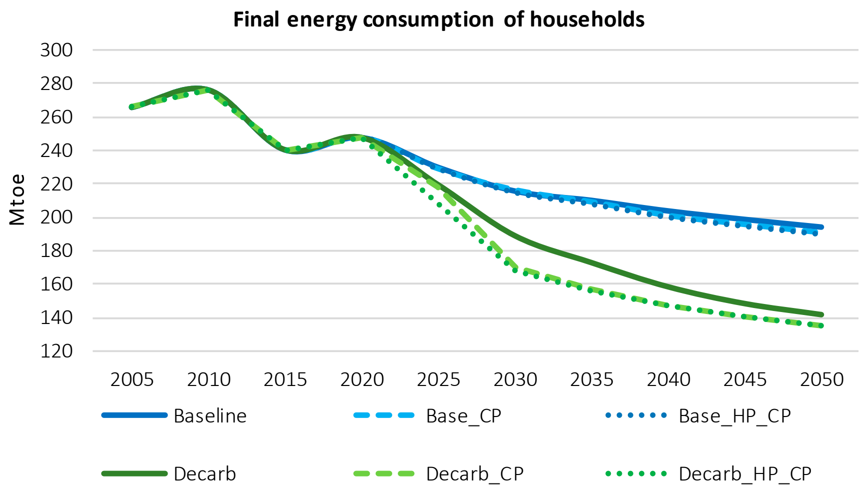


Figure 3. Final energy consumption in EU buildings in alternative scenarios.

Figure 4 presents the model-based results for energy-related CO_2 emissions from EU residential buildings in alternative policy scenarios. In all decarbonisation scenarios CO_2 emissions become zero in 2050, being in line with the climate neutrality goal. The extension of the EU ETS scope to the buildings sector, as well as the assumption of higher energy prices would result in faster emissions reduction in both contexts ("Base" and "Decarb") especially in the period 2025–2040. This is triggered by the acceleration of changes in the fuel mix for heating uses and the faster replacement of fossil-based heating equipment by the uptake of more efficient and low-carbon technologies (i.e., heat pumps).

The fuel mix used in the buildings sector is influenced by the different scenario settings. Even in the "Base" projections (Figure 5), there is a trend towards increasing electrification of energy demand, with the share of electricity in fuel mix increasing particularly in the longer term, as the capital costs of heat pumps decrease over time. On the other hand, there is a reduction in the share of fossil fuels (gas, coal, oil) over time in all scenarios. The decrease is even larger in scenarios assuming high carbon prices and energy prices.

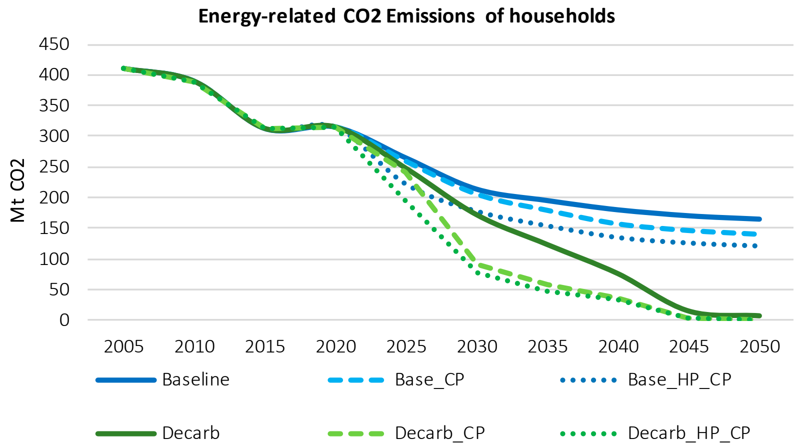


Figure 4. Energy-related CO_2 emissions of European residential buildings.

Figure 5. Fuel mix and final energy consumption in the EU households in alternative "Base" (**upper graph**) and "Decarb" scenarios (**low graph**).

In the decarbonisation scenarios (Figure 5), the electrification of heating in EU buildings is a dominant trend already in the short term: electricity shares almost double by 2030 compared to 2020 in all decarbonisation scenarios, because of the increasing penetration of heat pumps. The accelerated uptake of heat pumps is driven by both policies promoting the use of renewable energy in heating and policies promoting the use of efficient equipment. In the long term, electricity represents more than half of total energy consumption in all "Decarb" scenarios and reaches about 60% in the scenarios with high carbon prices and energy prices. In these scenarios, the remaining 40% of buildings' energy demands is covered by renewable energy (mostly biomass and solar energy) and decarbonised gases, including green hydrogen and clean synthetic gases.

3.2. Scenario Results for Specific Countries

This section focuses on representative country-specific results and delves into the behaviour of different building types to show how the different policy contexts affect the different building and consumer classes. This is important from a policy perspective to provide an enhanced understanding that a common policy context does not necessarily have the same impact in different MSs and building types, because the macroeconomic, climatic and other conditions interact with the ambition and effectiveness of the policies. In particular, this section compares the model results for Sweden and Greece. These two countries are considered as extreme cases, but still representative of the differences among EU Member States in terms of climatic conditions (and as a result their heating and cooling needs) but also households' private income (on a per capita basis). Furthermore, the building stock, or the characteristics thereof, differ between the two countries: Sweden has a relatively newer building stock compared to Greece and already today Sweden's households are largely equipped with heat pumps, which are being used as the main heating system, whereas households in Greece use mostly oil and gas boilers to meet their heating needs.

