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Decarbonisation pathways for the buildings sector (Deliverable D3.1-B.2 Report)

Annex 6 of Deliverable D3.1

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Executive Summary

In this report, we investigate what successful decarbonisation means at the sector level, and specifically for the buildings sector, by identifying viable socio-technical strategies for buildings transformation. This includes modelling the evolution of the sector for the European Union (EU27), with detailed analyses of potentials of and boundary conditions for the implementation of various technological options such as electrification, efficiency improvements, deep building retrofits, the changing role of gas, and integration of renewable energy technologies. Many of these options are still novel or have not been sufficiently reflected in existing NDCs.

The role of coupling the buildings sector with the electricity system via increased electrification and the role of heat and low-carbon gases must be considered to quantify effects of individual options in the context of a national power system transformation, as well. This work will be depicted in Task 3.6 of WP3.

Qualitative aspects, such as societal and political boundary conditions of transformation processes as a result of WP4, are integrated into the modelling of this work in WP3 as far as possible, allowing an improved understanding of the transition dynamics for the buildings sector in EU27.

This report is the outcome of three major pieces of work related to the transformation of the buildings sector. First, we worked on modelling the EU27 building stock with the well-established PRIMES-BuiMo model assessing different pathways to achieve carbon neutrality and the sector's contribution to the overall energy system transformation. In the course of the modelling work, following disruptive world events and specifically the Russian invasion of Ukraine, we thought it necessary to adapt the work accordingly and, also, research the impacts of the war, followed by the energy crisis with increased energy prices, on the transformation of the buildings sector. Second, we have performed a pathways, targets, and policy approaches comparison among three large-emitting world regions, namely China, India and the EU27. Last, but not least, we have researched how the energy transition impacts gender through a sectoral approach and performing a Gender Impact Assessment for buildings' renovation – an activity that in some world regions is the cornerstone of decarbonisation.

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1. Introduction

A key reason behind the sector's persistently high emissions is its diversity and complexity. Buildings come in all shapes and sizes, are used as residences or for commercial operations, and vary across a wide range of climate zones. The decarbonisation measures required for existing buildings also differ dramatically for those appropriate for ensuring new buildings are zero carbon. Nonetheless, the range of technologies needed to achieve building sector decarbonisation are mature and widely available, it is their widespread adoption that is proving elusive.

The Paris Agreement requests each country to draft and communicate their post-2020 climate actions and submit them in the form of Nationally Determined Contributions (NDCs). Countries submitted their NDCs (new NDCs or updated NDCs) by 2020 and following every five years thereafter (e.g. by 2020, 2025, 2030), regardless of their respective implementation time frame. Collectively, the national efforts should aim towards the global goal of keeping global warming to well below 2 °C or even limiting it to 1.5 °C (United Nations, 2016). Still, current and new NDCs fall very short of this global goal- they are not in line with 2C and 1.5C.

A sectoral approach to NDCs and its implications are hard to come by. On the one hand, existing national models often include detailed sectoral modules, and examine to what extent essential technology options are explicitly considered, in particular mitigation options required for deep decarbonisation (e.g. deep retrofiting). On the other hand, possible options and their implementation are investigated in sector models with a high technological resolution. The modelling of a whole sector including both bottom-up information (e.g. for detailed technology configurations) and top-down policies, in a hybrid engineering-economic approach can provide insights that are valuable for the energy transition and decarbonisation goals.

Buildings are crucial for climate change mitigation due to their significant share in final energy consumption and GHG emissions. However, the sector's decarbonisation has been moving slowly despite being identified by numerous research and policy studies as the one with the highest decarbonisation potential.

This study aims to identify key barriers to buildings decarbonisation and analyse how policy instruments and other structural elements of the sector can address these barriers to ensure a rapid, cost-efficient and just transformation of the buildings sector towards climate neutrality by mid-century.

The research begins with a quantitative modelling study that moves the literature forward by asking whether there is a preferred set of policy options for achieving long-term decarbonisation goals in buildings, based on the pace and magnitude of achieved energy and emissions savings to update the upcoming EU NDC and if there are lessons to be learned from different policy options towards buildings decarbonisation. When referring to mitigation pathways, in this report, the focus lies largely on policy implementation to harness "no regret" mitigation options in buildings, including energy efficiency and electrification of heating, rather than relying on more uncertain disruptive technologies.

The major objective of this study is to provide an improved understanding of the role of different mitigation pathways towards carbon neutrality within the building sector in quantitative terms. These pathways focus on, or combine two broad policy strategies, i.e., 1) buildings' energy efficiency and 2) heating electrification, and a new policy instrument being introduced from 2028 in the EU, which is the extension of the Emission Trading System (ETS) to buildings. In this respect, a quantitative analysis is performed, investigating the required energy policy strategies and measures as well as the potential

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contribution by residential and services buildings to achieving the EU ambitious energy efficiency and emission reduction targets in both the medium and long term.

To accomplish this, two families of scenarios are defined and modelled with the well-established PRIMES BuiMo model (Fotiou et al., 2019, 2022), and two policy contexts are explored, accordingly:

- The “existing policy framework” context derived from the current (2020) national energy and climate plans (NECPs) of the EU Member States and already adopted energy and climate policies in a stylized manner,
- the “decarbonization” context, based on accelerated energy efficiency improvements, electrification, fuel switch, net-zero energy buildings and deep renovation - in line with the FF55 package, the new EU NDC for 2030 and climate neutrality goal in 2050.

In addition, a variant of each scenario is also examined, namely the “high energy prices” variant, examining the effects of Russia’s war against Ukraine on the energy policies implementation within the building sector and especially in energy price increases. Not only that, but it is important to understand how energy crises leading to large energy price increases are affecting the short-, medium- and long-term decarbonisation goals and policy implementation to get there.

A second step of the work is the policy and roadmaps comparison among three major world regions – the EU, India and China – to gain a better understanding of the buildings sector transformation and priority areas based on the foreseen mitigation pathways from a policy perspective. In other words, this line of work in the report captures the diversity of building decarbonization policies in three major economies encompassing developed and emerging countries facing different challenges and opportunities for buildings sector transformation.

The third step researches the impacts and co-benefits of gender in the energy transition with a special focus on the buildings sector. The Gender Impact Assessment (GIA) framework for residential building renovations introduced in this report is based on the methodology of UBA (Spitzner et al. 2020, ed. by the German Environment Agency UBA, Spitzner 2020). The GIA analysis presented here puts the perspective of a single household and the individuals therein into the centre of the analysis, i.e. the micro-level of investigation, in the case of a household undergoing an energy renovation to reduce emissions. Here, the possible manifold impacts on the household members are described.

In the following section (Methods), we are describing the methodology followed in each of the three lines of work and how they aid in gaining a complete picture of the mitigation pathways in the buildings sector. In continuity, the modelling work related to decarbonization strategies for EU27 is presented, followed by the policy pathways comparison in the three world regions researched to reach the Gender Impact Assessment of the buildings sector.

We then, move on to briefly explain the work of WP3 in the buildings sector when it comes to opportunities and constraints of the energy transition and decarbonization potential while encompassing the results of the three lines of work. We also comment on and conclude the report touching upon policy implications and how can this study inform the next NDCs. The key barriers include: economic, technical, skilled workforce, information access, social (also through GIA) co-benefits and barriers of the energy transition. The higher renovation rates are very hard to realise in practise and they have a big impact on the quality of life of residents – high requirements to really enable such a renovation process—they require enormous financial resources and may raise energy poverty issues.

In this report we connect quantitative and social aspects in order to strengthen the knowledge base for a just energy transition in the buildings sector and the whole energy system. On top of other aspects

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researched we also dove into the high energy prices and whether they speed up the transition. However, though this research we came across the burden on the household budget – support schemes are needed. These aspects will be further analysed in the work we are performing for the Deep Dives in WP5.

The report concludes by acknowledging its limitations and suggesting areas for future research to further explore building decarbonisation policy measures in greater depth.

2. Methods

In this section we will introduce the methods followed in each line of work in the buildings sector. We start by introducing the design and implementation of energy transition scenarios in the EU27, we then move on to the methodology followed for the policy and decarbonization roadmaps in the EU27, China and India. Last, we explain the gender impact assessment performed in the buildings sector.

The main line of work the buildings' sector conducts quantitative analyses of possible ambitious transformation opportunities and processes considering potentials and boundary conditions of the countries under consideration – in particular in EU27. The following central research questions are considered:

- What promising ambitious technical, care economical and personal behavioural options are available for buildings transformation and how can they be characterised according to the state of knowledge?
- Which country-specific boundary conditions must be considered when implementing these options into current and future systems?
- How can sectoral transformation paths in the countries be assessed considering sector coupling – electrification of heat?

As a result, sectoral technology paths are presented in a consistent quantitative manner, based on the state of the art in research and technology and in line with the long-term climate protection goals. Sectoral modelling in WP3 is developed in close relation to the work on policy options and strategies in WP4 as techno-economic conditions are determined by the regulatory framework. The work provides quantitative background knowledge as relevant information for the Sectoral Conversation in WP1 and the analysis of sectoral international climate agreements in WP6. In addition, it provides possible sectoral paths and benchmarks for ambition as a detailed basis for the development of (usually aggregated) national transformation pathways and more ambitious NDCs and long-term low-emission strategies in WP5.

We performed the modelling of EU27 using the PRIMES-BuiMo model which projects the final energy consumption, fuel mix, CO₂ emissions, renovation rates and depth, equipment choice and replacement rates in the residential and services sectors, under alternative policy and regulatory measures (Fotiou et al., 2019, 2022). It covers market and non-market barriers; hidden costs and perceptions affecting consumer behaviour; and models a variety of policy instruments influencing decisions and possibly removing barriers.

The model accounts for behavioural aspects of energy consumers while also respecting engineering and technical constraints and specificities, as well as tapping possibilities for buildings transformation. PRIMES-BuiMo provides projections for residential and service buildings independently and covers all EU Member States individually and runs in 5 years' time steps from 2020 to 2070.

Two sets of scenarios are presented within the study. The scenarios are designed to explore two policy contexts: i) an "existing framework" context (i.e., a lower energy efficiency ambition reflecting the Baseline scenario assumptions) mirroring the 2020 National Energy and Climate Plans (NECPs) and already adopted policies in a stylized manner and ii) a "Decarbonisation" context meeting the upscaled EU climate targets in 2030, including the -55% GHG emission target of the revised EU NDC and specific, more ambitious targets for energy efficiency and renewables; also leading to climate neutrality in the EU by 2050.

The scenarios include a large set of specific current and future policies (e.g., policies to promote the renovations of buildings, obligations for renewable fuels in Heating & Cooling, support for the

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electrification of heating, etc.). The decarbonisation context also includes assumptions that a variety of regulatory and non-regulatory policies facilitate the transition and the achievement of the upscaled targets supporting the uptake of new clean technologies and the corresponding investment undertaking. The enabling conditions also bring cost benefits by pulling technology along the learning curves, through the learning-by-doing mechanism.

Exploring the energy crisis impacts, we also studied variants to the sets of scenarios described above. The “high energy prices” variants reflect the current energy crisis and the drastic reduction of Russian gas imports to the EU because of the Russian invasion in Ukraine and assess their impacts to the buildings energy sector. The main assumptions include international energy prices increasing drastically in 2025 by about 53% and 40% in oil and coal compared to their 2020 levels, respectively, while the gas price is more than double the 2020 price. The increase of energy import prices is reflected in year 2025 in PRIMES BuiMo as the model is operating in 5-year time steps. The methodological framework is described in detail in Subsection 1 of the report.

The second line of work we undertook replies to the question “how do policy analyses contribute to WP3 results?”. Policy analyses provide valuable input and further understanding of the ambition levels towards transforming the buildings sector of the three world regions. Among others, the task of this WP is to identify sectoral mitigation pathways, challenges and different approaches that can inform each other thus contributing to better informed and defined NDCs – where a sectoral approach is needed.

The first step was to synthesize the net-zero building decarbonization pathways for the three regions (EU, China and India) and the primary barriers potentially obstructing their realization. Secondly, the policy analysis consisted of two steps: policy landscape analysis and policy intensity analysis. This is the main instrument of understanding which are those policies and their implementation status in realizing the mitigation pathways in EU, India and China.

As a result, the policy analysis was conducted through a combination of literature review and consultations with national experts which participated in the Sectoral Conversation for the Buildings sector. Literature includes peer-reviewed papers, governmental documents (including assessment reports), grey literature, and news articles. This work was conducted among both WP3 and WP4 and is informing each other.

Last, and following one of the most prominent, in the last years, approaches to researching the energy transition we introduce the framework and structuring lines of a Gender Impact Assessment on the – energy renovation of buildings. This is especially relevant to the EU27 where the major activity towards emissions reduction in the buildings sector is the renovation of the existing building stock as new constructions emerge slowly.

Taking gender into account particularly relates to the following aspects of the specific objectives of this work:

- a. Understanding of the underlying socio-economic conditions/barriers of existing NDCs
- b. Systematically identifying transformation opportunities and challenges in the buildings sector, based on the high gender relevance of the sector.
- c. Deriving ambitious yet realistic national pathways for buildings that take improving gender equality into account.
- d. Developing policy and governance options for ambitious, effective, and transformative climate action that contribute to gender equality.
- e. Validating and promoting the integrated gender-responsive effectiveness and feasibility of the co-created policy and governance options in Sectoral Conversations

These three lines of work and methods followed encompass aspects on technical, financial, regulatory, social and co-benefits aspects of the buildings sector through the energy transition and decarbonisation efforts.

3. Decarbonisation pathways for the EU Buildings sector and the role of high energy prices

This section is based on the article manuscript “Decarbonisation pathways for the EU Buildings sector: what is the role of high energy prices?” submitted to the Energy Policy Journal

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Abstract

The Paris Agreement requests each country to draft and communicate their post-2020 climate actions and submit them in the form of Nationally Determined Contributions (NDCs). The European Union’s (EU) initial NDC was the commitment to decrease greenhouse gas emissions (GHG) by at least 40% by 2030 compared to 1990. This ambition level was already raised to 55% reduction on GHG by 2030 in 2021. The main research questions we are asking, in this study, are a) if there is a preferred mitigation pathway to update the upcoming EU NDC and b) if there are lessons to be learned from different options towards buildings decarbonisation. The objective is to provide an improved understanding of the role of different mitigation pathways within the EU building sector, i.e., buildings energy efficiency, equipment electrification and the extension of the Emission Trading System (ETS) to buildings. To accomplish this, two sets of scenarios are defined and modelled with PRIMES BuiMo, and two policy contexts are explored – an existing framework conditions and a decarbonisation one. In addition, a variant is also examined, namely the “high energy prices” variant – mirroring the effect of the Russian invasion of Ukraine on the energy policies implementation within the buildings sector. The results offer evidence on the different mitigation pathways towards the systemic transformations required to reach the EU Green Deal goals, presenting the effects and feasibility of climate neutrality in the buildings sector and capturing system interlinkages between energy demand, supply, CO₂ and energy prices, and fuel mix. We conclude that EU energy policy measures should be further developed focusing on the energy demand reduction, establishing strategies that promote energy efficiency renovations, and on both electrification and high energy efficiency of the buildings technical equipment along with the extension of carbon pricing in the building sector. With respect to the residential sector, at least 1.9% of dwellings should be renovated annually and a minimum of 2.6%-3.1% of the total building stock (including both residential and commercial buildings) should replace the heating equipment on an annual basis until 2030 and 2050, respectively. Last, the energy crisis impacts are much greater in the “decarbonization” context compared to the baseline scenario, since high energy prices alone are not sufficient to induce deep energy savings in the latter, as the market and non-market barriers to energy efficiency do not allow for extensive efficiency investments.

Keywords

decarbonisation pathways, energy efficiency, electrification, high energy prices, carbon neutrality

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1. Introduction

The Paris Agreement requests each country to draft and communicate their post-2020 climate actions and submit them in the form of Nationally Determined Contributions (NDCs). Countries submitted their NDCs (new NDCs or updated NDCs) by 2020 and following every five years thereafter (e.g. by 2020, 2025, 2030), regardless of their respective implementation time frame. Collectively, the national efforts should aim towards the global goal of keeping global warming to well below 2 °C or even limiting it to 1.5 °C (United Nations, 2016).

The European Union's (EU) initial NDC included the commitment to reduce greenhouse gas emissions (GHG) by at least 40% by 2030 compared to 1990, within its wider 2030 climate and energy policy framework (European Commission, 2008). However, with the adoption of the European Climate Law in 2021, the EU made a legal commitment to achieve the goal of reducing its emissions to net zero by 2050 at the latest - in line with the temperature goals set out in the Paris Agreement. The law also sets the intermediate more ambitious target of reducing net GHG emissions by at least 55% by 2030 compared to 1990 emission levels (European Commission, 2021c).

