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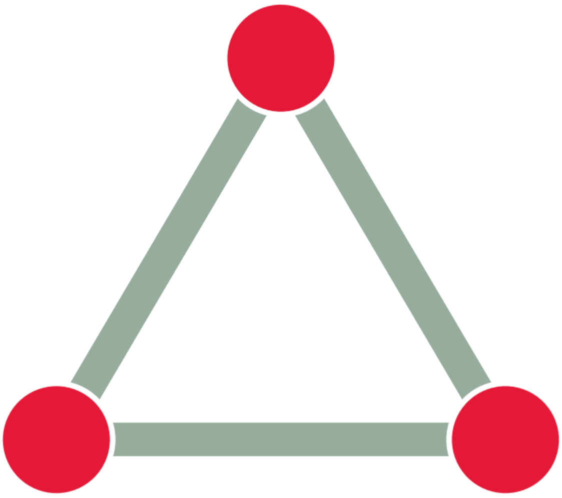
Energy
Transition

Flattening the Peak Demand Curve through Energy Efficient Buildings: A Holistic Approach Towards Net-Zero Carbon

Technical Report



Sponsored by the European Climate Foundation, the European Insulation Manufacturers Association, and the International Copper Association

Contents

1 Executive Summary

To achieve its climate objectives, the European Union must transition to a more efficient and renewable energy system. This transformation is crucial not only to achieve climate neutrality but also to ensure affordable heating, reduce dependency on imported fossil fuels, and enhance the global competitiveness of European industries. However, rising electrification rates present new challenges. The weather-dependent nature of renewable energy sources, combined with fluctuating heating demand, can place significant strain on Europe's energy system, particularly during cold and cloudy periods when energy demand is high and renewable output might be low. Additionally, the decarbonisation of sectors such as industry and transport is expected to exacerbate competition for electricity. This increased demand can lead to several adverse outcomes, including higher energy costs for end users, grid congestion, and blackouts. Recent scholarly research identifies building renovation as a crucial strategy for mitigating these issues by reducing peak energy demand and enabling a more efficient transition.

The present study assesses the benefits of energy efficiency measures in buildings, notably through energy retrofits via building envelope improvements, in flattening peak demand in the EU energy system. The study also considers the implementation of "active" efficiency and flexibility measures in buildings, providing modelling evidence for building heating operations with regards to operation of the whole EU energy system in different future renovation scenarios. A general framework has been developed using PyPSA-Eur to represent the major energy sectors and to reproduce connections between these in overall energy system operations. The PyPSA-Eur model, the modelling improvements introduced in the study, and the data on which the studys model has been built are openly available and can be re-used or modified. Building on an evaluated system that can replicate the energy mix of 2023, future time horizons for 2030, 2040 and 2050 have been considered, assuming emissions constraints which represent the evolution of Europes targets towards climate neutrality.

The study finds that, by reducing seasonal peak energy demand for heating by up to 49% compared to today, widespread energy efficiency and flexibility improvements in buildings allows to achieve the following benefits.

1	Reduce associated total energy system costs by €312 billion a year.
2	Cost-effectively save additional 0,2 billion tons of GHG emissions annually by 2030, allowing to reduce emissions by 10% beyond current emission targets. Lower peak demand also means that coal and gas can be phased out of the energy mix by 2040.
3	Save €44,2 billion annually in distribution grid investments and decrease levels of transmission grid congestion by a factor of approximately 4.
4	Ease the pressure on renewable energy infrastructure expansion. This reduction could reduce the need for up to 600 GW additional onshore and offshore wind capacity, and 872 GW solar PV capacity. Additionally, building improvements allow a more efficient operation of renewable energy sources, reducing levels of curtailment by up to 3 times.
5	Optimise transmission and supply investments, decreasing total electricity prices and increasing equality in electricity prices between European countries. These savings trickle down to end users, translating into substantial reductions in energy bills for European households and enabling European industries to operate decarbonised production processes at more competitive energy costs.
6	Optimise the average required size of a homes heat pump by up to 3 times, maximising the use of available resources and helping achieve Europes 60 million heat pump goal more affordably.

The model, data and the fully automated workflow developed to create the results of this study are openly available [1], enabling re-use and further development by the community.

2 Introduction & Goals

By burning fossil fuels directly and consuming energy in the form of electricity, heating and cooling, buildings account for 35% of the Europe's energy-related greenhouse gas emissions [2]. As Europe strives to meet its climate targets, there is an urgent need to reduce these emissions by transitioning to a more efficient and renewable energy-based system. This transition is pivotal in combating climate change and in addressing social challenges such as ensuring affordable heating, improving public health of citizens, and reducing Europe's reliance on imported fossil fuels.