3.2.1. Energy Consumption in Houses

Figure 6 presents the energy consumption in houses for heating and cooling, in the two countries across different scenarios modelled with PRIMES-BuiMo. Energy needs in Sweden are significantly higher compared to Greece throughout the projection period. This difference is expected due to the longer and colder winters experienced in Sweden, which result in much higher space heating requirements, which make up for most of the heating and cooling needs in both countries. Additionally, households in Sweden have, on average, a higher private income compared to those in Greece, contributing to higher energy consumption levels.

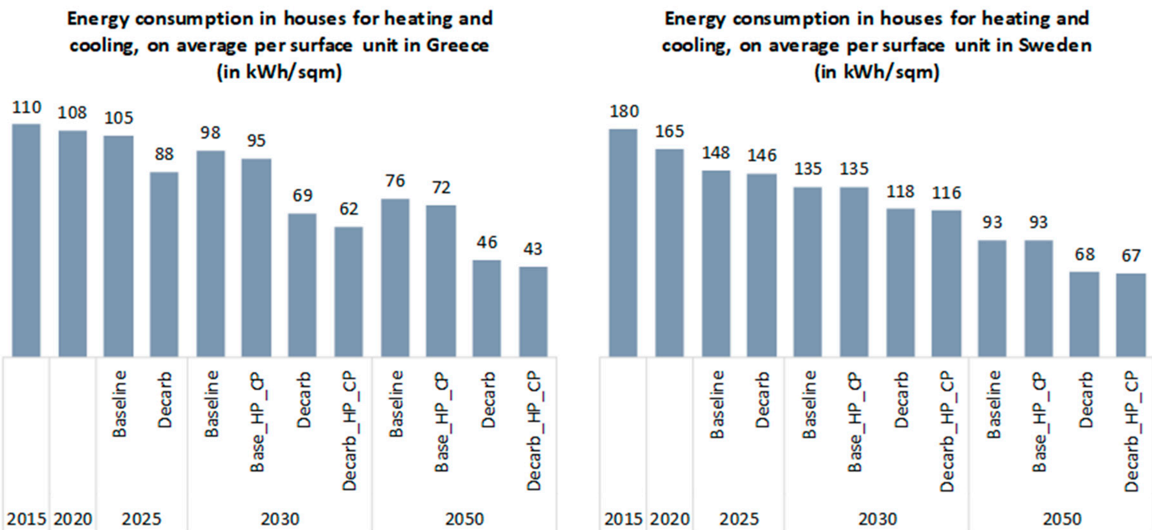


Figure 6. Energy consumption in houses for heating and cooling, on average per surface unit (in kWh/sqm) in Greece (**left**) and Sweden (**right**).

In both EU countries, energy consumption in the Baseline scenarios is set for a reduction over the period of 2020–2050; the reduction is higher in Sweden's households as they have a higher private income compared to households in Greece and can thus invest more into new, efficient equipment and renovation of buildings. In both Member States, the ambitious energy efficiency policies as well as the institutional measures included in the decarbonisation scenarios induce larger energy consumption reductions compared to the baseline scenarios. The climate neutrality goal in the decarbonisation scenarios results in a strong reduction in energy consumption for heating and cooling in both countries that is as high as 60% relative to the 2020 energy consumption, irrespective of the price scheme and other assumptions included in "Decarb" scenario variants.

3.2.2. Rates of Renovation and Equipment Replacement

Figure 7 represents the projections for annual renovation/equipment replacement rates for Greece and Sweden in alternative scenarios over the 2020–2050 period, providing an improved understanding of the factors driving the development of energy consumption. The model-based analysis shows that both renovation and equipment replacement rates are higher in the decarbonisation scenarios compared to their respective baseline scenarios in both countries, driven by the ambitious energy efficiency and net-zero policies. The composition of building stock differs between Greece and Sweden, influencing the renovation dynamics. The newer building stock in Sweden (and therefore the better energy performing) explains that the annual renovation rate of the building envelope is closer to the historic one (i.e., even without additional energy efficiency policy) in the short term in the "Base" scenarios. Conversely, Greece would experience higher renovation rates in the Baseline scenarios due to a larger proportion of older and less energy-efficient buildings in need of upgrades. However, the depth of renovations is projected to be higher in Sweden than in Greece (driven mainly by the higher private income of households), which is also depicted in the larger reduction in energy consumption for heating and cooling in the respective scenarios.