To implement the Climate Law, the EU recently adopted a key reform of its climate and energy legislation through a series of measures proposed in 2021 as part of the 'Fit for 55' package (European Commission, n.d.-b). With full implementation at the EU and national levels, these measures should enable the EU to achieve its emission reduction target of at least 55% by 2030, compared to 1990. This package consists of eight legislative acts setting the EU energy targets for 2030 and 2050 and suggesting the pathway for their achievement, while the recast Renewable Energy Directive (RED II) (European Council, 2018) and the amending Directive on the Energy Efficiency (EED) (European Commission, 2018b) (European Commission, 2021b) are central pillars of it.

With respect to the buildings sector, energy efficiency and decarbonization of the European building stock are considered as key drivers of Europe's transition to climate neutrality by mid-century. This is evident in the role they play in the new sectoral targets set as part of the EU Green Deal and the Fit for 55 policy packages, and most recently in the REPowerEU plan (European Commission, n.d.-b), mainly through the revised Energy Performance of Buildings Directive (EPBD) (European Parliament & Council of the European Union, 2018).

2. Research questions

The updated NDCs, to be submitted until 2025, should define new mitigation pathways in line with the latest climate science focused on specific energy policy strategies, in terms of the sectors with the greatest potential for both energy savings and CO₂ emissions, such as buildings, transport and energy supply, considering both the overall EU and each sector's specific targets achievement. Furthermore, they must determine the contribution of each sector on both the short and long-term overall emission reduction targets, while it is crucial to propose additional measures to successfully confront exceptional occasions (such as a shock on the fuel prices) and minimize their possible negative effects on the overall energy system.

Model-based scenario development is an essential tool previously used to examine the feasibility, and mitigation potential of various decarbonisation strategies in line with the EU's objective to reach climate-neutrality by 2050 (Capros et al. (2019), Tsiropoulos et., (2022), Costa et al, (2021)). These strategies are often expressed as narratives (Rodrigues et al., (2022), van Sluisveld et al. (2020), Granado et al. (2020)) which are translated into quantitative input to the modelling framework of energy-system and integrated-assessment models (ESMs/IAMs). Promoting energy efficiency and sufficiency measures, including lifestyle change, in the end-use sectors, accelerating the electrification and penetration of renewable energy sources in the energy system, and investing in alternative low-carbon fuels (e.g., biofuels, synfuels and hydrogen) infrastructure are a few examples of the examined strategies. In general, studies have shown that deep decarbonisation of the European energy system can be achieved through a combination of demand (e.g. energy efficiency, lifestyle changes) and

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supply-side options (e.g. renewable electricity, green hydrogen), each one associated with specific barriers, costs, and uncertainties.

In-depth sectoral assessments of decarbonisation targets and strategies are on the other hand rare in the literature. More specifically, while there is a recognition that buildings will play an important role in reaching overall decarbonisation objectives (Camarasa et al. (2022), Wang et al. (2018)), given their high contribution to total GHG emissions and mitigation potential (e.g., up to 85% reduction in GHG emissions from buildings in Europe compared to baseline projections in 2050 according to Cabeza et al. (2022)), less is known about the impacts of different policy mixes and fuel price assumptions on energy and emissions in the EU's buildings sector. Furthermore, the true mitigation potential and feasibility of families of decarbonisation policies remains unexplored.

This study moves the literature forward by asking whether there is a preferred set of policy options for achieving the EU's long-term decarbonisation goals in buildings, based on the pace and magnitude of achieved energy and emissions savings to update the upcoming EU NDC and long-term low-emission development strategy and if there are lessons to be learned from different policy options towards buildings decarbonisation. When referring to mitigation pathways, in this paper, the focus lies largely on policy implementation to harness “no regret” mitigation options in buildings, including energy efficiency and electrification of heating, rather than relying on more uncertain disruptive technologies.

The objective of this study is to provide an improved understanding of the role of different mitigation pathways within the building sector. These pathways focus on, or combine two broad policy strategies, i.e., 1) buildings energy efficiency and 2) equipment electrification, and a new policy instrument being introduced from 2028 in the EU, which is the extension of the Emission Trading System (ETS) to buildings. In this respect, a quantitative model-based analysis is performed, investigating the required energy policy strategies and measures as well as the potential contribution by residential and services buildings to achieving the EU ambitious energy efficiency and emission reduction targets in both the medium and long term.

To accomplish this, two sets of scenarios are defined and modelled with PRIMES BuiMo, and two policy contexts are explored, accordingly:

- The “existing framework” context derived from the national energy and climate plans (NECPs) and already adopted policies in a stylized manner, reflecting the initial EU NDC submitted to COP21 in 2015 and
- the “decarbonization” context, based on accelerated energy efficiency improvements, electrification, fuel switch, net-zero energy buildings and deep renovation towards meeting the EU's revised NDC target for 2030 and the 2050 climate neutrality goal.

In addition, a variant is also examined, namely the “high energy prices” variant, mirroring the effect of Russia's war against Ukraine on the energy policies implementation within the building sector and the impacts of increased energy prices.

The results offer evidence on the different mitigation pathways towards the systemic transformations required to reach the EU Green Deal goals, presenting the effects and feasibility of climate neutrality in the buildings sector and capturing system interlinkages between energy demand, supply, CO₂ and energy prices, and fuel mix.

Firstly, this study gives a clear view of measures that may be included in the updated NDCs, regarding both the residential and services buildings. In detail, minimum required building envelope and heating equipment replacement rates are determined, based on the energy policy framework considered in terms of each investigated mitigation pathway. These rates drive the fuel mix in buildings as well as the buildings final energy consumption and the CO₂ emissions, resulting in reduced emissions thus contributing to attaining the EU overall climate goals. Furthermore, this study defines specific strategies that should be considered so that the indicative EU building sector targets, both in short and long-term, can be accomplished. Finally, the study identifies the specific additional measures that

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should be considered in order for both the residential and services buildings to deal with the negative impacts of the war in Ukraine on fuel prices.

3. Policy framework

During the last decades, the EU is actively pursuing and implementing ambitious energy and climate policies, aiming to reduce its GHG emissions, while boosting growth, creating jobs and fostering environmental sustainability. The EU climate policy framework is based on the implementation of policy measures related to four key pillars, including:

- GHG emission reduction targets
- Energy efficiency improvement (e.g., in the form of efficiency standards)
- Increase of renewable energy shares in final energy consumption
- Carbon pricing through the EU Emission Trading System and Emission Trading System II

The targets for these key policy pillars have been gradually strengthened in the last decades with the adoption of increasingly ambitious targets, from the 20-20-20 targets in 2008 to the 40% GHG reduction target for 2030 (adopted in 2016) and the EC 2030 Climate Target Plan/ Fit For 55 policy package that introduced a more ambitious climate target for 2030, namely 55% GHG emission reduction relative to 1990 levels, while stepping up the ambition for energy efficiency and renewable energy uptake.

In parallel, the European Commission (EC) has explored long-term transformation pathways towards deep decarbonisation. While the EU energy roadmap 2050 and the Roadmap to a Low-Carbon economy explored the implications of achieving 80% reduction in EU GHG emissions over 1990-2050 (European Commission, 2011a; European Commission, 2011b), the focus has gradually shifted towards exploring more ambitious targets to climate neutrality by mid-century as communicated in the “A Clean Planet for all” strategy¹ published in November 2018 (European Commission, 2018a).

Recently, the EC launched the EU Green Deal (European Commission, n.d.-a). The EU Green deal is a roadmap accompanied by a set of policy initiatives and legislation packages with the overarching goal of making Europe climate neutral in 2050. The main legislative piece is the EU Climate Law setting the binding goals of 55% emissions reduction by 2030 (w.r.t. 1990) and climate neutrality by 2050. In July 2021, the Fit for 55 package was presented by the EC — a set of proposals to revise and update EU legislation and to put in place new initiatives with the aim of ensuring that EU policies are in line with the EU Green Deal and Climate Law.

These medium and long-term targets and strategies are accompanied by specific policy instruments, which are commonly included in EU and national legislation in the form of directives (e.g., EU Emissions Trading System - ETS or Energy Efficiency Directive - EED). Of special relevance to the buildings sector is the amended in 2018 EED and its recent (July 2021 and 2023) proposed update, by the EC, where buildings and the heating and cooling sector are recognized as the ones with the highest energy saving potential. In addition, the European Commission Regulation 2019/2021 laying down eco-design requirements for electronic devices, as reported in the Directive 2009/125/EC, is of importance to the white and black appliances¹ used in households along with consumer preferences for their replacement and choice.

The recast EED proposal raises the level of ambition of the EU energy efficiency target and makes it binding by requiring EU countries to collectively ensure an additional reduction of energy consumption of 9% by 2030 compared to the 2020 reference scenario projections (European Commission, 2020). On top of that, and following the latest energy crisis, in the REPowerEU plan, presented in May 2022, the EC proposed to increase the binding EU energy efficiency target from 9% to 13%, compared to the 2020 Reference Scenario. Last, in March 2023, the European Council presidency and the European

¹ White appliances include dryers, dishwashers, refrigerators, freezers, washing machines, lighting. Black appliances include vacuum cleaners, entertainment, information and communication and small appliances (i.e., battery chargers).

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Parliament reached a provisional political agreement to reduce final energy consumption at EU level by 11.7% in 2030 compared to the projections of 2020 Reference Scenario. This is translated into a final energy consumption target of 763 million tonnes of oil equivalent (Mtoe) and an indicative primary consumption target of 992.5 Mtoe by 2030 in the EU27. Furthermore, the annual energy saving obligation is almost doubled from 0.8% to 1.5% between 2024 and 2030. At the same time, when it comes to the public sector, the EU countries are required to attain an annual energy consumption reduction of 1.7% and to renovate at least 3% of the total floor area of public administration buildings.

Updates were also introduced in terms of the Renewable Energy Directive (RED). In July 2021 the Commission proposed a second revision of the RED, raising the use of renewables in the transport sector and in buildings heating and cooling target from 32%, which was the target after the first RED revision that entered into force in 2018, to 40%. However, less than a year later, a target of 45% was proposed as a result of the Russian invasion of Ukraine and the EU's need to improve its energy security by reducing the amounts of imported fossil fuels. Finally, in March 2023, a provisional agreement of at least 42.5%, but aiming for 45%, target was reached.

Within both already accepted as well as the expected EED and RED recasts the buildings sector is recognized as one with the highest potential for emissions reduction and energy efficiency and updated measures relating to national long-term building-related strategies are covered under the amended Energy Performance of Buildings Directive (EU) 2018/844 (EPBD) (European Parliament & Council of the European Union, 2018) and the Directive 2009/125/EC (European Parliament, 2009). In terms of the EPBD, EU countries should determine strong long-term renovation strategies aiming at decarbonizing the national building stocks by 2050, with specific milestones for 2030 and 2040. In addition, they must also define cost-optimal minimum energy performance requirements for both new and undergoing major renovation buildings as well as for the replacement of technical building systems, such as heating and cooling systems, and building envelope renovation. Regarding Directive 2009/125/EC, the European Commission Regulation 2019/2021 (European Commission, 2019), laying down eco-design requirements for electronic displays, is of great importance to the white and black appliances used in both residential and services sector along with consumer preferences for their replacement and choice.

To illustrate the evolution of energy policy in the EU and its alignment to international climate protection agreements, Figure 1 shows the timeline of the energy policy development in the EU from 1986 until today and its connection to international climate protection milestones within the last five decades.

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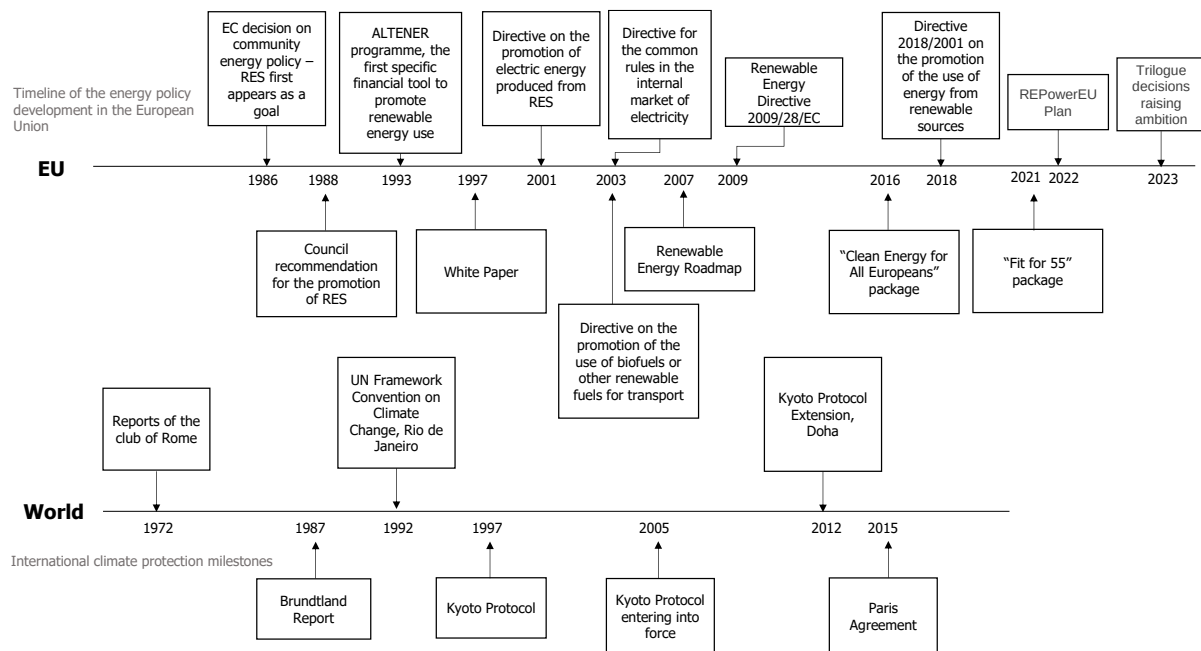


Figure 1 Energy policy development in the World and the European Union²

² Negotiations between the institutions on legislative proposals generally take the form of tripartite meetings ('trilogues') between Parliament, the Council and the Commission (<https://www.europarl.europa.eu/olp/en/interinstitutional-negotiations>).

4. Modelling framework and scenario development

Brief description of PRIMES-BuiMo

The PRIMES-BuiMo model projects the final energy consumption, fuel mix, CO₂ emissions, renovation rates and depth, equipment choice and replacement rates in the residential and services sectors, under alternative policy and regulatory measures (Fotiou et al., 2019, 2022). It covers market and non-market barriers; hidden costs and perceptions affecting consumer behaviour; and models a variety of policy instruments influencing decisions and possibly removing barriers. Figure 2 provides a description of PRIMES BuiMo including input and output variables.

The model accounts for behavioural aspects of energy consumers while also respecting engineering and technical constraints and specificities, as well as tapping possibilities for buildings transformation. PRIMES-BuiMo provides projections for residential and service buildings independently and covers EU Member States individually. The model splits the stock of buildings into many categories, namely by: geographic locations, age of construction, income classes and service sector sub-sectors. Income classes help to simulate the heterogeneity of the economic position of energy consumers and their idiosyncratic behaviour, which generally depends (among others) on a multitude of factors, including income, gender, personal preferences, climatic conditions, access to loans, location and household composition. Instead of a single representative actor, the model includes a variety of groups of actors with distinct behavioural patterns. In particular, discount rates differ by income class with low-income classes typically facing higher discount rates, representing their difficulty to access to low-cost loans. Through the differentiation of the discount rates based on real-world estimates, the model can reproduce consumer decisions (e.g. to purchase a heat pump or improve thermal insulation) capturing the heterogeneity of consumers in each class, thus addressing the drawbacks of the representative consumer assumption.

The modelling of renovation is based on the concept of dynamic discrete choice, where, out of a finite set of dynamic renovation strategies, heterogeneous agents choose the most cost-efficient ones. These agents are differentiated based on the splits available for each of the buildings' subsectors – residential and services. A dynamic strategy, endogenous to the model, may involve renovation of building envelope, technical building system equipment selection, including self-production equipment for electricity, premature replacement of equipment, and fuel switching. Starting point, based on the renovation strategy by building class, is the calculation of the useful energy demand to be met by the purchase of energy products (technical building systems and electric appliances). This, in turn, is translated to the final energy consumed (through dynamic evolution and keeping track of equipment vintages) by the space heating and cooling system. The choice of the space heating strategy depends on the timing and depth of the envelope renovation. Likewise, the dynamic strategy of hot tap water and cooking equipment depends on the space heating system. Keeping track of capital turnover as technology vintages, PRIMES-BuiMo determines the fuel mix for the technical building equipment. As a result, it derives energy consumption by fuel, associated CO₂ emissions, operating costs, and investment expenditures. In addition, PRIMES-BuiMo includes a sub-module projecting electricity use in households, which first determines the energy service to be provided and then chooses the type of technology to purchase to meet the desired level of energy use. The turnover of the stock of appliances is dynamic and endogenous to the model. Policy instruments and specifically eco-design regulations influence the technology types that the market offers to consumers.