However, decarbonising the buildings sector involves several challenges. One primary issue is the dependency of thermal supply and demand on weather conditions [3]. During cold periods, particularly when there is minimal wind and sunshine, the demand for space heating surges while the output from renewable sources like wind and solar declines. This scenario increases the strain on the grid as the efficiency of technologies such as air-source heat pumps also decreases. Additionally, heating demand shows significant seasonal fluctuations, with peak demands in winter and lower demands in summer, and daily peaks typically occurring in the early morning and late evening when residents use heating and hot water. Prior research has indicated that if heating demand were more evenly distributed throughout the year, the overall strain on the system would be significantly reduced, leading to a more stable and manageable energy system [4]. Therefore, given the long lifespan of buildings approximately 75% of Europes building stock is energy inefficient, and over 85% of these buildings will still be in use by 2050 [5] building renovations are widely regarded as a critical strategy for reducing both current and future peak demand. As part of its European Green Deal package, the EU has introduced legislative measures such as the revised Energy Performance of Buildings Directive (EU/2024/1275) [6] and the Energy Efficiency Directive (EU/2023/1791) [7], which set ambitious targets for reducing energy use in residential and non-residential buildings and introduced new performance standards for public buildings. The successful implementation of these directives is pivotal to maintaining Europes trajectory towards climate neutrality. This necessitates an efficient allocation of available resources across Europe's building and economic sectors.

While building heating is a significant source of carbon emissions, it is not the only carbon-intensive sector. Major contributors also include the power, transportation, and industrial sectors. The prevailing decarbonization strategy involves first reducing emissions in the power sector and then focusing on electrifying the remaining sectors. However, this approach introduces additional complexities. The decarbonisation of Europes energy-intensive industries, along with the shift towards electrified mobility, will increase competition for electricity and further strain grid infrastructure. If peak electricity demands, particularly in the heating sector, are not effectively managed, the consequences could include elevated energy prices, reduced capacity for decarbonising other sectors, and potential grid instability or blackouts [8].

Energy system modeling can help to better understand the complex interactions within the energy system. Given the intricate relationships between different sectors, it is essential for models to accurately capture these interactions. Effective modeling must account for the interplay between heating, transport, and power demands, as well as the supply from both variable renewable and conventional energy sources. It should also include balancing mechanisms such as grid constraints, efficiency improvements, and energy storage, alongside overall electrification trends [9, 10, 11].

Previous research has explored various aspects of energy efficiency and its impact on heating demand. Studies have investigated how energy efficiency measures can mitigate seasonal and daily peaks in heating demand [4, 12, 13]. These works provide valuable insights but often focus on individual components rather than the integrated effects of comprehensive policy scenarios, and rarely build on an evaluated network model that can reproduce historical statistics, such as curtailment or the generation mix.

This study builds upon prior research by employing a top-down, sector-coupled European model that integrates the power, heating, transportation, and key industrial sectors, along with stringent carbon dioxide emissions constraints. The novelty of this research is its policy based scenario building approach. The model starts with a detailed evaluation of the 2023 European energy system, accurately reproducing the historical electricity mix with less than a 5% error for each energy carrier, including renewable (solar, wind, hydro) and fossil (coal, gas) generation, and nuclear. It then myopically projects potential energy pathways for 2030, 2040, and 2050, closely aligned with current European climate targets and projected technology cost assumptions. The primary focus is on providing a holistic system assessment of how building renovations impact the European energy system under evolving emissions regulations, and the cost-optimal timing for these actions. Therefore, this study introduces key industrial sectors and their interactions with the power system for the first time, along with an improved demand-side response implementation for the heating sector, to align with upcoming regulations such as the flexibility needs assessments and [14]. The research also features a novel methodology for integrating waste water heat recovery in residential buildings. Extensive collaboration with stakeholders has further enhanced the models transparency and validity, ensuring robust insights into the future role of energy-efficient and flexible buildings in managing peak demand.

This method enables us to explore key research questions about the future role of energy-efficient and flexible buildings in reducing peak demand curves within a decarbonised energy system:

- *What effect does flattening seasonal and daily peak demand curves through building renovations have on Europe's energy system?*
- *To what extent do energy efficient and flexible buildings affect peak heating and electricity demand curves?*
- *What impact does reducing peak demand have on energy prices for European countries, households, and industries?*

The outcomes of this study are anticipated to provide substantive guidance for policymakers, presenting actionable recommendations to bolster the resilience and efficiency of Europes energy system in a cost-effective manner.