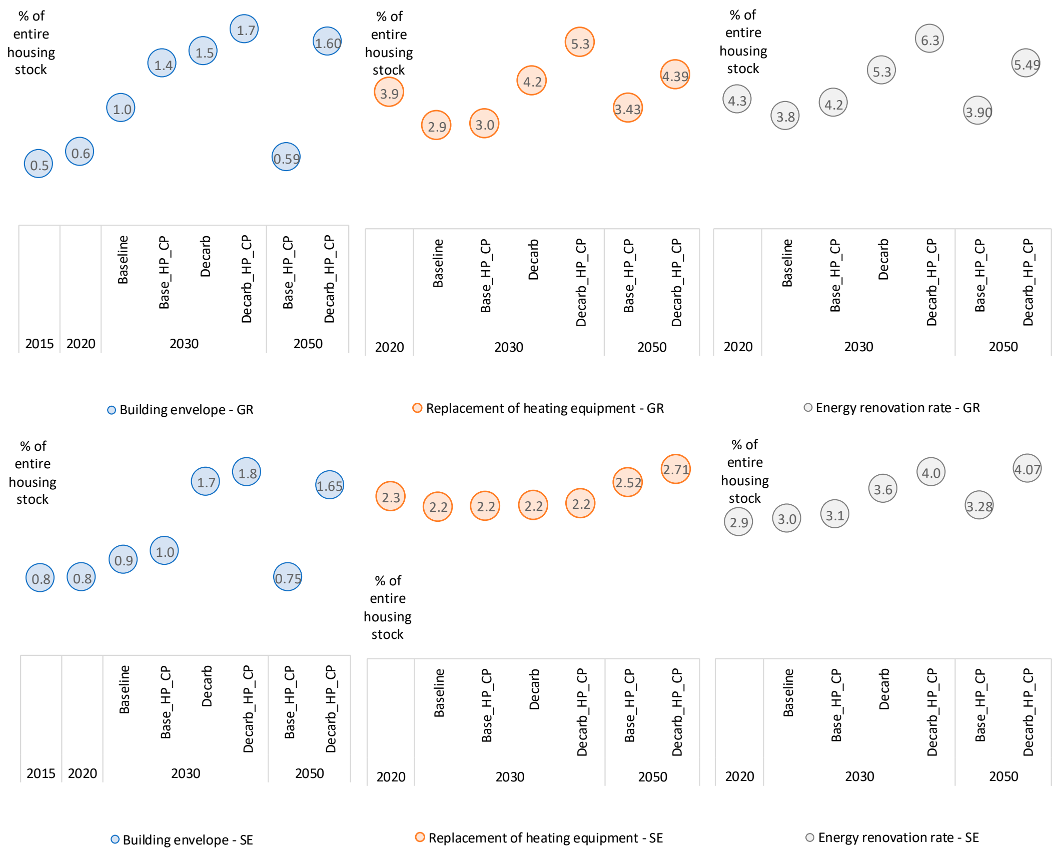
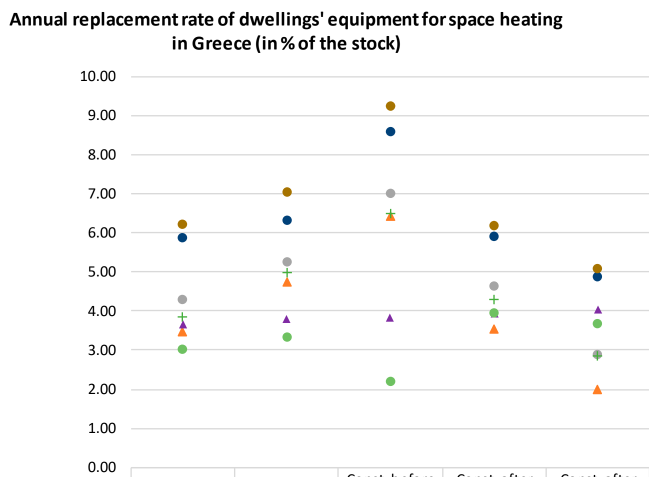


Figure 7. Projection of annual rates of renovations of building envelope and replacement of heating equipment in houses in Greece (**top**) and Sweden (**bottom**).

The ambitious energy efficiency policies of the decarbonisation scenarios together with the enabling conditions representing the ambitious regulatory and institutional measures would enable a larger replacement rate of space heating equipment in Greece compared to Sweden. This is driven by the fact that almost one third of the current building stock in Sweden is already equipped with heat pumps; therefore, replacements of heating equipment with more efficient ones are mainly due to the end of the equipment's life. Also, district heating makes up of a large part of Swedish heating, and replacing it with other technologies is usually scarce in these cases. On the other hand, Greece still relies more heavily on fossil fuels for heating (mostly diesel and natural gas), making equipment replacements a more impactful strategy for reducing energy consumption and associated emissions. The extension of EU ETS to the buildings sector, regardless of the policy context, is therefore more effective in Greece compared to Sweden, taking into account the fuel mix in the two countries. The EU ETS mechanism drives significant shifts towards cleaner heating technologies in Greece, while in Sweden, where heat pumps already dominate, the relative impact of the policy is lower in magnitude.

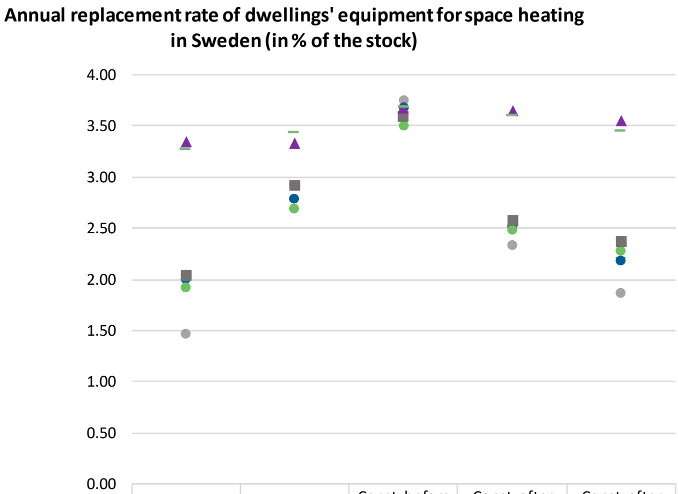
3.2.3. Replacement Rate of Space Heating Equipment by Building Type and Age