Energy labelling and other policies are represented in the model and facilitate the uptake of highly efficient, yet more expensive, technology types through reducing the uncertainty and lack of information factors. In particular, PRIMES-BuiMo can represent various policy instruments including: Taxes and subsidies for energy products, Financial facilitation for renovation and the purchase of low-carbon technologies, Information campaigns, Eco-labelling of technical equipment, Eco-design standards, Building code standards and levels of compliance, Energy efficiency standards, Carbon pricing (EU and national), white certificates and targets for RES-heating and cooling.

Annex 6 of Deliverable D3.1 Decarbonisation pathways for the buildings sector

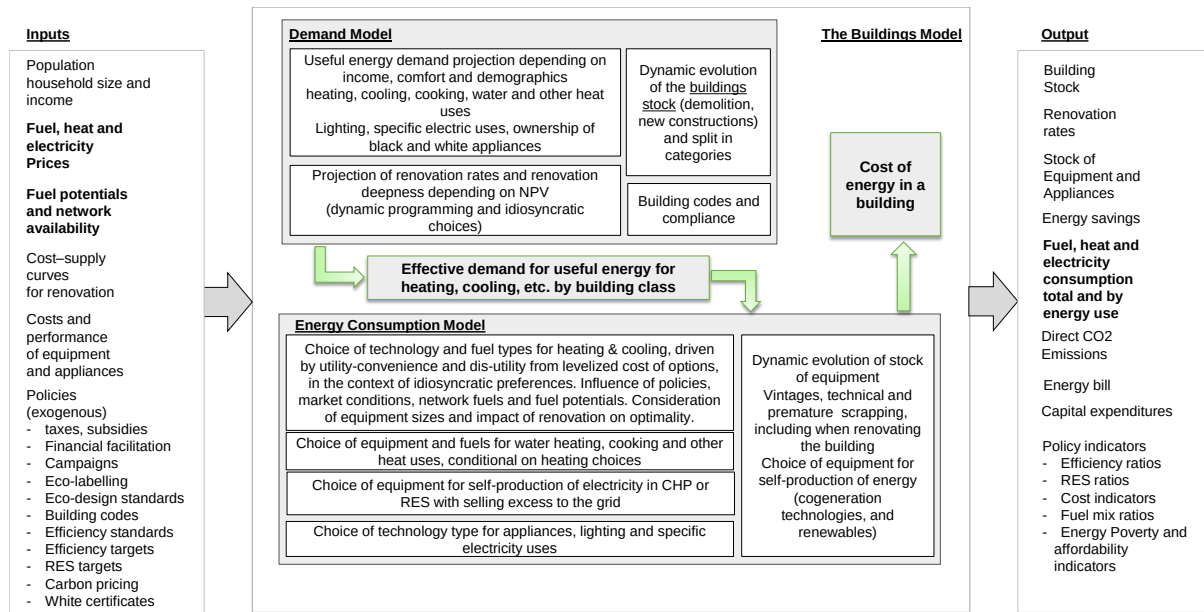


Figure 2 PRIMES BuiMo description

External Variables

External variables are considered those that are provided as exogenous inputs to the modelling analysis and their development is based on a set of exogenous assumptions. The future development of external variables influences the projections of internal variables, which are derived using PRIMES-BuiMo. The main external variables can be categorized as below and are inputs to PRIMES-BuiMo:

- Socio-economic developments (GDP, population, household income, household size – i.e. persons per dwelling), including the potential effects from COVID-19 pandemic and the “energy crisis” from 2022 on resulting e.g. from the drastic reduction of Russian gas imports to the EU
- Assumptions on technology costs and performance (e.g. heat pumps, boilers, storage etc)
- Prices of energy products and energy and carbon taxes
- Targets on emission reduction, electrification, efficiency improvement, emergence of low-carbon fuels (e.g. hydrogen), decarbonization of district heating/cooling networks
- Energy and climate policies (regulatory, fiscal, economic, knowledge, informational)
- Parameters influencing the adoption of low-carbon technologies (e.g. fuel potentials, network availability, cost-supply curves for renovation, discount factors)
- Climate related parameters (e.g. Heating and Cooling Degree Days)

To provide additional insights on the external variables underpinning the study, the following subsection includes the quantitative projections for the main exogenous drivers, which are largely based on the recent EC Reference scenario 2020 (European Commission 2021).

1) Socio-economic developments

The evolution of population and GDP are used in the sectoral modelling analysis to provide an outlook of the future socio-economic development of the European economy. The historical and recent demographic and economic evolution of EU countries is the starting point for their projection, which are provided by Eurostat and the joint work of the Economic Policy Committee and the European Commission. The GEM-E3 macro-economic model is used to simulate the socio-economic developments and sectorial production in each EU Member State by 2050 (Leonidas Paroussos, 2019). As a CGE (Computable General Equilibrium) model with high country and sectoral resolution, GEM-E3 ensures that macroeconomic and sectorial projections of the EU economy are consistent with the

Annex 6 of Deliverable D3.1 Decarbonisation pathways for the buildings sector

global economy context. The impacts of the COVID-19 pandemic have been fully reflected in the demographic and macro-economic projections as well as in the sectoral composition of GDP (European Commission 2021).

The EU population is projected to slightly increase until 2030 and then decline in the long term. Still, there are differences between national population trends, as in 11 Member States the population is projected to grow by 2050. Figure 3 shows the population projection in the EU until 2050.

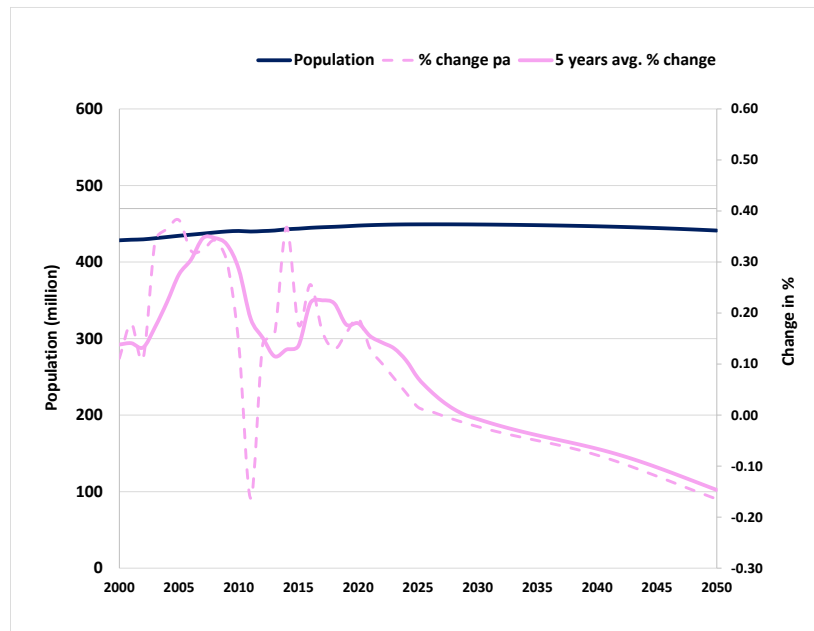


Figure 3 Population evolution and projection in the EU (source: (EUROPOP 2019)

The GDP projection is based on the European Commission's 2021 Ageing Report and the Spring 2020 Economic Forecast (European Commission, 2020, 2021a). Projections on GDP growth are uncertain due to effects from COVID-19 pandemic and vary widely across different sectors of the economy with sectors like aviation and tourism suffering the most negative impacts. The pandemic struck the European economy at a time when it had started to grow at a moderate pace, recovering from the 2008 financial crisis (Figure 3). As a result, the economic growth will highly depend on the duration of the pandemic and on new trends emerging in the post-COVID-19 era regarding among others remote work, fewer business trips and changes in global supply chains (European Commission, 2020, 2021a).

2) Technology costs for the buildings sector

In the modelling, the cost development of technologies is also provided exogenously, both for electric appliances and heating and cooling equipment, as well as the renovation of buildings' envelope. Consumer decisions related to the purchase of household appliances, space and water heating technologies and technical building system equipment largely depend on the total purchasing costs, which are based on acquisition costs, the prices of energy products and efficiency by vintage. The technical and economic characteristics of each technology category are assumed to change over time as a result of learning-by-doing and economies of scale. In Table 1, we give the example of heat pump technologies considered and the evolution of their cost.

Table 1: Purchasing costs for heat pump technologies

Heat pump technology	in EUR/kW						
	Current	2030			Ultimate		
		From		To	From		To
Heat pump air	784	603	835	1080	267	673	1030
in South Countries							
in Middle South countries							
in Middle North countries							
in North countries	1036	847	1104	1428	487	960	1287
Heat pump water							
Heat pump ground							
Heat pump gas							
	1695	1385	1805	2335	1203	1570	1774
	1176	904	1194	1512	400	942	1339

Assumptions on envelope renovation costs depend on the climate zone and depth of such renovation. Here, we consider investment costs which are the incremental energy related expenditures needed to implement an energy renovation of a building envelope — without considering usual renovations performed for other purposes (structure, decoration etc.). The energy savings rate refers to a typical building as in the current stock of existing buildings, not savings in new constructions.

3) Prices of energy products

In PRIMES, electricity and fuel prices are calculated in such way that allows recuperating all costs, including those related to RES policies (e.g., feed-in-tariffs), grid costs, charging infrastructure for EVs and investment costs including stranded investments, back-up, and reserve costs as well as profit margin. PRIMES differentiates electricity prices by sector reflecting load profiles, generation, and grid costs. Weighted average electricity prices modestly increase until 2030 in the households' sector, due to the increasing carbon taxes that impacts the costs of fossil-fuel-based electricity producers and the higher grid costs due to infrastructure development to support grid expansion to facilitate expansion of variable RES and new interconnections. Fossil fuel products (e.g. natural gas, diesel oil, LPG) see increasing prices until 2050 driven mostly by increasing international import prices in the absence of strong global climate action, whereas end user prices of steam and biomass slightly increase by 2050. Figure 4 depicts the evolution of fuel prices as described above.

However, in the context of the latest energy crisis due to the war in Ukraine we will be considering the short and long-term impact of the fossil fuel price increase. In section "Scenario development and definition" we explain in detail the assumptions.

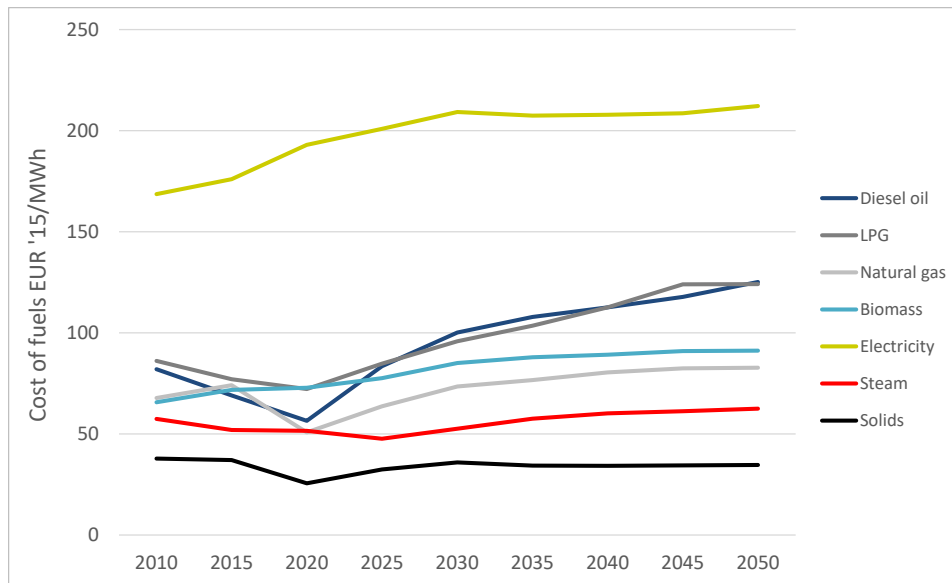


Figure 4 Average end user price for fuels in the residential sector (European Commission, 2020)

4) Discount factors used for the decision in buildings

Private discount rates pertaining to individual agents play an important role in their decision-making as they highly influence their decision to purchase technologies and appliances with different cost structure, e.g. balance between up-front investment costs vs long-term operating and maintenance costs. This is especially the case for a household, or a small enterprise deciding to renovate a building or choose a new type of heating equipment. Agents' economic decisions are usually based on the concept of cost of capital. Depending on the sector, this is either the weighted average cost of capital (for larger firms) or a subjective discount rate (for individuals or smaller firms). In both cases, the rate used to discount future costs and revenues involves a risk premium which reflects business practices, various risk factors or even the cost of lending. In the buildings sector, the discount rate for individuals (households) also reflects an element of risk averseness as consumers tend to prefer technologies with low upfront investment costs (and relatively higher operating costs).

The discount rates vary across sectors. In this study, we use discount rates of up to 14% for the decision making for buildings renovation of households. In Table 2, we show the discount rates for different elements during an energy renovation and the variation by income class. The discount rates are also necessary for annualising capital or investment expenditures (CAPEX) for cost reporting.

Table 2 Discount rates of households (source: European Commission 2021)

Assumptions for Baseline Scenario	Discount rates	Modified discount rates due to EE policies ³
Households for renovation of houses and for heating equipment	14.75%	12%
Households for choice of appliances	13.5%	9.5%
By income class (for the decision on renovation and the choice of equipment)		
Low		14.1%
Low-Mid		13.6%
Mid		13.2%
Mid-High		12.8%

Internal Variables

Internal variables are those that are endogenously calculated by the PRIMES BuiMo model based on the evolution of exogenous variables, other assumptions (e.g. elasticities) and the modelling framework used. The main internal variables are listed below:

- Useful energy demand for heating and cooling needs and electricity
- Dynamic evolution of the building stocks
- Envelope renovation strategies (rate and depth of buildings' renovation)
- Technical building equipment choice and replacement options
- Electric appliances equipment choice and replacement options
- Choice of equipment for self-production of electricity
- Rates of replacement of heating and cooling equipment
- Final energy consumption — by country, building type, income group and energy use
- Fuel mix used in residential sector by country, building type and energy use
- Direct CO₂ emissions
- Final energy savings relative to base year or a Business-As-Usual scenario
- Costs and investment for envelope renovation and technical building equipment
- Interlinkages with transport and electricity sectors through PV, EVs, storage
- Scenario impacts on fuel, heat and electricity prices
- Energy-related expenditure for households
- Policy indicators: including the efficiency improvement ratio, RES shares, cost indicators, fuel, energy poverty and affordability

³ It is assumed that standard discount rate values are pushed downwards by policies addressing the barriers which caused the high discount rate values in the first place.

Scenario development and definition

The section below presents the PRIMES-BuiMo projections for scenarios based on the current modelling set-up. Two sets of scenarios are presented within the study. The scenarios are designed to explore two policy contexts: i) an “existing policy framework” context (i.e., a low energy efficiency ambition reflecting the Baseline scenario assumptions) mirroring the National Energy and Climate Plans (NECPs) and already adopted policies in a stylized manner and ii) a “Decarbonisation” context meeting upscaled targets in 2030, including the -55% GHG emission target and specific, more ambitious targets for energy efficiency and renewables; also leading to climate neutrality in the EU by 2050.

The “existing policy framework” context reflects the outcomes of adopted EU level policies by 2020 and considers national contributions and planned policies as well as Member State projections as provided in their NECPs. It also assumes no intensification of current energy and climate policies or development of new policies fostering the uptake of renewable energy, energy efficiency and clean fuels beyond 2030, assuming that regulatory, financial or enabling measures will not be strengthened to support higher climate ambition.

In this respect, it is assumed that within the Baseline Scenario the MS achieve their national climate targets for 2030, as reflected in their NECPs of 2020, including:

- A core target of at least 40% reduction in domestic economy wide GHG emissions in the period 1990-2030 as included in the first EU NDC submitted in Paris COP
- An at least 32% renewable energy share in total gross energy consumption in 2030 (in line with the EU Renewable Energy Directive)
- Increased energy efficiency improvements to at least 32.5% in 2030 compared to the 2007 projections for the same timeframe (in line with the provisions of the Energy Efficiency Directive - EED), making use of the tools foreseen in the Governance Regulation.