3 Approach: Data & Methodology

This section describes the PyPSA-Eur model used in this study and focuses on features related to the space heating sector. Fist, the general architecture of the model is described, including an introduction to all considered sectors and technology options. Subsequently, the assumptions are outlined for demand, supply, transmission and flexibility with an emphasis on representing retrofitting of the building envelope. The PyPSA-Eur model represents the backbone of the proposed energy transition pathways spanning from 2030 to 2050. The model is required to achieve decarbonization of all considered energy sectors in three planning horizons (2030, 2040 and 2050), ultimately reaching net-zero by 2050, in accordance with the most recent policy and planning guidelines for each planning horizon.

3.1 Description of the PyPSA-Eur Model

The study was conducted using PyPSA-Eur, which has been customised and adjusted to consistently address the effects of peak demand smoothing within the broader context of the European energy system. PyPSA-Eur is a model of European energy system built using the open source PyPSA framework and based exclusively on open data and open code [15]. This means that the model's methodology and assumptions, as well as data and source code, are completely transparent and fully available for modifications and reuse. All modifications made for this study have been contributed back to the upstream model or are available in the project's GitHub repository[1]. A detailed description of PyPSA-Eur can be found in [16], while customised setting and the novelties introduced for the purpose of this study are outlined in this report.

The model encompasses the most carbon-intensive energy sectors that require decarbonization: power, transport, space heating and industry, as illustrated in Figure 1. A unique feature of the model is its detailed representation of the relevant transmission infrastructure and demand distribution at a high spatial resolution. To accurately capture system dynamics, especially peaks in space heating demands, the model is built with the highest possible time resolution of one hour.

The model operates under the assumption of a partial market equilibrium and belongs to a class of optimisation models. The overarching objective is to minimise the total system costs while meeting all demands and carbon emissions targets for a given planning horizon. The considered energy carriers include electricity, heat, methane, hydrocarbon fuels (including synthetic ones), hydrogen and biomass. The transport of each energy carrier is modelled with consideration of the transmission capacity of the respective infrastructure.

3.1.1 Considered economical sectors

The model represents the flows of energy carriers and their transformations (PtX), governed by interactions between different energy-related sectors. The following energy sectors are taken into consideration:

- power
- space heating
- transport
- carbon-intensive industries.

In addition, the model incorporates heat loss in buildings to capture the physical and economic effects of building shell retrofit. This allows for a holistic assessment of the energy efficiency and heat supply technologies within the energy system, taking into account synergies and competition between different technologies.

3.1.2 Main principles

To ensure that the modelling results accurately reflect reality, a number of specific conditions are enforced on the model variables.

Modeling constraints include, but are not limited to:

- the power balance must be satisfied for every energy carrier at every moment of time, taking into account also the energy storage dynamics with charging and discharging cycles, and different types of losses
- meeting spatially and hourly resolved demands across a full weather year at all places and all times
- respecting Kirchhoffs circuit laws which means a proper representation of electricity transmission bottlenecks
- accounting for different types of losses, such as conversion losses between different types of the energy carriers, standing losses in storage systems, losses of the transmission and distribution grids

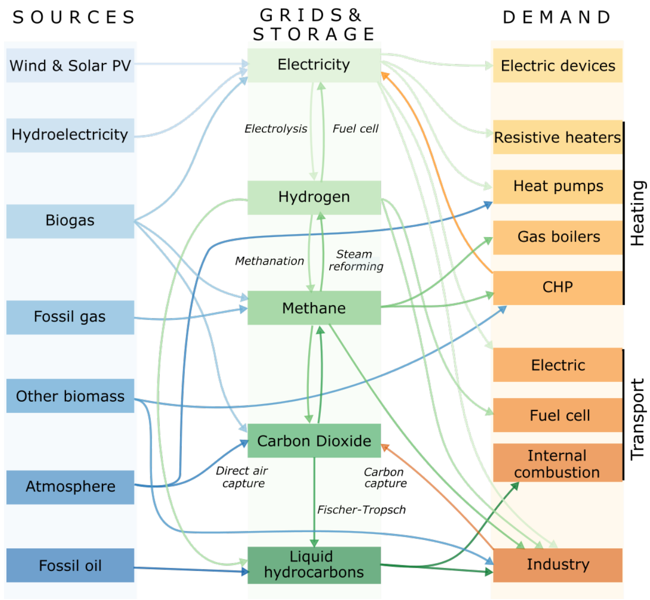


Figure 1: Interactions of Demand, Supply, Storage and Grids of the sector-coupled PyPSA-Eur model.