Figures 8 and 9 present the annual replacement rate of dwellings' equipment for space heating in Greece and Sweden for different building types in different policy scenarios, respectively. In both countries, and irrespective of the scenario, the replacement rates are higher in single-family households compared to multi-family ones. This is logical as multi-family households may be usually equipped with central heating systems that serve many dwellings in one building. In these cases, it may be hard to reach an agreement on changing the central heating system with an individual one, and this may well explain the lower replacement rates in multi-family buildings. As a result, the replacement rates tend to be lower in multi-family buildings and this reflects the logistical and practical considerations involved in the transitioning from centralised to individual heating solutions.



	Multi	Single	Const. before 1975	Const. after 1975	Const. after 2000
2016–2020	3.46	4.72	6.42	3.54	1.97
2026–2030 Baseline	4.28	5.26	7.00	4.63	2.87
2026–2030 Base_HP_CP	3.83	4.97	6.50	4.29	2.83
2026–2030 Decarb	5.85	6.30	8.58	5.91	4.88
2026–2030 Decarb_HP_CP	6.21	7.03	9.24	6.18	5.06
2031–2050 Baseline	3.64	3.80	3.81	3.92	4.01
2031–2050 Decarb_HP_CP	3.00	3.32	2.20	3.95	3.68

Figure 8. Annual replacement rate of dwellings' equipment for space heating by building type and building age in Greece.



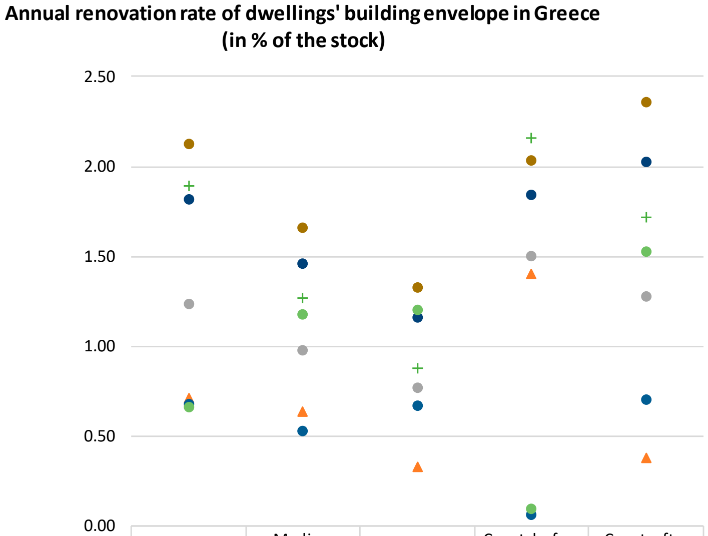
	Multi	Single	Const. before 1975	Const. after 1975	Const. after 2000
2016–2020	1.47	2.93	3.76	2.33	1.87
2026–2030 Baseline	2.05	2.69	3.68	2.53	2.21
2026–2030 Base_HP_CP	2.01	2.79	3.69	2.52	2.18
2026–2030 Decarb	1.93	2.69	3.51	2.49	2.29
2026–2030 Decarb_HP_CP	2.04	2.93	3.60	2.58	2.37
2031–2050 Baseline	3.35	3.33	3.67	3.66	3.55
2031–2050 Decarb_HP_CP	3.27	3.43	3.68	3.60	3.45

Figure 9. Annual replacement rate of dwellings' equipment for space heating by building type and building age in Sweden.

Comparing the replacement rates of the increased price variants with the respective rates of the "normal" price variants, increased prices drive replacement rates upwards in both EU countries, and this is more pronounced in the single-family households. This is driven by the updates of the modelling parameters that reflect consumer behaviours regarding energy use. The projected rates of replacement differ based on the age of the building, with older constructions having higher rates compared to more recent ones in both regions. The model-based analysis shows that energy efficiency and climate policies have a larger impact in the replacement of the heating equipment in Greece compared to Sweden, which effectively means that replacement rates in decarbonisation scenarios are larger than in the baseline scenarios in Greece compared to Sweden.

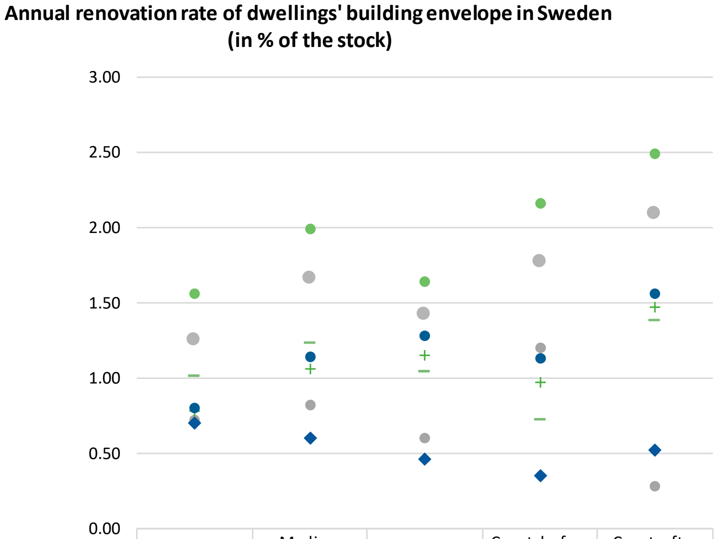
3.2.4. Renovation Rate of Building Envelope by Building Age and Consumer Income