In addition, the Baseline Scenario acts as a benchmark for future policy initiatives, reflecting policies and market trends in the mid- and long-term, notably in 2030 and 2050. The “decarbonization” context reflects policies that include more ambitious market- and regulatory-based measures aiming at achieving the 55% GHG emission reduction target for 2030 relative to 1990 levels and leading to climate neutrality in 2050. It assumes a high increase in the ambition of energy efficiency and renewable energy policies in line with the “Fit For 55” policy package. Except for the aforementioned CO₂ emissions targets, it also aims at reaching at least 42.5% renewable energy share in gross final energy consumption in 2030 and achieving an overall 11.7% reduction of the final energy consumption compared to projections of the expected energy use in 2030 - 2020 Reference Scenario).

The scenarios include a large set of current and future policies (e.g., policies to promote the renovations of buildings, obligations for renewable fuels in Heating & Cooling, support for the electrification of heating, etc.). The decarbonisation context also includes assumptions that a variety of regulatory and non-regulatory policies facilitate the transition and the achievement of the upscaled targets supporting the uptake of new clean technologies and the corresponding investment undertaking. The enabling conditions also bring cost benefits by pulling technology along the learning curves.

To thoroughly reflect the above-mentioned policies, targets and assumptions, three policy scenarios are designed and developed:

1. The “Decarb_HE” scenario
2. The “Decarb_Helec” scenario
3. The “Decarb_Helec_ETS” scenario

In the “Decarb_HE” and the “Decarb_Helec” scenarios, it is assumed that only specific current and future policies will enhance energy efficiency and electrification in EU buildings compared to the

“existing framework”. The “Decarb_HE” scenario gives priority to higher building envelope renovation rates and energy demand reduction, whereas in terms of the “Decarb_Helec” the focus is largely on the electrification of the buildings technical equipment (e.g. space and water heating). Both scenarios incorporate 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 to use reasonable discount rates in the investment decisions in energy efficiency while minimising hidden and perceived costs. Thus, the enabling conditions can accelerate investment in deep refurbishment above the “existing framework” trends.

In the “Decarb_Helec_ETS” scenario, it is assumed that there is 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 scenario. The carbon price is defined exogenously and increases linearly by USD 15 per year, reaching USD 300 in 2040, and USD 450 in 2050, as shown in Figure 5.

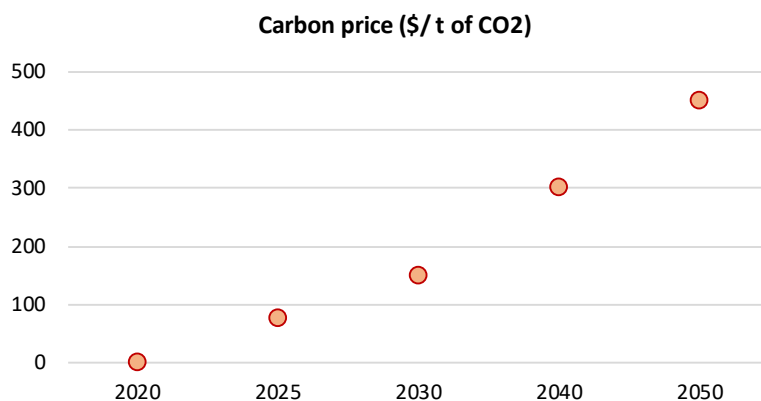


Figure 5 Exogenous carbon prices applied in the buildings sector

The “high energy prices” variants reflect the current energy crisis and the drastic reduction of Russian gas imports to the EU as a consequence of the Russo-Ukraine war. As shown in Figure 6, the international energy prices increase drastically in 2025 by about 53% and 40% in oil and coal compared to 2020, respectively, while the gas price is more than double the 2020 price. Then, they are still higher but to a lower extent until 2035. In 2035 and onwards, previously assumed prices as on the Reference 2020 scenario (European Commission, 2020) are projected regarding oil and coal, whereas the gas price never gets back to previously assumed prices until 2050. These are international import fuel prices and differ from the end-user prices in different energy sectors (supply or demand sectors).

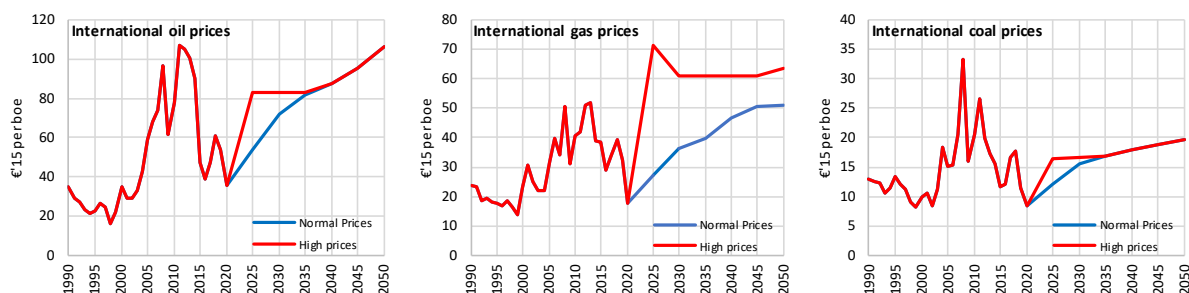


Figure 6 International oil, gas and coal prices projections in different scenarios

The high energy prices act on top of the assumptions described above in the four scenarios. Accordingly, four more scenario variants are developed and investigated: The “Baseline_HP”, the “Decarb_HE_HP”, the “Decarb_Helec_HP” and the “Decarb_Helec_ETS_HP” scenario.

5. Results and discussion

Baseline Scenario

The Baseline scenario projections show a remarkable decoupling of EU energy demand from income growth, much above historical trends, which intensifies in the period 2021-2030 as a result already of the pre-2020 Energy Efficiency Directive, national renovation strategies and the policies included in NECPs. These policies have an impact after 2030 as well, causing demand for energy in buildings to further decline. They also lead to CO₂ emissions reduction between 2020 and 2050, mainly until 2030 but at a slower pace within the following twenty years in the absence of additional policies during that period.

Heating (both for space and water heating) consumption is dominant in the buildings sector, representing the largest share of buildings energy demand throughout the period to 2050 despite its reduction due to efficiency improvements of the building envelope and heating equipment. Economic growth drives an increase in the stock of electric appliances (black and white) that increases on average by 2% per year following historic trends and income growth in EU countries. Growth for black appliances is at the same levels (2% per year) with information and communication technologies increasing by about 4.5% per year in that period due to increased digitization of services. Advancements in lighting technologies are projected to continue at a moderate pace resulting in further efficiency improvements. Cooking demand drops due to the uptake of more efficient equipment, yet the cooking share remains rather stable. Finally, the increase in the final energy for cooling is associated with increasing cooling degree days (CDD) – driven by higher temperatures and climate extremes due to climate change – and the increase in income, which together lead to higher penetration of cooling equipment in EU27 Member States.

The following graphs present an overview of the baseline scenario results. Figure 7 displays the final energy consumption and the related CO₂ emissions of the buildings sector from 2015 to 2050 in the Baseline scenario, while Figure 8 illustrates the sector fuel mix for 2015 and 2020, as well as the projected buildings fuel mix in 2030 and 2050.

From 2015 to 2050 the final energy consumption is continuously decreasing, mainly due to the decrease in buildings heating requirements, as mentioned above. In 2030, it is just under 350 Mtoe, while in 2050, it is roughly over 300 Mtoe, indicating a reduction of 7% and 14% compared to 2020 levels, respectively. The CO₂ emissions of the EU buildings sector are also constantly decreasing, following a steeper trend than the final energy consumption due to fuel shifts away from carbon-intensive fuels (e.g. coal, oil) and towards electrification. Again, this reduction is steeper until 2030, namely 29% compared to 2020, and continues at a slower pace afterwards with a just 24% decrease over the twenty-year period. This trend also underlines the evolution of the fuel mix presented in Figure 8.

Annex 6 of Deliverable D3.1 Decarbonisation pathways for the buildings sector

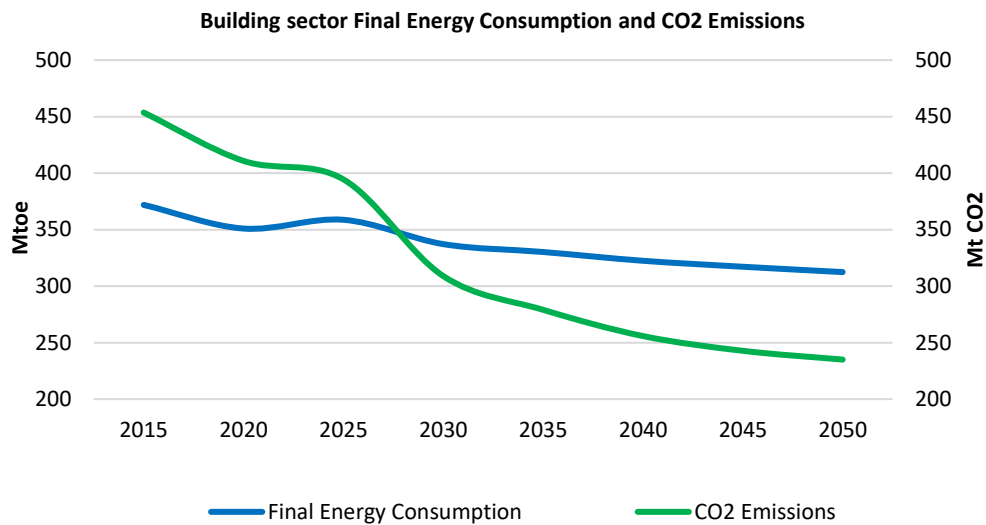


Figure 7 Final Energy Consumption and CO2 Emissions for the buildings sector in the Baseline scenario

In previous years, electrification has been already dominant within the buildings domain, representing close to 50% of final energy consumption in services sector and about 24% in households in both 2015 and 2020. Then, it is clear from Figure 8 that there is a trend towards increasing electrification of energy demand as well as taking advantage of district heating networks, where present, and renewable energy forms. In this respect, the share of electricity in fuel mix of the buildings sector is projected to increase from 33% in 2020 to 37% in 2030 and to 43% in 2050. In addition, a moderate growth in fuel mix shares regarding heat and renewable energy shares is also presented. Conversely, there is a reduction in the share of fossil fuels (gas, coal, oil) over time, as their contribution in fuel mix decreases from 46% in 2020 to 35% in 2030 and to 31% in 2050, respectively. Similar to the electrification share case, these trends are driven from both the residential and the services sectors.

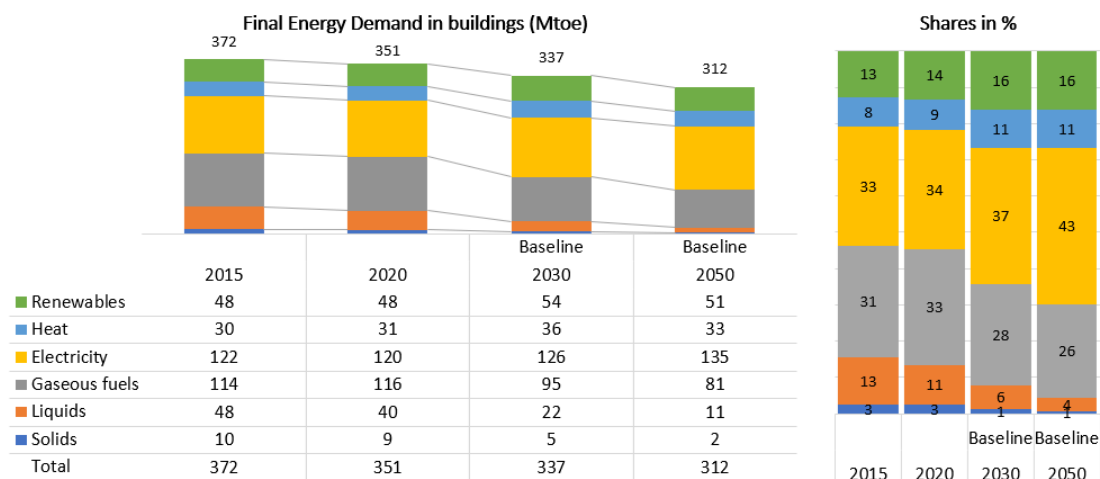


Figure 8 Final Energy Demand fuel mix for the buildings sector in the Baseline scenario

Decarbonization Scenarios without high energy prices

Using the PRIMES-Buimo modelling framework, the “Decarb_HE” scenario induces deep building shell renovation, namely windows replacement, envelope insulation thickness and air permeability enhancement. The “Decarb_Helec” scenario focuses more on the replacement of heating equipment (with electric heat pumps) and other policies such as eco-design standards and labelling, which also induce acceleration of capital turnover in the heating systems of buildings. The “Decarb_Helec_ETS” scenario additionally considers the introduction of the Emissions Trading System in the buildings sector.

In comparison to the baseline scenario, the decarbonization scenarios show a considerably larger reduction in buildings’ final energy consumption, and CO₂ emissions coupled with massive shifts in fuel mix. They also show that these impacts are evident both in the medium and in the long-term, resulting from energy policies considered within the decarbonization context throughout the investigated period.

In this respect, the following figures show the model-based results for EU buildings in the series of decarbonization scenarios examined. Figure 9 and Figure 10 show the average renovation rate of the building envelope and the equipment replacement rates for the residential and services buildings, respectively, while Figure 11 displays the total buildings sector final energy consumption, Figure 12 presents the fuel mix, while Figure 13 illustrates the overall energy-related CO₂ emissions evolution of the EU building stock.

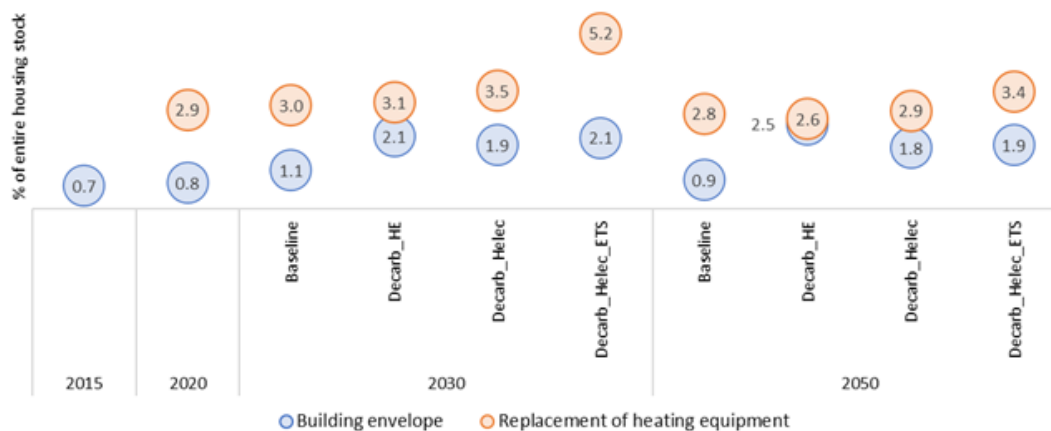


Figure 9 Projection of renovation rates in households in the series of policy scenarios

We observe an increase in both the building envelope renovation and the replacement of equipment for all decarbonization scenarios within the entire building stock. Households show higher building envelope renovation rates than the services sector buildings, whereas in sharp contrast to this, the services sector buildings illustrate greater rates of equipment replacement, as the differences in working hours as well as in the desired indoor temperature and ventilation requirements among them drive different energy measures. Regarding the different decarbonization scenarios, the “Decarb_HE” scenario reaches the highest building envelope renovation rates as by assumption it puts a focus on energy efficiency strategies, whereas the “Decarb_Helec” and the “Decarb_Helec_ETS” scenarios maximise heating and cooling equipment replacement rates, as a result of the interventions described above.