- variability of the available renewable potential in space and time according to the realistic weather dynamics
- land-usage restrictions for renewable generators, for example accounting for natural reserves or available rooftop area of buildings.

3.1.3 Demand

The model considers the demands for each sector, which are spatially distributed based on statistics on population density and GDP. Hydrogen demand is generated endogenously in the course of the optimisation, ensuring that the modeling constraints are met in a way that minimizes overall costs.

Electricity demands are set exogenously for every economic sector included in the model and covers all the types of electricity consumption, including electricity using for space heating, transport and industry. Openly available demand time-series [17] are used as inputs at the country level. Electricity demand is spatially distributed based on a linear relationship with population and gross domestic product (GDP), using the highest available resolution for these data.

Heating demand accounts both for space heating and domestic warm water for all the sectors considered by the model. Space heating demand is disaggregated both spatially and temporally, considering the following factors:

- socioeconomic features, such as population distribution and the overall energy consumption by economic sectors
- interdaily variations due to weather effects
- hourly patterns of space heat demand depending on a user type and day of the week.

The spatial and temporal features of space heating demand across Europe are pre-processed as follows. The ERA5 reanalysis dataset, with its highest available hourly resolution, provides input for ambient air temperature t. A raster of ERA5-derived t time series is used to calculate heating degree days (HDDs), a common indicator of space heating demand. To convert HDD values into actual space heating demand, a calibration procedure is applied, which incorporates economic and demographic parameters. During calibration, an official Eurostat population dataset at the NUTS 3 administrative level is combined with aggregated country-level energy balances, accounting for differences between urban and rural areas, as well as residential and service heating needs.

Typical hourly dynamics are modelled following the methodology of the German Association of Energy and Water Industries (BDEW) [18]. The space heat demand profiles differentiate between residential and service consumers, as well as between workdays and holidays.

Industry demands include electricity and space heat, as well as chemical substances used in the industrial processes, such as coal or hydrogen as a reducing agent for steel production. The mitigation strategies for the industrial sector replace CO_2 emitting processes by net-zero alternatives, wherever possible. Certain processes are considered not electrifiable, and any remaining emissions are captured by carbon capturing technologies. Competing decarbonisation approaches are considered which allow the model to select ones most beneficial from the economical perspective. All types of industrial demand are spatially distributed using raster data on industrial emissions and population, and calibrated using nationally-aggregated statistical data on industrial production.

Transport demands The model includes the following types of transportation:

- land transport, which accounts for both heavy and light transport
- marine transport
- aviation.

The demand for transport energy carriers is determined exogenously based on available statistics on various transport modes. Land transport uses internal combustion engines, fuel cells, electric batteries; marine transport is fuelled by oil or methanol; and aviation relies solely on kerosene. The scenarios assume decarbonisation of land and marine transport, necessitating the replacement of fossil fuels with non-emitting technologies. The sources of the energy carriers are determined through optimisation to meet the preset electric or e-fuel demand in the most cost-effective manner, while adhering to all technical constraints.

Hydrogen demand is defined by various needs across all considered sectors, with competition allowed between sectors and different types of hydrogen use. The main application of hydrogen are:

- energy storage
- stationary fuel cells for space heat and power supply
- transport fuel cells
- decarbonisation agent for technological processes in the industry
- as a component to produce synthetic fuels.

Hydrogen in the model can be produced by steam methane reforming combined with a water-gas shift reaction or by electrolysis. For the chemical production method, the model can select options with or without carbon capture.

3.1.4 Energy supply technologies

Energy sources are optimised for siting and capacity, except for gas turbines, nuclear and coal plants, which are fixed in location based on the current power system or published plans for the respective planning horizon.

Energy generation is enabled using the following technologies:

- electricity
  - photovoltaic (utility and rooftop)
  - onshore and offshore wind, both AC and DC connected for offshore generation
  - hydro power
  - thermal generation fired with coal, natural gas and biomass
  - nuclear power plants
- space heating
  - air- and ground source heat pumps
  - resistive heaters
  - combined heat and power plants, powered by natural gas and synthetic gas
  - solar thermal collectors
  - gas boilers (natural gas and synthetic gas).