Figures 10 and 11 show the PRIMES-BuiMo scenario projections for annual renovation rate of the building envelope in Greece and Sweden differentiated by building and consumer income level, respectively. The ambitious energy efficiency policies implemented in the decarbonisation scenarios drive renovation rates upwards in both countries compared to the respective baseline scenarios. Also, older constructions (and therefore worse performing ones) experience a higher renovation rate compared to more recent ones, at least in the short term. As the projection period advances, a shift occurs wherein newer constructions begin to undergo renovation in higher rates, due to the completion of initial renovation cycles for older buildings. This explains why the annual renovation rates of the more recent constructions are higher after 2030 compared to those of the older ones.



	Low income	Medium income	High income	Const. before 1975	Const. after 1975
2016–2020	0.72	0.64	0.33	1.41	0.39
2026–2030 Baseline	1.24	0.98	0.77	1.51	1.28
2026–2030 Base_HP_CP	1.90	1.27	0.88	2.16	1.72
2026–2030 Decarb	1.82	1.46	1.17	1.85	2.03
2026–2030 Decarb_HP_CP	2.13	1.66	1.33	2.04	2.36
2031–2050 Baseline	0.68	0.53	0.67	0.07	0.71
2031–2050 Decarb_HP_CP	0.66	1.18	1.20	0.10	1.53

Figure 10. Annual renovation rate of dwellings' building envelope by income class and building's age in Greece.



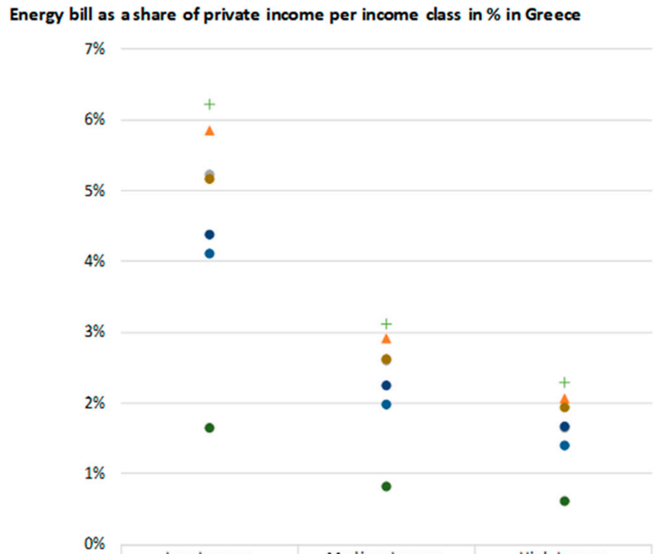
	Low income	Medium income	High income	Const. before 1975	Const. after 1975
2016–2020	0.72	0.82	0.60	1.20	0.28
2026–2030 Baseline	0.78	1.06	1.15	0.97	1.47
2026–2030 Base_HP_CP	0.80	1.14	1.28	1.13	1.56
2026–2030 Decarb	1.56	1.99	1.64	2.16	2.49
2026–2030 Decarb_HP_CP	1.26	1.66	1.42	1.77	2.09
2031–2050 Baseline	0.70	0.60	0.46	0.36	0.52
2031–2050 Decarb_HP_CP	1.01	1.23	1.04	0.72	1.38

Figure 11. Annual renovation rate of dwellings' building envelope by income class and building's age in Sweden.

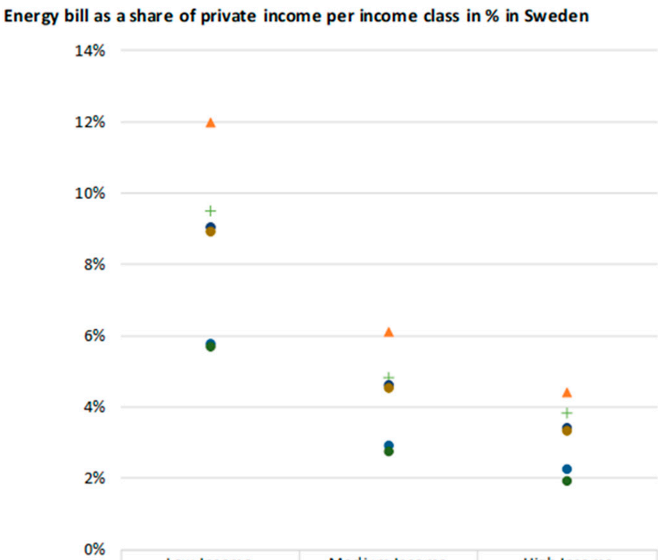
The two Member States present differences regarding the performance of different income classes. In Greece, lower-income consumers show the higher renovation rates in both “Base” and “Decarb” contexts, whereas in Sweden the medium-income consumers show the higher rates. This relates to the distribution of ages of constructions in the different income groups: in Greece, most of the very old constructions commonly belong to low-income families, and this is why the annual renovation rates of these categories (i.e., low-income and constructions before 1975) show a similar performance in all contexts and periods. In contrast, in Sweden, the medium-income families live in the oldest constructions, and this is why the performance of these two categories is similar in all contexts and time periods. These results underscore the importance of considering country-specific characteristics (such as income distribution, building age demographics) when formulating and implementing energy efficiency and climate policies.