Annex 6 of Deliverable D3.1 Decarbonisation pathways for the buildings sector

In the “Decarb_HE” scenario, the residential sector’s renovation rate is continuously greater compared to the baseline scenario from 2020 to 2050, being more than 2.1% per year beyond 2025, while the replacement rate of heating equipment in both the “Decarb_Helec” and the “Decarb_Helec_ETS” scenarios are also consistently higher than the ones for the baseline scenario throughout the period to 2050, reaching their maximum values in 2030, where 3.5% and 5.2% of the existing heating equipment stock is upgraded. With respect to the services sector, the equipment replacement rate considerably increases compared to the baseline context over the twenty-year period, reaching almost 4.0% and 4.4% in 2030 and in 2050 for the “Decarb_Helec” and the “Decarb_Helec_ETS” scenarios, respectively. In the “Decarb_HE” scenario, the building renovation rate is also higher than the baseline scenario, yet its magnitude compared to residential sector is still lower. Overall, the energy policies considered within the decarbonization context scenarios lead to higher renovation and replacement rates compared to the baseline one. Yet, following the different energy measures requirements regarding each building type and mitigation pathway, both the renovation and equipment replacement rate depths also vary among them.

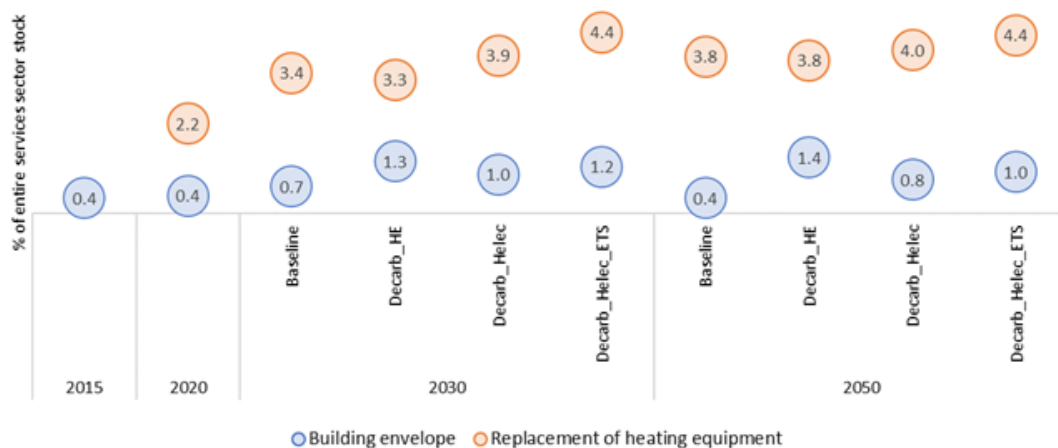


Figure 10 Projection of renovation rates in services sector in the series of policy scenarios

As shown in Figure 11, the final energy demand in all scenarios is decreasing throughout the projected period, but the reduction is faster and deeper in the decarbonization scenarios (compared to the baseline scenario) as a result of the increased rates of renovation and replacement of heating equipment, that reduce final energy consumption of the sector from around 370 Mtoe in 2015 to around 230 Mtoe. According to the analysis presented in Figure 11, the “Decarb_Helec_ETS” scenario can reduce the final energy consumption up to 22% in 2030 and up to 35% in 2050, respectively compared to the 2020 levels. The “Decarb_HE” and the “Decarb_Helec” scenarios show a similar trend with however a lower decrease around 15% in 2030 and just over 30% in 2050.

Annex 6 of Deliverable D3.1 Decarbonisation pathways for the buildings sector

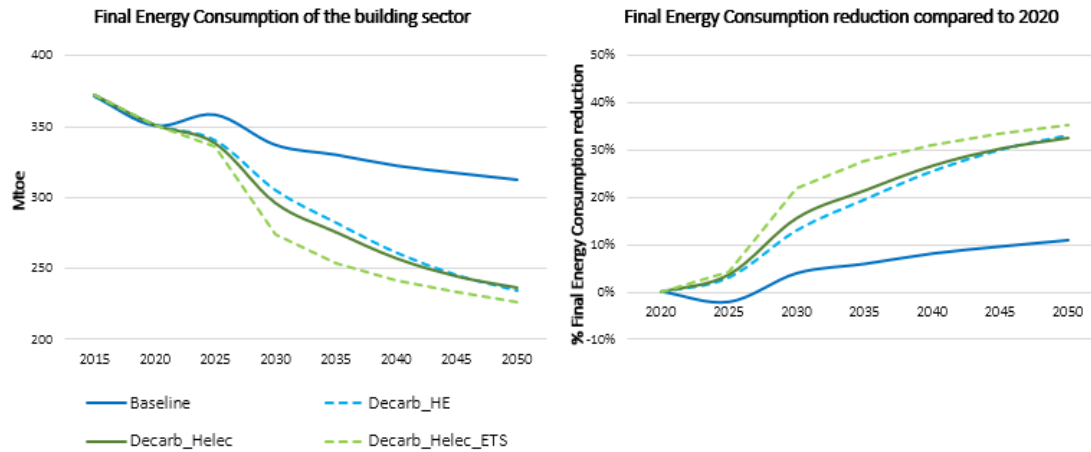


Figure 11 EU buildings Final Energy Consumption outlook

The graphs depicted in Figure 12 and Figure 13 show that the increased rates, particularly the replacement of heating systems, drive the electrification of energy demand through the accelerated uptake of heat pumps that increasingly replace conventional fossil-fired heating systems in the EU residential and commercial sector.

The baseline scenario leads to an increased electricity share in final energy consumption. This electrification trend accelerates further in the decarbonization context with electricity share accounting for 53% of final energy consumption in the “Decarb_Helec_ETS” scenario in 2030, achieving a 20% increase compared to 2020. A more moderate increase is observed in the “Decarb_HE” and the “Decarb_Helec” scenarios, as the electricity share increases to 41% and 45%, indicating a raise of 8% and 12% in 2030 compared to 2020, respectively.

Similarly, in the long term, while the baseline scenario electricity share is 43%, in all the decarbonization scenarios electricity represents more than 50% of the total energy consumption in the sector, because of the increasing penetration of heat pumps, driven by policies promoting RES uptake and efficient equipment use for heating and cooling. The electricity share reaches 66% in the scenario that takes into consideration the application of the ETS within the EU buildings sector and it is roughly 60% in the “Decarb_HE” and the “Decarb_Helec” scenarios. The remaining buildings energy demand is covered by the direct use of renewable energy (mostly biomass and solar thermal) and by decarbonized heat and gases, including hydrogen, while the use of both solids and liquids fossil fuels is phased out.

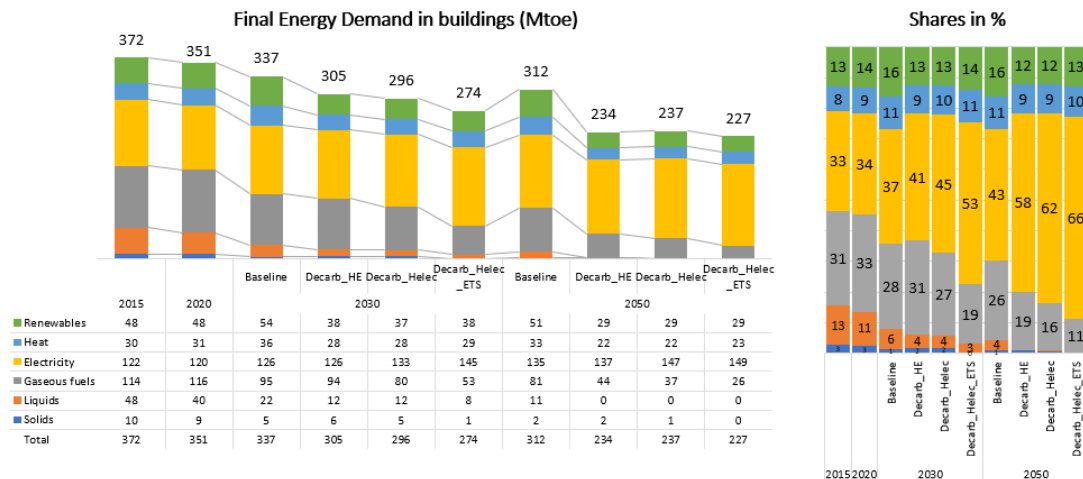


Figure 12 Final energy consumption fuel mix in buildings in the series of policy scenarios

The aforementioned changes in EU buildings fuel mix led to the large reduction of energy-related CO₂ emissions in the 2020-2050 period (in Figure 13). In this respect, CO₂ emissions are consistently decreasing until 2050 even for the baseline scenario, as described in the above section, but this scenario fails to achieve the decarbonization target by 2050. In contrast to the baseline scenario, accelerated building envelope enhancement, faster and deeper renovation rates, replacement of heating equipment with more efficient and low-carbon technologies (e.g. heat pumps) as well as the extension of the EU ETS scope to the buildings sector, which are included in the decarbonization scenarios, result in a steeper reduction of the CO₂ emissions that are close to reach net zero by 2050, being in-line with the EU's climate neutrality objective.

In Figure 13, the “Decarb_Helec_ETS” scenario already shows a remarkable decrease in CO₂ emissions equal of 65% in 2030, while a more moderate but still higher than the baseline scenario decrease is shown in the “Decarb_HE” and the “Decarb_Helec” scenarios, namely 32% and 41%, respectively. Hence, the adoption of policy instruments, such as demand electrification and ETS II, may act complementarily and achieve a further and faster CO₂ emissions reduction, especially in the critical decade until 2030. From 2045, the EU buildings CO₂ emissions in all the decarbonization scenarios are close to zero, in-line with the climate neutrality objective and the EU's aim to decarbonize the national building stocks by 2050.

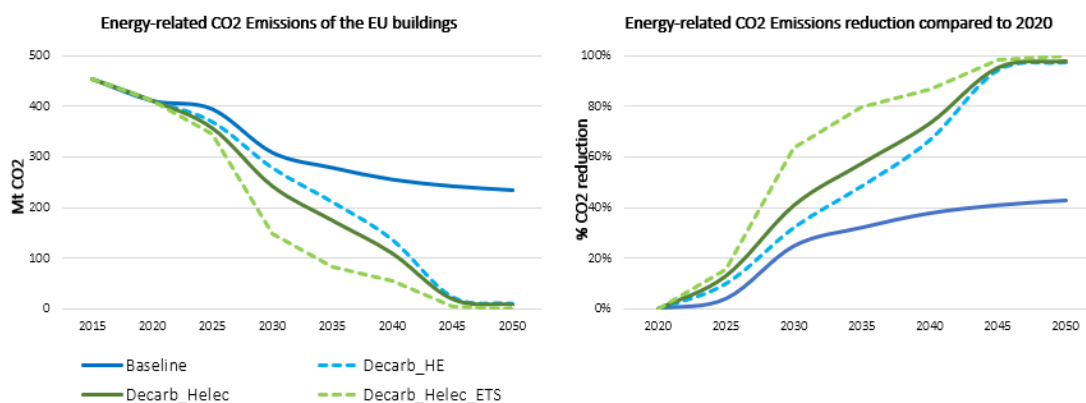


Figure 13 CO₂ emissions outlook for the buildings sector

Decarbonization Scenarios with high energy prices

As described in the Scenario development section, to reflect the current energy crisis and the drastic reduction of Russian gas imports to the EU, a series of high energy prices scenario variants were also investigated (Figure 6). The impacts of high energy prices are higher in 2025 (when the energy price increase is the highest) but gradually phase out in the period after 2025. This energy price increase drives higher equipment replacement and building envelope renovation rates than the ones in the policy scenarios until 2025, but their impacts are phase out after 2025.

We, first, present the differences in the final energy consumption between the initial and the high prices scenarios (Figure 14). In all the investigated scenarios, the increased energy prices reduce energy consumption in the buildings sector. Within the “decarbonization” context, this decrease is higher in 2025 (up to 15 Mtoe), while it gradually phases out after 2025 as the energy price increases become gradually smaller, following the, aforementioned, renovation and equipment replacement rates trend.

The energy crisis impacts are much greater in the “decarbonization” context compared to the baseline scenario, since high energy prices alone are not sufficient to induce deep energy savings in the latter, as the market and non-market barriers to energy efficiency do not allow for extensive efficiency investments. On the other hand, the regulatory and institutional measures of the decarbonization 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 prices for final consumers increase (either due to the increased fuel import prices or due to the introduction of carbon taxes).

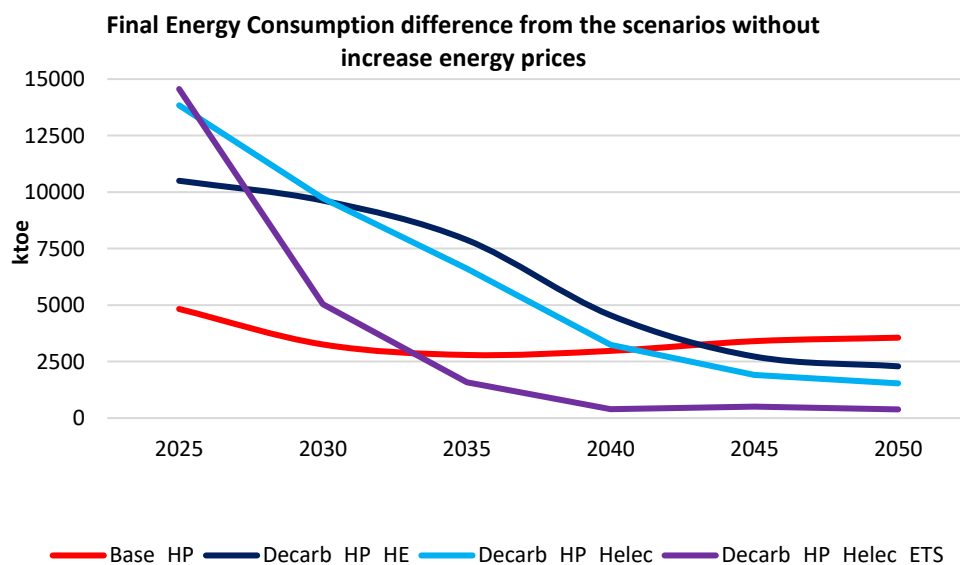


Figure 14 Impacts of increased energy prices on Final energy consumption in the series of policy scenarios

The significant impacts of high energy prices on the overall energy system until 2025 is reflected not only in the building envelope renovation and heating equipment replacement rates but also in the final energy consumption and in the fuel shares that are presented in Figure 15 for all policy scenarios in 2025. It is clear that the high energy prices also change the fuel mix, as fossil fuels shares decrease due to the increased fuel prices, while electricity, renewables and heat shares increase compared to the scenarios without increased energy prices to compensate for the declining fossil fuel shares.

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More specifically, gas is characterized by the highest increase in prices and shows an at least 3 percentage points (pp) decrease in its share until 2025. Conversely, following the high level of equipment replacement rate resulting from the high energy prices, the electricity share increases, representing almost 40% of the total energy demand for all the decarbonization scenarios already by 2025. In the baseline scenario, the gas decrease mainly drives the use of renewables (mostly biomass) and district heating. The greatest share of electricity is observed in the scenario with high energy prices that also considers the application of the ETS within the buildings sector in the EU and it is equal to 41% showing the potential synergies between energy prices and ETS taxation promoting deeper electrification in the EU buildings sector.



Figure 15 Impacts of high energy prices on the fuel mix of buildings

Figure 15 illustrates the differences in the building's energy-related CO₂ emissions between the initial and the high prices scenarios. The emission impacts of higher energy prices are considerably high until 2025, and gradually phases out in the period after 2025, similar to both the renovation and equipment replacement rates and the final energy consumption trends. Accordingly, in 2025, the buildings-related CO₂ emissions are at least 47 Mt CO₂ lower for the high prices scenarios, driven from the changes in the energy consumption and fuel-mix described in the previous paragraphs, whereas from 2025 and onwards these differences gradually phase out (following the assumed trajectories for energy price increases).

With respect to the decarbonization scenarios, these differences are steeply reducing until 2045 and are being eliminated afterwards, as a result of the applied decarbonization policies, reducing CO₂ emissions close to net zero in all decarbonisation scenarios. On the other hand, in the baseline scenario, the difference in CO₂ emissions between the high prices variant and the initial scenario remains roughly constant from 2030 until 2050. Indeed, due to the lack of an ambitious decarbonization context, the shock in fuel prices is the main driver leading to reduced energy consumption and CO₂ emissions compared to the initial baseline scenario throughout the whole investigated period.

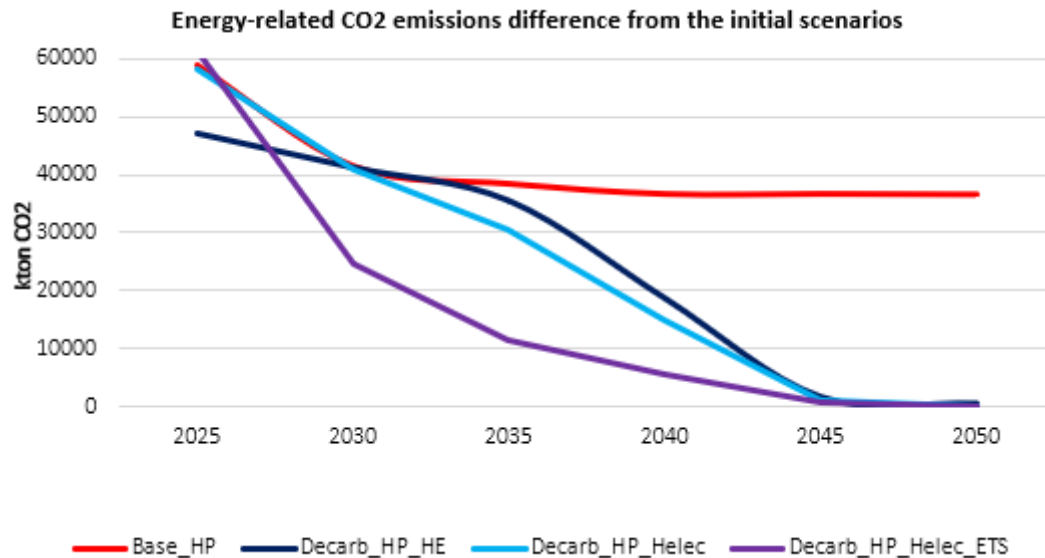


Figure 15 Energy-related CO2 emissions difference relative to the initial (non-high energy prices) scenarios

6. Conclusion and policy implications

This paper examined different transformation pathways for the EU buildings sector in the 2020-2050 period inducing mitigation options like ambitious energy efficiency improvements in buildings and electrification of their energy demand to attain the EU targets – related to both CO2 emissions and final energy consumption, as well as renewable energy shares.

With the adoption of the European Green Deal, the Fit for 55 policy packages, and most recently the REPowerEU plan, the EU targets, in terms of the final energy consumption, use of renewables and CO2 emissions, are updated, indicating both binding medium term for 2030 and 2050 carbon neutrality goals. Accordingly, the energy demand sectors energy policy frameworks should be revised in order for the EU's updated NDC submission (European Commission, 2023) to be complemented in light of the adoption of these upgraded targets, while integrating the specific sector contribution to them.

The objective of this study is to investigate different energy policy contexts in terms of the building sector, contributing to the definition of the optimum mitigation pathway that should be included in the next EU NDC. To accomplish this, three sets of scenarios, reflecting different mitigation pathways, climate policy contexts, and fuel import prices, were developed and quantified with the PRIMES-BuiMo model. Within these scenario sets, four general policy setups were designed, reflecting the different mitigation approaches and pathways: The “Baseline” scenario referring to the “existing policy framework” and three policy scenarios, i.e., the “Decarb_HE”, the “Decarb_Helec” and the “Decarb_Helec_ETS” scenarios. Then, to assess the impacts the current energy crisis involving the decrease in the Russian gas imports to the EU, the initial scenarios were enriched to consider the drastic increase in international fuel prices. Therefore, the variants are developed based on three decarbonization scenarios combined with assumptions for high energy prices– “Decarb_HP_HE”, “Decarb_HP_Helec” and “Decarb_HP_Helec_ETS”.

The study was performed using the PRIMES BuiMo, which following the methodology of hybrid-energy-economy models, projects into the future final energy consumption, fuel mix and CO2 emissions in the EU buildings sector. These projections are made within the framework of specific energy and climate policies, regulatory measures and climate targets that define the examined scenarios. These frame conditions drive renovation decisions and choices in terms of both building envelope renovation and technology equipment. The pathways cover the development and technical change of all energy end-uses in the buildings sector, which in the different combinations of options

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lead to different mitigation pathways towards the carbon neutrality goals while attaining to the binding medium-term goals for 2030 in the EU – 55% GHG emissions reduction.

We conclude, from our study, that EU countries should base their updated energy policies and NDCs on measures that prioritize building envelope renovations as well as heating equipment replacements. With respect to the residential sector, at least 1.9% of dwellings should be renovated annually and a minimum of 2.6%-3.1% of the total building stock (including both residential and commercial buildings) should replace the heating equipment on an annual basis until 2030 and 2050, respectively.

EU energy policy measures should be further developed focusing on the energy demand reduction, establishing strategies that promote energy efficiency renovations, and on both electrification and high energy efficiency of the buildings technical equipment along with the extension of carbon pricing in the building sector. In other words, despite the rapid development of clean and sustainable solutions of technical building equipment – for all end uses – the principle of energy efficiency first is of great importance to achieve demand reduction.

The alternative mitigation pathways analysed are based on different energy policy priorities that prioritise different mitigation options (e.g. renovation, electrification) that also affect, the contribution of the building sector on the overall energy efficiency, CO₂ emissions reduction and renewable energy targets, especially in this critical decade to 2030.

Within the “Decarb_HE” policy framework, focusing on energy efficiency improvements, the EU countries must significantly accelerate annual energy efficiency renovations especially in the residential sector where 3.1% and 2.5% of total households should be annually renovated by 2030 and 2050, respectively.

Conversely, within the policy setups emphasizing the buildings electrification (Decarb_Helec and Decarb_Helec_ETS), Member States must further develop their energy policy measures, establishing stronger equipment replacement strategies and prioritizing the uptake of heat pumps. More specifically, the “Decarb_Helec” framework should be accompanied by 3.5%/3.9% and 2.9%/4% annual heating equipment replacements rates in the residential/services sector until 2030 and 2050, respectively.

The ETS extension in the building sector is followed by a remarkable increase in the aforementioned replacement rates, especially in the short term, as 5.2%/4.4% and 3.4%/4.4% of the total residential/services building stock should replace the heating equipment on an annual basis until 2030 and 2050.

Since the overall long-term objective is climate neutrality by 2050, policy measures included in each investigated mitigation pathway lead to an almost similar buildings performance for all the decarbonization scenarios in terms of final energy consumption, fuel mix and energy-related CO₂ emissions in the long term. Yet, the building sector contribution to the short-term targets in 2030 varies among them.

For all investigated energy policy setups, and scenarios thereof, within the “decarbonization context”, the buildings’ sector final energy consumption in 2050 is around 230 Mtoe, comprised of electricity, renewables, heat, and decarbonized gas, leading to almost zero CO₂ emissions. In this respect, carbon neutrality is achieved through the LULUCF sector activities and carbon capture technologies to overall energy system carbon neutrality.

Today buildings are responsible for approximately 40% of EU final energy consumption. Considering final energy consumption with regard to the investigated energy policy setups in 2030 as well as the overall final energy consumption target of 763 Mtoe in 2030, this percentage remains stable in terms of the “Decarb_HE” policy framework, whereas it decreases regarding the “Decarb_Helec” (38.7%) and the “Decarb_Helec_ETS” policy setups (35.9%). As a result, a reduction equal to 9.5%, 12.5% and 18.8% compared to the Baseline scenario projections for 2030 occurs, respectively. Therefore, the buildings contribution on the overall energy efficiency in terms of the “Decarb_HE” scenario is lower than the overall established target of 11.7% reduction compared to the 2020 Reference Scenario expected final

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energy consumption in 2030, whereas the “Decarb_Helec” and the “Decarb_Helec ETS” scenarios energy efficiency achievement is even greater than the more ambitious target of 13%, respectively. Consequently, depending on the mitigation pathway followed, the effort of the other sectors with high potential for energy savings, such as transport, industry and energy supply sectors, should be higher/lower than 11.7%.

According to EEA estimates, in 2020, EU-27 CO₂ emissions were 31% lower than in 1990. Therefore, an additional 24% reduction is required by 2030 for the updated target of 55% reduction to be met (compared to 1990). The examined mitigation pathways indicate building sector CO₂ emissions reduction of 32%, 41% and 65% compared to 2020 with respect to the high efficiency, the electrification and the ETS policy framework, respectively. Therefore, the buildings contribution on the overall CO₂ emissions reduction is well over the established target. In this respect, the other sectors contribution may be lower than 24% in terms of each policy setup followed.

However, the 2030 building sector CO₂ emissions comparison to the 2015 values displays a decrease of 39%, 47% and 67% in terms of the “Decarb_HE”, “Decarb_Helec” and the “Decarb_Helec_ETS” scenario, respectively. This means that the carbon pricing extension in buildings plays a key role for the EC new proposal of reaching the target of at least -60% emission reductions by 2030 in the building sector in comparison to 2015 to be attained.

The building sector contribution on the overall short-term targets (2030) is higher within the electrification setup energy policy measures compared to the high efficiency ones, while considering the ETS within the building sector gives a further considerable boost. Nonetheless, according to the impact assessment of the EED in 2021 (European Commission, 2021), special attention is required regarding the buildings energy efficiency since except for the energy savings, energy efficiency also drives improved indoor environments in terms of comfort, health and well-being. In addition, a holistic analysis of the examined mitigation pathways also requires the comparison of both the capital (in terms of renovation of old constructions and purchasing of equipment and appliances) and the operating expenditures – fuel purchasing expenses per household/service building – needed, which is out of the scope of this study.

Within the “decarbonization” framework, high energy prices resulting from the war in Ukraine lead to significantly greater equipment replacement rates and higher buildings envelope renovation rates already in 2025. These high rates drive a considerable EU buildings final energy consumption reduction, demand electrification and remarkable CO₂ emissions decrease earlier in time compared to the normal fuel prices variants. Yet, it is vital to note that these positive effects shown in the results require a remarkable increase (of 11%) in the capital expenditures, while a significant raise (of 24%) in the operating expenditures that is of even greater importance.

The high energy prices scenario variants show different effects in terms of both the “existing” and the “decarbonization” framework after 2030. Since the high renovation and equipment replacement rates until 2025 succeed in confronting the energy crisis and fuel prices are getting back to normal there is no need for further higher investments. Therefore, results reflect a remarkable decrease in both the renovation and the equipment replacement rates regarding the high prices scenario variants, which are even slightly lower than the initial scenarios ones.

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4. Comparative Analysis of Residential Building Decarbonization Policies in Major Economies: Insights from the EU, China, and India

This section is based on the article manuscript “Comparative analysis of Residential Building Decarbonization Policies in major Economies: Insights from the EU, India and China?” to be submitted.

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1. Introduction

Globally, the building sector was responsible for more than 30% of CO₂ emissions in 2019 (IPCC, 2023). Although building energy efficiency has improved, according to IEA, the energy intensity of buildings needs to reduce almost five times faster over the next decade than it did in the past five years to reach net zero emissions by 2050 (IEA, 2021d). In developing and emerging economies, building energy demand is set to surge, propelled by the rapid expansion of new construction and increasing demand for energy services. This growth is a consequence of rapid urbanization, the escalating need for floor space, and the rising standards of living (Camarasa et al., 2022a). Thus, the IPCC (2023) underscores that, by 2050, the building sector in developing countries have the largest mitigation potentials. In most developed countries, despite increased building energy performance since 1990, there are still significant mitigation potentials in its huge existing building stock to be renovated (IEA, 2021c).

Against this background, this paper and part of this WP3 report, captures the diversity of building decarbonization policies in three major economies encompassing developed and emerging countries: the European Union (EU), China, and India. In 2020, these economies collectively accounted for more than 40% of global CO₂ emissions.

Meanwhile, each of them has set long-term national net zero targets. The EU aims to be climate-neutral by 2050 and reduce its greenhouse gas (GHG) emissions to at least 55% compared to 1990 by 2030 (European Commission, 2023). China has pledged to peak its CO₂ emissions before 2030 and achieve carbon neutrality before 2060, while India aspires to reach net-zero emissions by 2070 (Government of India, 2022). Buildings significantly contribute to emissions in all three regions. Among different building types, existing literature demonstrates higher per capita CO₂ emissions from residential buildings compared to commercial buildings worldwide, including these three regions (Camarasa et al., 2022a). This underscores the crucial role of residential buildings in the endeavor of decarbonizing the building sector. Therefore, residential buildings will be the central focus of this paper and line of work.

In the EU, the residential buildings stock amounts to 17,108 million m² and is projected to grow moderately in the future. The residential sector plays a significant role as well, contributing to 27% of the total final energy consumption in 2021. The total final energy consumption for residential buildings stood at 142 kWh/m² in 2020 and is anticipated to steadily decline, culminating in 2050, aligning with the climate neutrality objectives. Within this sector, space heating was the primary driver, representing a significant 64.4% of the final energy consumption. In contrast, energy consumption for space cooling remained negligible in most Member States. Natural gas dominated as the leading energy source at 33.5%, followed by electricity at 24.6%, renewables and waste at 21.2%, and oil and petroleum products at 9.5% (Eurostat, 2023). According to Spinoni et.al., both heating and cooling demands will exhibit relatively stable patterns through 2050. It is worth noting that between 75% to 95% of EU buildings existing today will still be in use in 2050, and nearly all of them will require energy renovations to support the EU meet its climate targets (BPIE, 2017). However, the current annual energy renovation rate is a mere 1% and many of these renovations achieve low energy savings (European Commission., 2019).

China has an extensive residential building stock, exceeding 53 billion m² in 2021 (urban: 30.5 billion m², rural: 22.6 billion m²). Driven by the continuous urbanization (projected to rise from 61% in 2020

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to 80% in 2050 (Camarasa et al., 2022b)), the building stock is expected to expand, estimated at around 40% growth between now and 2060, according to an IEA scenario (IEA, 2021a). Meanwhile, most of China's residential building stock is relatively young and will remain in use for an extended period. Residential buildings have continued to account for a substantial portion of China's energy consumption, totaling 16.4 million terajoules (TJ) and representing 70% of the total building energy consumption. In urban areas, residential energy consumption reached 8.9 million TJ, encompassing 657 billion kWh of electricity. Rural areas contributed 7.5 million TJ, including 2.6 million TJ from biomass and 375 billion kWh from electricity. CO₂ emissions from residential buildings exceeded 1.3 billion tons, comprising nearly 60% of the total building emissions (including direct and indirect emissions) (THUBERC, 2023). The country has diverse climates, leading to varying heating and cooling demands. For instance, the northern region predominantly experiences cold and severely cold climates and relies on district heating systems, whereas the southern region primarily employs decentralized heating solutions. Furthermore, China's demand for space cooling has exhibited the fastest growth globally. Cooling, primarily using individual air conditioning units (AC), currently constitutes approximately 7% of the total final energy demand in buildings (IEA, 2021a).

In India, residential buildings covered a vast floor area of 15.3 billion m² in 2017. In contrast to the EU and China, a significant portion of India's building stock in 2040 is yet to be constructed. Urbanization and replacement of informal settlements with new modern buildings will trigger a substantial increase of residential building stock surging from less than 20 billion m² today to over 50 billion m² within two decades (IEA, 2021b). The residential sector stands as the second-largest final energy consumer, consuming 6.7 million TJ in 2020 (IEA, 2022). India's predominately tropical and sub-tropical climate leads to limited heating demand and high cooling demand. In the year 2020-2021, the residential sector accounted for approximately 32% of the total electricity consumption (Government of India et al., 2022). Climate conditions coupled with improved income and living standards are anticipated to drive a rapid growth in AC ownership, from currently 8% surging to 40% by 2037-38, leading to a corresponding increase in electricity consumption from less than 150 TWh in 2017 to a projected 400-600 TWh by 2037-38 (Ministry of Environment, Forest & Climate Change, 2019). Furthermore, traditional biomass for cooking, in particular, in rural areas, currently accounts for 12% of the nation's overall final energy consumption (IEA, 2021b).

Considering the disparities in climate conditions, heating and cooling demands, and socio-economic drivers, it becomes evident that effective residential building decarbonization strategies differ across the three regions⁴.

In the EU, given the extensive existing building stock, deep energy renovation stands out as the primary strategy for achieving building decarbonization. If all EU residential buildings were renovated to achieve a minimum 20% energy savings in the building envelope, 777 TWh of energy could be saved⁵. Another pillar of EU building decarbonization is the electrification of heating, closely linked to the rapid expansion of renewable energy sources in power generation.

In China, considering the unprecedented urbanization and new construction trends, it is imperative for China's new buildings to strive for near-zero or zero-energy standards. On the other hand, the huge existing building stock makes energy retrofits a paramount strategy for building decarbonization in China. By 2030, existing buildings should undergo retrofitting to significantly enhance their energy performance. By 2060, deep retrofitting should be completed for all existing buildings. Simultaneously, a critical element for building decarbonization in China is the transition to low-carbon heating, primarily through electrification and district heating systems. In northern urban areas characterized by historically high heating demand, the share of low carbon heating (heat pumps and district heating) should exceed 70% by 2030 and surpass 90% by 2060. In other urban areas, the share of heat pumps should reach nearly 100% by 2060. Moreover, in rural areas, the reliance on traditional biomass

⁴ While acknowledging the growing relevance of embodied energy and emissions in buildings, this paper confines its scope to the operational phase, encompassing energy usage for HVAC, domestic hot water, and lighting.