3.2.5. Scenario Impacts on Households’ Energy Bill

Figure 12 shows the energy bill as a share of private income per income class in Greece and Sweden as projected by PRIMES-BuiMo in alternative policy scenarios. In both countries, low-income consumers need to spend a higher share of their income for energy purchases compared to medium- and high-income consumers irrespective of the policy or price context, pointing towards higher risks of energy poverty. The investments in energy efficiency in the decarbonisation scenarios would result in reduced share of income that all consumer classes need to spend for energy purchases, but low-income consumers are more positively affected in the sense that the share for them decreases more than for the other consumers. Finally, the shares of energy expenditure in Sweden are always higher than in Greece. This is to be expected as the higher income per capita in Sweden is more than counterbalanced by the higher energy consumption per capita (due to the longer and colder winters increasing heating requirements) and higher energy prices in Sweden compared to Greece.



	Low Income	Medium Income	High Income
▲ 2020	5.84%	2.91%	2.06%
● 2030 Baseline	5.22%	2.60%	1.65%
+ 2030 Base_HP_CP	6.22%	3.12%	2.29%
● 2030 Decarb	4.38%	2.25%	1.66%
● 2030 Decarb_HP_CP	5.16%	2.62%	1.94%
● 2050 Baseline	4.10%	1.98%	1.41%
● 2050 Decarb_HP_CP	1.66%	0.82%	0.60%



	Low Income	Medium Income	High Income
▲ 2020	12.01%	6.12%	4.41%
● 2030 Baseline	9.06%	4.61%	3.40%
+ 2030 Base_HP_CP	9.49%	4.83%	3.82%
● 2030 Decarb	9.06%	4.62%	3.43%
● 2030 Decarb_HP_CP	8.91%	4.53%	3.36%
● 2050 Baseline	5.79%	2.91%	2.26%
● 2050 Decarb_HP_CP	5.70%	2.76%	1.95%

Figure 12. Energy bill as a share of private income per income class in alternative policy scenarios in Greece (**top graph**) and Sweden (**bottom graph**).

4. Discussion and Conclusions

The current study provides a comprehensive analysis of the implications, challenges and opportunities for the EU buildings sector on the road to climate neutrality by mid-century, while offering new insights for key energy, emissions and cost indicators for the transformation of the buildings sector. The enhanced representation of consumer behaviours and multiple building types in PRIMES-BuiMo enables a more realistic assessment of the impacts and effectiveness of energy efficiency and climate policies based on real-world data, increasing their relevance for policy making and the model's integrity.

From a policy perspective, the study shows that the deep decarbonisation of buildings in the EU is technically and economically feasible, and it can be achieved through the deep renovation of the building's envelope accompanied by the massive electrification of heat uses. The extension of ETS in the buildings sector accelerates the energy transition, but this needs to go hand in hand with bottom-up policies like, for example, subsidisation policies to promote the energy upgrade of the building envelope, the replacement of the heating equipment and the purchase of heat pumps by consumers. Comparing the model results on a Member State level, the stringency and ambition of climate policies, or even the type of policy instruments to reduce emissions, should not be horizontal and should fully consider the specificities of each EU Member State. In addition, policies need to also have a social dimension (e.g., to alleviate energy poverty risks); thus, such national specificities need to be considered.

Insights into factors that influence the energy-related choices in the residential sector are explored and the study offers a nuanced understanding of how these factors can be integrated into large-scale models. Detailed assessments of the potential for adopting low and zero-carbon solutions in the residential sector have been conducted considering system effects and broader implications. The model-based analysis provides several emissions, energy efficiency, fuel mix and technology indicators, as well as their impacts on energy costs and prices for households by income class reflecting energy affordability and energy poverty risks. The study presents a comprehensive assessment that incorporates diverse indicators to track the transformation of the EU buildings, providing an enhanced granularity compared to similar studies in terms of building types, income classes and national specificities. The co-design of scenarios with the stakeholders has also ensured a more inclusive and informed approach to policy interventions, enhancing the relevance and effectiveness of the study.

Based on the scenario analysis, comparing the results for two EU countries and different building types, we conclude that there are some similarities in the model-based projections and in consumers' behaviours and thus in the effectiveness of different policies. However, certain differences exist that relate to the macroeconomic, climatic and building age factors that are specific to each country. The latter boils down to the fact that although all countries need to make efforts to meet certain climate and energy efficiency targets on an EU and national level, the stringency and ambition of policies, or even the type of policy instrument, should not be horizontal and should consider the specificities of each EU Member State.

Modelling results for Greece and Sweden show disparities that are largely attributed to differences in climatic conditions and household incomes. Sweden, with its colder and longer winters, exhibits higher energy needs for heating compared to Greece, but the higher private incomes in Sweden enable larger investment in deep retrofits and in new, efficient equipment, and thus stronger energy demand reductions until 2050. Overall, the impacts of specific energy and climate policy instruments differentiates by country based on their climatic and macroeconomic conditions as well as the current state of the buildings sector (e.g., construction age, technologies used), the level of energy prices and the societal context, in particular focusing on low-income households which commonly live in older, poorly insulated constructions, use inefficient energy equipment, lack access to finance for energy investment and face higher risks of energy poverty. As the energy and climate policies need to also have a social dimension (e.g., to alleviate energy poverty), such national specificities should be considered for policy design and implementation.