⁵ https://www.bpie.eu/wp-content/uploads/2022/12/How-to-stay-warm-and-save-energy_final-report.pdf

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sources is expected to rapidly decrease, falling below 10% by approximately 2040. Furthermore, the rapid AC growth also necessitates the widespread adoption of highly energy-efficient AC units, in conjunction with improvements in building envelopes.

In India, in contrast to the EU and China, the expected growth of new building stock and increasing AC ownership makes enhancing new building energy efficiency for passive cooling and widespread of highly energy efficient ACs fundamental for India's building decarbonization. Additionally, addressing the use of traditional biomass for cooking, which also carries significant health implications, is vital for India's building decarbonization.

These divergent decarbonization strategies, shaped by distinct national contexts, have led to varying sets of policies in these three regions. This paper aims to systematically analyse existing residential building decarbonization policies in these three regions, pinpointing policy gaps. It also aims to highlight similarities and differences in these policies across the regions to facilitate mutual learning and offer valuable insights for global policymakers. While we are aware of the growing relevance of embodied energy and emissions in buildings, this paper confines its scope to the operational phase, encompassing energy usage for HVAC, domestic hot water, and lighting.

2. Methodology

Firstly, a policy landscape analysis was conducted to map and compare the existing building decarbonization policies across the three regions. It involved a systematic categorization of policy instruments based on their potential to address specific barriers in the context of building decarbonization. The categorization was adapted from bigEE.net for residential building policies and encompasses the following key types of policy instruments: governance and planning, regulatory instruments, economic instruments, information instruments, policies supporting capacity building, and policies promoting energy services and business models.

Policy design is widely acknowledged as a critical determinant of policy effectiveness (Schmidt & Sewerin, 2019). Thus, the second step of policy analysis captured the design features of three selected policy instruments that are generally considered to be highly effective (Ürge-Vorsatz et al., 2007) and common across the three regions: building energy code, building information disclosure, and economic incentives. For this purpose, we adapted the concept of policy intensity introduced by Schaffrin et al. (2015).

3. Key findings

The policy mapping exercise revealed that all three regions have implemented a mix of policies aimed at decarbonizing their residential building stocks. The EU and its MSs have a long history of implementing building energy efficiency measures, which began as a response to the 1973 oil embargo (Economidou et al., 2020). It boasts a diverse array of policy instruments, particularly in the realm of governance and planning, including EEOs, overarching cross-sectoral funding programs, and carbon pricing for fuels used in buildings. China, on the other hand, initiated its journey toward building decarbonization with the development of building energy codes for residential buildings in the 1980s. Over the years, it has expanded its policy toolkit to cover all climate zones, incorporating various policy instruments. In contrast, India has started developing building energy efficiency policies more recently. Its predominately tropical and sub-tropical climate has resulted in a limited need for heating. This in turn delayed the formulation of comprehensive building energy efficiency policies. The absence of a building decarbonization roadmap with ambitious targets and a defined timeline for achieving a net-zero building stock remain a significant political barrier in India. The development of such a roadmap will require robust data and quantitative modelling support, which are currently lacking. Despite the long-standing implementation of energy efficiency policies in the EU and China, both regions face a persistent challenge in the form of fossil fuel price-distorting subsidies in their residential sector. Additionally, China's low area-based residential heating prices present a notable barrier to energy efficiency investments. The policy packages in the EU and China, while extensive, seem to fall short in addressing these and other barriers, particularly in the context of decarbonizing the existing building

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stock. This is evident in the fact that rates and depth of energy renovations still fall considerably short of harnessing the cost-effective potential and achieving the necessary pace for decarbonization by 2050 and 2060, respectively.

In our analysis of building energy codes, disclosure of information, and financial incentive schemes in the three regions, we observed variations in ambition, scope, and implementation, even when similar policy instruments are employed. Building energy codes are fundamental for building decarbonization. The EU and China have made significant advancements, particularly in terms of code stringency and compliance checks. The EU stands out with its ambitious, mandatory code covering both new and – conditional on major renovation of existing buildings and promoting higher energy efficiency through a performance-based approach. While China has continuously increased code stringency, its roadmap towards achieving net-zero goals remains less ambitious. To achieve a net-zero building sector in China, mandating building codes also for rural areas and existing buildings is essential. It is underscored by the fact that rural areas account for over 45% of residential building energy consumption and the rising importance of energy use in existing building stocks. Furthermore, employing a performance-based approach or a hybrid combination of performance and prescriptive methods is advisable, as it has the potential to yield higher energy efficiency. Both the EU and China exhibit high compliance rates for new buildings. In contrast, India's adoption of residential building energy codes remains limited, which stands as a significant obstacle to its journey towards net-zero. This limitation is not only due to design features (e.g., voluntary code, weak compliance check) but also associated with India's governance structure. Although the central government has the authority to establish building codes, the adoption and modification of these codes fall under the jurisdiction of the States/Union Territories.

All three regions have introduced residential building energy labelling. The EU shows the most advanced policy in this regard, although improvements are necessary for greater effectiveness in driving zero-emission buildings and deep renovations. In China, challenges such as the voluntary labelling, costly procedures, calculation complexity, and lack of qualified assessors have hindered widespread implementation. In India, apart from issues related to voluntary labelling and assessor qualifications, low stakeholder awareness has proven to be a significant barrier.

While financial incentives for decarbonizing residential buildings exist in all three regions, they fall short of facilitating net-zero building transformation. These incentives are predominantly in the form of subsidies, potentially straining public budgets. Additionally, financial incentives specifically aimed at promoting net-zero new construction and deep renovation hold the potential to mitigate the higher initial costs associated with these projects and expedite the transformation of the market. However, our analysis across all three regions reveals a marked deficiency in such financial incentives.

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COMMISSION STAFF WORKING DOCUMENT IMPACT ASSESSMENT REPORT

Accompanying the Proposal for a Directive of the European Parliament and of the Council on the energy performance of buildings (recast)

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5. Gender Impact Assessment deep dive

In this subsection of the report the analytical and structural elements of the Gender Impact Assessment (GIA) methodology and its application to the buildings sector are outlined. It sets the analytical ground for a more comprehensive in-detail Gender Impacts Assessment according to Spitzner et al. 2020 with its pre-analysis and main phase, addressing all seven gender dimensions on the basis of the Gender+ approach for the micro-, meso- and macrolevel of actors and institutional frameworks for residential buildings renovation projects.

The renovation of existing buildings is one of the key approaches for GHG emission reduction in the buildings sector. The GHG emission reduction pathways for residential buildings sector in EU27, as presented in this report, show that a large percentage of the emission reductions originate from renovating the stock of residential buildings. At the same time, increasing the historically observed average renovation rates of 1% between 2% and 3% annually in the EU27 countries is among the hardest to achieve sectoral goals.

One key reason lies in the inherent complex structure and interaction between a multitude of actors. These complications result in a considerable need of planning and interaction to make renovation measures successful or being considered and started at all. Such a complex interaction network is underlying each single renovation project, revealing the following features: On the one hand, the institutional and regulatory frameworks as well as professional and social habits determine general properties of the actors' network. This allows for generalized analyses and conclusions on leverages and success factors within the national or regional scope considered. On the other hand, even within the same background conditions, each renovation project usually involves different individual persons as actors. These individual persons need to interact and consent in specific ways to make a renovation project being brought to life at all and being then finalized according to its targeted outcomes. Standardization is limited in such projects. The efforts and resources necessary for renovation projects are high per ton of CO₂ emission avoided, compared to large scale projects with fewer number and diversity of actors (e.g. renewable energy plants). Apart from this technical view, individual persons are in the centre of residential renovations measures. Underlying the technical term of the desired "deep renovations" is also a deep intervention with and a fundamental impact on the lives of the persons whose homes the affected dwelling are. "Being the home" for the persons sharing a dwelling our house incorporates a large number of basic and highly important functions for the individuals. Care-related functions are among the most prominent. Care, however, is one of the most prominent gender-related and gender-biased domains. If personal safety, as another example, is assigned to a physical place, this most often is the personal dwelling.

Residential renovation projects are thus most suitable for applying a structured Gender Impact Assessment; on the one hand from the fundamental claim of designing such projects and activities in a gender-responsive and gender-transformative way; on the other hand from the Gender Impact Analysis revealing key barriers and in indicating leverages and opportunities as co-benefits for the more technical targets of the renovation projects, the reduction of GHG emissions and energy consumption, among others. It is not a new insight that the regulatory, institutional, and entrepreneurial frame conditions are a key factor for successfully initiated renovation projects and thus high national renovation rates. Yet, these structures and their gender-responsive transformation are directly addressed by the gender dimensions structuring the Gender Impact Assessment according to Spitzner et al. 2020, which are "public infrastructures and resources" (also and even mainly non-material) as well as "institutionalized gender hierarchisations and androcentric models, methods and

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problem perceptions”. As these frame conditions for renovation projects usually do not vary with each individual renovation project but are linked to national conditions on different scales, they are very much suitable for deriving generalized sectoral conclusions on barriers and enabling designs of these frame conditions.

The methodology of the Gender Impact Assessment (GIA) laid down here for residential building renovations is based on the key publication of Spitzner et al. 2020 by the German Environment Agency UBA.

The GIA focus chosen here puts the perspective of a single household and the individuals therein into the centre of the analysis, i.e. the micro-level of investigation. Here, the manifold impacts on the household members are described.

As a large variety of different household compositions exists and as the household members strongly determine the influence of and on renovation measures, an exemplary household composition is referred to, here. This serves as the basis for drawing concrete conclusions on the requirements and leverages for mitigating the negative effects of deep renovation measures; or even realizing benefits and opportunities during these measures under the gender-transformative perspective. “Victimization” of the residents is avoided as far as possible, but the step is made toward identifying and supporting transformative opportunities.

The individuals of the household under consideration are characterized as general as possible. The example household composition underlying the following consideration is:

- one adult person predominantly bearing the care work in the household
- one adult person caring for the paid work in the household
- 2 children, e.g. 1 and 6 years old.

Further household members could be assumed and would expand the spectrum of individual interests, impacts and intersectional aspects, like elderly persons requiring comprehensive home care activities. However, for elaborating the general structures and logic of renovation measures in a household context, this further complexity will not contribute.

For concrete and applicable results and conclusions, the renovation project also needs to be described concretely, i.e. what construction works are performed and how the residents are situated therein. The following definitions are made in line with the PRIMES BuiMo residential buildings scenarios presented in Section 3 of this report:

Renovation measure: substitution of an oil-fired central heating by an air heating pump with reduced heating water flow temperature, decentral preparation of hot potable water based on heat exchangers, exchange of the heating pipes, enlarged heat exchange surfaces of radiators in the rooms and outside insulation of the buildings envelope.

The term „renovation measure“ is understood in the context of the GIA as building shell measures like improving thermal insulation as well as equipment replacement measures like the exchange of the heating installations. The interpretation of this term differs along countries and regions as well as contexts. As both, building shell measures as equipment replacements affect the individuals of the households this extended definition is used here.

To lift the perspective beyond the “victimization” of the individuals affected, the meso-level of the other actors as well as the technical and social structures and practices of the renovation project under investigation is incorporated. In the broader perspective the involved actors on the meso-level are:

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- Residents of the dwelling under consideration
- Their relatives and friends
- Their employer(s)
- Care institutions (nursery, school, ...)
- Hotel and rental apartments operators
- Residents of other dwellings in the building
- Lessor of the dwelling
- Janitor(s)
- Community of owners or owner of the entire estate (who is lessor then in the same time)
- Builder of the renovation measures = owner(s) of the estate
- Planning company
- Construction company
- Investor(s)
- Community
- Local politicians (responsible for the legal and regulatory framework for the mitigation measures)
- Local media (local press, TV, bloggers)

The meso-level itself is strongly influenced by the frame conditions set at the (national) macro-level of the involved institutions and regulations for construction and renting. In Germany, for example, key regulatory legal and practical guidelines for constructions and installation works at buildings are the (former) fee regulations for architects and engineers (“Honorarordnung für Architekten und Ingenieure” HOAI) and the national contracting rules for construction works (“Verdingungsordnung für Bauleistungen” VOB). These key regulatory frameworks would needed to be concretely analysed in regard to their contributions to gender-biased conditions and, moreover, for opportunities of adaption for gender-transformative improvements.

The GIA follows the division into two phases of analysis: Firstly, it conducts the pre-analysis which investigates the relevance of the gender aspect for renovation in general and already indicates where to best direct the detailed main analysis regarding the gender dimensions and other focal points. Not surprisingly, and as stated above, there is a high relevance of the gender perspective in residential renovations measures. Maybe even more important here, the pre-analyses define the concrete scope of the analysis. This is necessary according to multiple aspects (definition of the personal life situations of the persons in the household under investigation, technical definition of the renovation measure(s) performed etc.).

Further, the pre-analysis describes the analytical dimensions and aspects which are relevant for the analysis in a broader entirety, to be able to select the aspects which are of the highest relevance and are thus in the focus. This comprises the properties and goods of the personal lives of the residents which are clearly or could potentially be affected by the renovation measures:

- eating, cooking, drinking, breathing
- conditioned residing (protection from cold, heat, wind)
- physical and emotional safety
- familiarity, habituality and aesthetic perception
- communication (speaking, listening)
- intimate personal contact and connectedness
- social contact with persons outside the household (friends, relatives, other persons)
- representation of personal or social status
- home office

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- leisure activities (hobbies, sportive activities)
- relaxation and recreation (reading, listening to music)
- personal hygiene
- medical care
- intimacy and sexuality
- sleeping

This setting of the boundary conditions of the investigation and definition of the object of analyses constitutes the basis for the following main GIA analyses.

The main phase of the GIA comprises two key aspects: the impact analysis in the detailed and narrow sense as well as the question of what approaches can be found for transforming the setup of the renovation project towards gender equality. All levels of the micro, meso and macro perspective are incorporated here. Identifying co-benefits for the project itself is an inherent step, asking how the transformative approach can also support the highly ambitious GHG emission mitigation targets. The assessment therein needs to differentiate social impacts and conclusions in general from gender-related perspectives. The GIA for renovation measures of buildings is generally to be founded on the “Gender+” approach as described by Spitzner et al. 2020. It claims that the intersectional interrelations as part of the gender perspective are not blinded out but part of the analytical perspective. With this, the complete process of the GIA as conceptualized here for residential building renovations reveals a considerably high number of analytical dimensions and aspects. It means assessing the impacts of the diverse technical renovation measures on the different personal functions for the seven gender dimensions and deriving transformative measures for each of these combinations under the Gender+ approach on the micro-, meso- and macro level. It is thus proposed to focus on key “routes” of impact and transformative measures within the renovation project which are concretely investigated under the methodical framework of the GIA. This can prepare the ground for in-depth analysis for other impact “routes” within building renovation measures as well as for similar GIA applications in the field of GHG mitigation options in the buildings sector.

6. Opportunities and constraints in the buildings sector

To accelerate the buildings sector's decarbonisation, a number of barriers still need to be addressed. Within the NDCASPECTS project, we focus on the building operational phase. This section summarises the significant barriers the implementation of buildings decarbonisation.

Political factors represent a crucial barrier. These are overarching barriers lacking clear vision and signals for building decarbonisation. First, decarbonising the building sector requires long-term commitment given the low stock turnover of buildings, unlike short-term election cycles in many countries (UNEP, 2020). Second, there is often an absence of clear policy signals and incentives for different actors on the value chain to be engaged and invest in building energy efficiency (IEA, 2021f). It is challenging for many governments to develop an ambitious and comprehensive long-term roadmap to outline the building sector decarbonisation pathway and even more so to implement them (Gaur et al., 2021; Global ABC et al., 2020). These aspects have been analysed in detail in WP6 and W4.

In addition, there are economic and financial barriers to invest in energy efficiency and low-carbon heating equipment in buildings. Energy efficient building envelopes, heat pumps and super-efficient ACs, and clean cooking are often associated with higher upfront costs and longer payback time than conventional ones (Cohn & Efram, 2022; IEA, 2020; Ürge-Vorsatz et al., 2020). This has been a significant barrier to their adoption. The cost barrier is aggravated by split incentives, where the investors, who own the tenant-occupied buildings, do not financially benefit from their investment in, e.g. energy retrofits and energy systems such as heat pumps (Höfele & Thomas, 2011). Depending on pricing mechanisms for electricity and fossil fuels, the operational costs for electrification can also be high. The fact that fossil boilers are financially supported further reduces the economic attractiveness of heat pumps (Lowes et al., 2022). Economic factors also persist as a barrier for suppliers. Besides, electric heating and cooling appliances can provide flexibility to the grid system, increasing its cost-effectiveness (OVOENERGY & Imperial College London, 2018). However, policies and power market in many countries do not incentivise consumers to provide flexibility (Yule-Bennett & Sunderland, 2022). Transitioning to low carbon products and services is particularly costly for suppliers, considering the prevailing price competition with conventional options (Höfele & Thomas, 2011). Meanwhile, suppliers are often uncertain about the market demand for energy efficiency options (ibid.). On top of cost issues, there is generally a lack of access to affordable finance to invest in building energy efficiency and low carbon heating and cooling options. Many households and companies cannot bear to finance the high upfront costs from their resources while access to affordable finance options is limited due to informal and irregular income, high transaction costs and interest rates, taxes and down payment requirements. Capital providers (e.g., banks and institutional investors) are inhibited by a lack of liquid capital markets and lacking policy and governance frameworks (Climate Action Tracker, 2022a). They often lack technical knowledge of building energy efficiency projects and assessments. There is also no supporting energy performance data (G20 EEFTG, 2017). They also perceive high lending and investment risk associated with these projects due to lenders' lack of track records, low collateral asset value, a long project lifetime, and high-performance risks. In addition, individual building projects are relatively small; thus, the transaction costs of assessing each project are high (ibid.). Last but not least, governments, in particular, in developing economies, often lack adequate funding to finance policies for supporting the implementation of energy efficiency investments and research and development activities as well as demonstration projects (RD&D), such as deep retrofits, net-zero carbon buildings, plus-energy buildings.

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Another key barrier is the lack of capacity, i.e., the knowledge and skills required on the supplier chain, such as designing (in particular, identifying the best technology mix) and construction of high-energy-performance buildings and designing, installers of low carbon heating and cooling systems, building energy managers, etc. This was revealed as a common barrier that significantly impedes the scaling-up of these building decarbonisation options (UNEP, 2020).

Building decarbonisation also faces technical barriers, ranging from infrastructure (network) and building characteristics (e.g., structure, orientation) to technical processes which were especially relevant to the modelling work presented in Subsection 1. For example, a critical barrier to market penetration of decentralised heat pumps is the incumbent heating infrastructure (e.g., the gas grid), which is associated with significant sunk costs invested by gas utility companies (Lowes et al., 2022). The overall physical characteristics of the built environment, e.g. shape, size, density and configuration, can influence energy consumption and implementation of renewable-based heating and cooling (Global ABC et al., 2020; Sheldon et al., 2018). Property owners and users may be discouraged from undertaking deep renovations because of the associated disruptions due to the involved technical works (Trinomics. et al., 2022). Also, the technology maturity of specific technologies and solutions can impede the uptake of specific options and measures, e.g. solar cooling and zero/plus energy buildings (Sheldon et al., 2018). Beyond the building level, the increasing electrification of heating and cooling will significantly increase electricity demand and thus create challenges posing stresses in the grid system, particularly the distribution grid (Love et al., 2017) while also increasing the investment requirement for power generation plants.

Availability and lack of access to information about decarbonisation measures impede consumers and investors from adopting these measures (Höfele & Thomas, 2011; Mata et al., 2021, 2022). To make well-informed investment decisions, consumers and investors need to know the best energy efficiency that suits their needs, installation and operation complexity, and cost-effectiveness (Mata et al., 2021). Data on energy performance and cost savings after implementing measures are essential, but they are not always available or consistent (Criado-Perez et al., 2020). Although the improved technology enables heat pumps to operate well even in cold regions (Wei et al., 2020), the previous low performance of heat pumps in these regions causes concern among consumers about their reliability.

Social and cultural factors also have a significant impact. In North America and Europe, in combination with information availability, consumers' attitudes and values were identified as one of the most critical factors in improving the building envelope (Mata et al., 2021). Besides, building occupants' behaviour can limit the emission reduction potentials of building energy performance improvement, e.g., through increasing ownership and use of appliances (IEA, 2019a) and demand for more living space (Bierwirth & Thomas, 2015).

Last but not least, structural factors such as population and economic growth, as well as urbanisation, in particular, in emerging and developing economies, have been driving the increases in floor area expansion and energy demand and associated CO₂ emissions. These factors may outweigh improvements in energy efficiency (Zhou et al., 2018; IEA, 2021b)

7. Conclusions and policy implications

In this report, we investigated what successful decarbonisation means for the buildings sector, by identifying viable socio-technical strategies for buildings transformation. This included modelling the evolution of the sector for the European Union (EU27), analyses of potentials of and boundary conditions for the implementation of various technological options such as electrification, efficiency improvements, deep building retrofits, the changing role of gas, and integration of renewable energy technologies. Many of these options are still novel or have not been sufficiently reflected in existing NDCs.

This paper examined different transformation pathways for the EU buildings sector in the 2020-2050 period inducing mitigation options like ambitious energy efficiency improvements in buildings and electrification of their energy demand to attain the EU targets – related to both CO₂ emissions and final energy consumption, as well as renewable energy shares.

To accomplish this, three sets of scenarios, reflecting different mitigation pathways, climate policy contexts, and fuel import prices, were developed and quantified with the PRIMES-BuiMo model. Within these scenario sets, four general policy setups were designed, reflecting the different mitigation approaches and pathways: The “Baseline” scenario referring to the “existing policy framework” and three policy scenarios, i.e., the “Decarb_HE”, the “Decarb_Helec” and the “Decarb_Helec_ETS” scenarios. Then, to assess the impacts the current energy crisis involving the decrease in the Russian gas imports to the EU, the initial scenarios were enriched to consider the drastic increase in international fuel prices. Therefore, the variants are developed based on three decarbonization scenarios combined with assumptions for high energy prices– “Decarb_HP_HE”, “Decarb_HP_Helec” and “Decarb_HP_Helec_ETS”.

The study was performed using the PRIMES BuiMo, which following the methodology of hybrid-energy-economy models, projects into the future final energy consumption, fuel mix and CO₂ emissions in the EU buildings sector. These projections are made within the framework of specific energy and climate policies, regulatory measures and climate targets that define the examined scenarios. These frame conditions drive renovation decisions and choices in terms of both building envelope renovation and technology equipment. The pathways cover the development and technical change of all energy end-uses in the buildings sector, which in the different combinations of options lead to different mitigation pathways towards the carbon neutrality goals while attaining to the binding medium-term goals of 55% GHG emission reduction for 2030 in the EU.

We conclude, from our study, that EU countries should base their updated energy policies and NDCs on measures that prioritize building envelope renovations as well as heating equipment replacements. With respect to the residential sector, at least 1.9% of dwellings should be renovated annually and a minimum of 2.6% - 3.1% of the total building stock (including both residential and commercial buildings) should replace the heating equipment on an annual basis until 2030 and 2050, respectively.

EU energy policy measures should be further developed focusing on the energy demand reduction, establishing strategies that promote energy efficiency renovations, and on both electrification and high energy efficiency of the buildings technical equipment along with the extension of carbon pricing in the building sector. In other words, despite the rapid development of clean and sustainable solutions of technical building equipment – for all end uses – the principle of energy efficiency first is of great importance to achieve demand reduction.

The alternative mitigation pathways analysed are based on different energy policy priorities that prioritise different mitigation options (e.g. renovation, electrification) that also affect, the contribution of the building sector on the overall energy efficiency, CO₂ emissions reduction and renewable energy targets, especially in this critical decade to 2030.

Within the “Decarb_HE” policy framework, focusing on energy efficiency improvements, the EU countries must significantly accelerate annual energy efficiency renovations especially in the

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residential sector where 3.1% and 2.5% of total households should be annually renovated by 2030 and 2050, respectively.

Conversely, within the policy setups emphasizing the buildings electrification (Decarb_Helec and Decarb_Helec_ETS), Member States must further develop their energy policy measures, establishing stronger equipment replacement strategies and prioritizing the uptake of heat pumps. More specifically, the “Decarb_Helec” framework should be accompanied by 3.5%/3.9% and 2.9%/4% annual heating equipment replacements rates in the residential/services sector until 2030 and 2050, respectively. The ETS extension in the building sector is followed by a remarkable increase in the aforementioned replacement rates, especially in the short term, as 5.2%/4.4% and 3.4%/4.4% of the total residential/services building stock should replace the heating equipment on an annual basis until 2030 and 2050.

Since the overall long-term objective is climate neutrality by 2050, policy measures included in the decarbonisation pathways lead to an almost similar long-term performance in terms of CO₂ emissions and fuel mix. Yet, the building sector contribution to the short-term targets in 2030 varies significantly across the scenarios.

For all investigated policy scenarios, within the “decarbonization context”, the buildings’ sector final energy consumption in 2050 is around 230 Mtoe, comprised of electricity, renewables, heat, and decarbonized gaseous fuels (e.g. biomethane, hydrogen), leading to almost zero CO₂ emissions from buildings.

According to the EEA estimates, in 2020, EU-27 CO₂ emissions were 31% lower than in 1990. Therefore, an additional 24% reduction is required by 2030 for the updated target of 55% GHG reduction to be met (compared to 1990). The examined mitigation pathways indicate building sector CO₂ emissions reduction of 32%, 41% and 65% compared to 2020 in the high efficiency, the electrification and the ETS policy framework scenarios, respectively. Therefore, the buildings contribution on the overall CO₂ emissions reduction is well over the established target removing some of the burden from the other sectors.

The building sector contribution on the short-term climate targets for 2030 as described in the Fit-for-55 package is higher within the electrification policy setup compared to the high efficiency one, while considering the ETS within the building sector gives a further considerable boost. Nonetheless, according to the impact assessment of the EED in 2021 (European Commission, 2021), special attention is required regarding the buildings energy efficiency since except for the energy savings, energy efficiency also drives improved indoor environments in terms of comfort, health and well-being, while it may also create additional domestic job opportunities especially in construction services and their supply chains (e.g. cement, steel). In addition, a holistic analysis of the examined mitigation pathways also requires the comparison of both the capital (in terms of renovation of old constructions and purchasing of equipment and appliances) and the operating expenditures – fuel purchasing expenses per household/service building – needed, which is out of the scope of this study.

Within the “decarbonization” framework, high energy prices resulting from the war in Ukraine lead to significantly higher equipment replacement rates and higher buildings envelope renovation rates already in 2025. These high rates drive a considerable final energy consumption reduction, demand electrification and remarkable CO₂ emissions decrease earlier in time compared to the normal fuel prices variants. Yet, it is vital to note that these positive effects shown in the results require a remarkable increase (of 11%) in the capital expenditures, while a significant raise (of 24%) in the operating expenditures that is of even greater importance. These aspects need further research that is planned as a follow-up to this study.

The high energy prices scenario variants show different effects in terms of both the “existing policy” and the “decarbonization” framework after 2030. Since the high renovation and equipment replacement rates until 2025 succeed in confronting the energy crisis and fuel prices are getting back to normal there is no need for further increased investments for energy efficiency in buildings. Therefore, results reflect a remarkable decrease in both the renovation and the equipment

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replacement rates in the high prices scenario variants in the long-term, which are even slightly lower than the initial scenarios ones in the period after 2030.

In continuity, we have performed a pathways, targets and policy approaches comparison among three world regions, namely China, India and EU27. From this part of the report several novel conclusions are drawn.

The policy mapping exercise revealed that all three regions have implemented a mix of policies aimed at decarbonizing their residential building stocks. The EU and its MSs have a long history of implementing building energy efficiency measures, which began as a response to the 1973 oil embargo (Economidou et al., 2020). It boasts a diverse array of policy instruments, particularly in the realm of governance and planning, including EEOs, overarching cross-sectoral funding programs, and carbon pricing for fuels used in buildings. China, on the other hand, initiated its journey toward building decarbonization with the development of building energy codes for residential buildings in the 1980s. Over the years, it has expanded its policy toolkit to cover all climate zones, incorporating various policy instruments. In contrast, India has started developing building energy efficiency policies more recently. Its predominately tropical and sub-tropical climate has resulted in a limited need for heating. This in turn delayed the formulation of comprehensive building energy efficiency policies. The absence of a building decarbonization roadmap with ambitious targets and a defined timeline for achieving a net-zero building stock remain a significant political barrier in India. The development of such a roadmap will require robust data and quantitative modeling support, which are currently lacking. Despite the long-standing implementation of energy efficiency policies in the EU and China, both regions face a persistent challenge in the form of fossil fuel price-distorting subsidies in their residential sector. Additionally, China's low area-based residential heating prices present a notable barrier to energy efficiency investments. The policy packages in the EU and China, while extensive, seem to fall short in addressing these and other barriers, particularly in the context of decarbonizing the existing building stock. This is evident in the fact that rates and depth of energy renovations still fall considerably short of harnessing the cost-effective potential and achieving the necessary pace for decarbonization by 2050 and 2060, respectively.

In our analysis of building energy codes, disclosure of information, and financial incentive schemes in the three regions, we observed variations in ambition, scope, and implementation, even when similar policy instruments are employed. Building energy codes are fundamental for building decarbonization. The EU and China have made significant advancements, particularly in terms of code stringency and compliance checks. The EU stands out with its ambitious, mandatory code covering both new and – conditional on major renovation of existing buildings and promoting higher energy efficiency through a performance-based approach. While China has continuously increased code stringency, its roadmap towards achieving net-zero goals remains less ambitious. To achieve a net-zero building sector in China, mandating building codes also for rural areas and existing buildings is essential. It is underscored by the fact that rural areas account for over 45% of residential building energy consumption and the rising importance of energy use in existing building stocks. Furthermore, employing a performance-based approach or a hybrid combination of performance and prescriptive methods is advisable, as it has the potential to yield higher energy efficiency. Both the EU and China exhibit high compliance rates for new buildings. In contrast, India's adoption of residential building energy codes remains limited, which stands as a significant obstacle to its journey towards net-zero. This limitation is not only due to design features (e.g., voluntary code, weak compliance check) but also associated with India's governance structure. Although the central government has the authority to establish building codes, the adoption and modification of these codes fall under the jurisdiction of the States/Union Territories.

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All three regions have introduced residential building energy labelling. The EU shows the most advanced policy in this regard, although improvements are necessary for greater effectiveness in driving zero-emission buildings and deep renovations. In China, challenges such as the voluntary labelling, costly procedures, calculation complexity, and lack of qualified assessors have hindered widespread implementation. In India, apart from issues related to voluntary labelling and assessor qualifications, low stakeholder awareness has proven to be a significant barrier.

While financial incentives for decarbonizing residential buildings exist in all three regions, they fall short of facilitating net-zero building transformation. These incentives are predominantly in the form of subsidies, potentially straining public budgets. Additionally, financial incentives specifically aimed at promoting net-zero new construction and deep renovation hold the potential to mitigate the higher initial costs associated with these projects and expedite the transformation of the market. However, our analysis across all three regions reveals a marked deficiency in such financial incentives.

Last, though our work on the GIA we conclude that the main phase of the GIA comprises two key aspects: the impact analysis in the detailed and narrow sense as well as the question of what approaches can be found for transforming the setup of the renovation project towards gender equality. All levels of the micro, meso and macro perspective are incorporated here. Identifying co-benefits for the project itself is an inherent step, asking how the transformative approach can also support the highly ambitious GHG emission mitigation targets. The assessment therein needs to differentiate social impacts and conclusions in general from gender-related perspectives. The GIA for renovation measures of buildings is generally to be founded on the “Gender+” approach as described by Spitzner et al. 2020. It claims that the intersectional interrelations as part of the gender perspective are not blinded out but part of the analytical perspective. With this, the complete process of the GIA as conceptualized here for residential building renovations reveals a considerably high number of analytical dimensions and aspects. It means assessing the impacts of the diverse technical renovation measures on the different personal functions for the seven gender dimensions and deriving transformative measures for each of these combinations under the Gender+ approach on the micro-, meso- and macro level. It is thus proposed to focus on key “routes” of impact and transformative measures within the renovation project which are concretely investigated under the methodical framework of the GIA. This can prepare the ground for in-depth analysis for other impact “routes” within building renovation measures as well as for similar GIA applications in the field of GHG mitigation options in the buildings sector.

In this report we connected quantitative and social aspects in order to strengthen the knowledge base for a just energy transition in the buildings sector and the whole energy system. On top of other aspects researched we also dove into the high energy prices and whether they speed up the transition. However, through this research we came across the burden on the household budget – support schemes are needed. These aspects will be further analysed in the work we are performing for the Deep Dives in WP5.

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