Ambitious energy efficiency and climate policies included in decarbonisation scenarios would lead to even larger reductions in energy consumption for heating and cooling compared to baseline scenarios in both countries. Specifically, the climate neutrality goal results in a remarkable 60% reduction in energy consumption in the 2020–2050 period in both Greece and Sweden, regardless of the price scheme or other assumptions. The annual renovation and replacement rates for building envelopes and heating equipment are higher in the decarbonisation scenarios compared to baseline scenarios in both countries. The differences in these rates are influenced by factors such as building age, income levels and housing types. For instance, single-family households exhibit higher replacement rates compared to multi-family dwellings, particularly due to challenges in coordinating central heating system changes in multi-family buildings.

The analysis reveals that energy efficiency and climate policies have a more pronounced impact on heating equipment replacement rates in Greece compared to Sweden. This discrepancy is attributed to Greece's current heavier reliance on fossil fuels for heating (while heat pumps already dominate in the Swedish market), making climate policy interventions more effective in driving replacement rates. The study highlights that low-income consumers consistently spend a higher share of their income on energy purchases compared to medium- and high-income households in both countries. While investments in energy efficiency under decarbonisation scenarios reduce the energy burden for all consumer classes, low-income households are particularly affected, experiencing a larger reduction in their income spent on energy purchases.

This study can be further expanded by including additional variables, such as building occupancy patterns, lifestyle changes and behavioural dynamics, to provide a more comprehensive understanding of energy consumption patterns and the factors driving renovation behaviours. This study examined two diverse EU countries, Greece and Sweden, but can be further expanded to capture regional variations, as well as in other EU Member States, that have different climatic and economic characteristics and different building stock composition. Finally, investigating the interactions of various energy efficiency and climate policies (building codes, financial incentives, carbon pricing), including their synergies and trade-offs, could provide more insights for designing coherent policy packages and identifying optimal policy mixes—differentiated by country, income and/or building type—for achieving decarbonisation objectives in a cost-efficient and equitable manner.

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References

1. European Commission. 2020, 2050 Long-Term Strategy. Available online: https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en (accessed on 12 March 2024).
2. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings (Recast). Available online: https://eur-lex.europa.eu/eli/dir/2010/31/oj (accessed on 12 March 2024).
3. Commission Welcomes Political Agreement on New Rules to Boost Energy Performance of Buildings across the EU. 2023. Available online: https://ec.europa.eu/commission/presscorner/detail/en/IP_23_6423 (accessed on 12 March 2024).
4. Maduta, C.; Melica, G.; D'agostino, D.; Bertoldi, P. Towards a decarbonised building stock by 2050: The meaning and the role of Zero Emission Buildings (ZEBs) in Europe. *Energy Strategy Rev.* **2022**, *44*, 101009. [CrossRef]
5. European Parliament. Revision of the Energy Performance of Buildings Directive-Q4. 2021. Available online: https://www.europarl.europa.eu/legislative-train/carriage/revision-of-the-energy-performance-of-buildings-directive/report?sid=7801 (accessed on 12 March 2024).

6. Directive (EU) 2023/959 of the European Parliament and of the Council of 10 May 2023 amending Directive 2003/87/EC Establishing a System for Greenhouse Gas Emission Allowance Trading within the Union and Decision (EU) 2015/1814 Concerning the Establishment and Operation of a Market Stability Reserve for the Union Greenhouse Gas Emission Trading System. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2023.130.01.0134.01.ENG&toc=OJ:L:2023:130:TOC (accessed on 12 March 2024).
7. European Parliament. Combating Climate Change, Fact Sheets on the European Union—2024. Available online: https://www.europarl.europa.eu/erpl-app-public/factsheets/pdf/en/FTU_2.5.2.pdf (accessed on 12 March 2024).
8. European Academies' Science Advisory Council. Decarbonisation of Buildings: For Climate, Health and Jobs. 2021. Available online: https://easac.eu/fileadmin/PDF_s/reports_statements/Decarb_of_Buildings/EASAC_Decarbonisation_of_Buildings_Web_publication030621.pdf (accessed on 12 March 2024).
9. D'Agostino, D.; Tzeiranaki, S.T.; Zangheri, P.; Bertoldi, P. Assessing Nearly Zero Energy Buildings (NZEBs) development in Europe. *Energy Strategy Rev.* **2021**, *36*, 100680. [CrossRef]
10. IEA. *Tracking Clean Energy Progress 2023*; IEA: Paris, France, 2023. Available online: https://www.iea.org/reports/tracking-clean-energy-progress-2023 (accessed on 6 May 2024).
11. Jodeiri, A.M.; Goldsworthy, M.J.; Buffa, S.; Cozzini, M. Role of sustainable heat sources in transition towards fourth generation district heating—A review. *Renew. Sustain. Energy Rev.* **2022**, *158*, 112156. [CrossRef]
12. Fotiou, T.; de Vita, A.; Capros, P. Economic-Engineering Modelling of the Buildings Sector to Study the Transition towards Deep Decarbonisation in the EU. *Energies* **2019**, *12*, 2745. [CrossRef]
13. Abbasi, M.H.; Abdullah, B.; Ahmad, M.W.; Rostami, A.; Cullen, J. Heat transition in the European building sector: Overview of the heat decarbonisation practices through heat pump technology. *Sustain. Energy Technol. Assess.* **2021**, *48*, 101630. [CrossRef]
14. Thomassen, G.; Kavvadias, K.; Navarro, J.P.J. The decarbonisation of the EU heating sector through electrification: A parametric analysis. *Energy Policy* **2021**, *148 Pt A*, 111929. [CrossRef]
15. Filippidou, F.; Navarro, J.P.J. Achieving the Cost-Effective Energy Transformation of Europe's Buildings. *JRC Tech. Rep.* **2019**, *219*, 278207. [CrossRef]
16. EC. *Commission Staff Working Document 'Impact Assessment Accompanying the Document Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions—Stepping up Europe's 2030 Climate Ambition: Investing in a Climate-Neutral Future for the Benefit of Our People*; SWD(2020) 176 Final; EC: Brussels, Belgium, 2020.
17. EC. *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions 'A Renovation Wave for Europe: Greening Our Buildings, Creating Jobs, Improving Lives'*; COM(2020) 662 Final; EC: Brussels, Belgium, 2020.
18. EEFIG. The Evolution of Financing Practices for EE in Buildings, SMEs and Industry, Publications Office of the European Union. 2021. Available online: https://op.europa.eu/en/publication-detail/-/publication/a3032517-c761-11ec-b6f4-01aa75ed71a1/language-en/format-PDF/source-256242892 (accessed on 23 May 2024).
19. EEA. *Accelerating the Energy Efficiency Renovation of Residential Buildings—A Behavioural Approach*; European Environment Agency: Copenhagen, Denmark, 2023. Available online: https://www.eea.europa.eu/publications/accelerating-the-energy-efficiency (accessed on 23 May 2024).
20. Navarro, J.P.J.; Bueso, M.C.; Vázquez, G. Drivers of and Barriers to Energy Renovation in Residential Buildings in Spain—The Challenge of Next Generation EU Funds for Existing Buildings. *Buildings* **2023**, *13*, 1817. [CrossRef]
21. Drummond, P.; Ekins, P. Cost-effective decarbonization in the EU: An overview of policy suitability. *Clim. Policy* **2017**, *17* (Supp. 1), S51–S71. [CrossRef]
22. Camarasa, C.; Mata, É.; Navarro, J.P.J.; Reyna, J.; Bezerra, P.; Angelkorte, G.B.; Feng, W.; Filippidou, F.; Forthuber, S.; Harris, C.; et al. A global comparison of building decarbonization scenarios by 2050 towards 1.5–2 °C targets. *Nat. Commun.* **2022**, *13*, 3077. [CrossRef] [PubMed]
23. Levesque, A.; Pietzcker, R.C.; Baumstark, L.; Luderer, G. Deep decarbonisation of buildings energy services through demand and supply transformations in a 1.5 °C scenario. *Environ. Res. Lett.* **2021**, *16*, 054071. [CrossRef]
24. Nacht, T.; Ganglbauer, J.; Pflugradt, N.; Neuroth, D. WHY Toolkit Libraries. 2023. Available online: https://www.why-h2020.eu/materials/articles-and-reports/why-toolkit-libraries-d32-1 (accessed on 12 March 2024).
25. Available online: https://www.why-h2020.eu (accessed on 23 May 2024).
26. Thonipara, A.; Runst, P.; Ochsner, C.; Bizer, K. Energy efficiency of residential buildings in the European Union—An exploratory analysis of cross-country consumption patterns. *Energy Policy* **2019**, *129*, 1156–1167. [CrossRef]
27. Schild, P.G.; Klinski, M.; Catherine, O.G. *Analyse og Sammenlikning av Krav til Energieffektivitet i Bygg i Norden og Europa*; Regjeringen: Oslo, Norway, 2010.
28. Filippini, M.; Hunt, L.C.; Zorić, J. Impact of energy policy instruments on the estimated level of underlying energy efficiency in the EU residential sector. *Energy Policy* **2014**, *69*, 73–78. [CrossRef]
29. Ó Broin, E.; Nässén, J.; Johnsson, F. Energy efficiency policies for space heating in EU countries: A panel data analysis for the period 1990–2010. *Appl. Energy* **2015**, *150*, 211–223. [CrossRef]

30. Fotiou, T.; Capros, P.; Fragkos, P. Policy Modelling for Ambitious Energy Efficiency Investment in the EU Residential Buildings. *Energies* **2022**, *15*, 2233. [CrossRef]
31. Schibline, A.; Ceglarz, A. Improving Demand-Side Modelling to Inform Ambitious Climate Policies in the European Union. Workshop Report. 2021. Available online: https://www.why-h2020.eu/fileadmin/Inhalte/Dokumente/WHY__The_EU_Use_Case_Workshop_Report.pdf (accessed on 12 March 2024).
32. European Commission. EU Reference Scenario 2020. Available online: https://energy.ec.europa.eu/data-and-analysis/energy-modelling/eu-reference-scenario-2020_en (accessed on 12 March 2024).