Investment and fuel costs for energy generation technologies are provided exogenously and fixed for each planning horizon, incorporating cost evolution due to the learning effect for technologies that have not yet reached maturity. Cost assumptions and technical parameters for electricity generation technologies are detailed in Table 15, which includes information on investment costs, fixed and variable operating and maintenance costs, efficiency, and technology lifetimes. Table 16 outlines the cost assumptions for heat generation technologies. For a comprehensive overview of cost assumptions for all technologies, see the appendix A, which includes a full table. Fuel cost assumptions for various technologies are detailed in Table 18.

3.1.5 Emissions management

Carbon capture and storage (CCS) is incorporated into the model as an additional option which may be needed to meet emission targets. CCS technologies are integrated into combined heat and power systems and steam methane reforming processes. The model can choose between options with and without carbon capture for these technologies. Additionally, direct air capture (DAC) technology is considered, which extracts CO_2 directly from the air. DAC is modelled such that, once invested, a fixed per unit share of electricity and heat is required to capture a specific amount of CO_2. The captured CO_2 can be used in industrial processes, such as the production of synthetic fuels (e.g. Fisher-Tropsch synthesis, methanation), or stored underground, with the model accounting for the limited capacity of underground storage.

3.1.6 Energy transmission and distribution

Transmission and distribution grids are modeled using a graph-based representation, where the grid is presented as a network of buses and branches. Buses represent points where power is either injected or withdrawn, such as substations or load centers, while branches represent the physical connections between these points, including transmission and distribution lines.

For the power sector, the grid topology data published online by the ENSTO-E [19], using the Gridkit extraction toolkit, is utilized. The PyPSA modelling framework supports the representation of electrical components and their operational constraints, enabling simulations of power flow, optimisation of generation and storage, and assessment of grid reliability and efficiency.

A simplification procedure is applied to the power grid data to ensure numerical tractability while maintaining the integrity of grid topology and transmission capacity. An result of this simplified representation is shown in Figure 2.

The model can expand the total volume of the transmission grid to align with published network development plans, aiming for 42840km and 55TVAkm, representing an approximate 15% increase from the 2022 transmission grid [20]. For 2040 and 2050 we extrapolate the ambitions and assume an increase of the line volume of 30% and 50%, respectively.

3.2 Efficiency and flexibility measures

Efficiency and flexibility measures are central to the study presented. This Subsection therefore begins with a general overview of available measures and then delves into a detailed description of building retrofit.

3.2.1 Overview

The model includes several advanced options for balancing supply and demand without requiring additional energy generation. These options include:

- **Demand-side flexibility** (DSR) through an energy management system, which reduces daily demand peaks according to endogenously derived electricity prices. This approach offers a method for covering daily space heating demand during off-peak hours, in line with the model's cost-optimization strategy. Is applied for heating systems and electric vehicle charging.
- Various types of **energy storage**, which decouple energy supply from demand over time: battery and hydrogen storage (for electricity), gas storage, and hot water tanks (thermal storage).
- **Improvements in the thermal quality of a building envelope** to reduce the space heating demand, thereby enhancing energy efficiency. This reduction in seasonal demand peaks has several positive effects on the system, which are central to the study's focus and further detailed below.
- **Waste water heat recovery systems** (WWHRS) that reduce the demand for hot water in the residential sector.
- **Waste heat recovery** in the industrial and residential sector.

3.2.2 Representation of buildings renovation

The model includes a representation of the physical and economic effects of improving the thermal quality of buildings through renovation. Renovation involves retrofitting the building envelope by replacing windows and adding thermal insulation layers to the exterior walls. The extent of renovation is determined endogenously through cost optimisation, considering the dynamic effects of energy savings. The model selects optimal shares of three different renovation depths for Europe's building stock:

- maintenance renovation
- moderate renovation
- ambitious renovation.

In the course of an optimisation run, the model can choose a share of the building stock which are renovated according to each of the considered renovation depth for each country.

The moderate and ambitious renovations depths differ in the thickness of thermal insulation and the quality of window glazing. The details of the definitions are given in the annex for both renovation depths in the tables 13 and 14.

The performance and costs of the envelope retrofitting measures are determined by modelling heat transfer in the renovated buildings from first principles and using a seasonal balance approach. The main relationships used for calculations are presented in Appendix B, the costs inputs are outlined in Table 1.

Table 1: Costs of building envelope renovation

	Costs $\left[\frac{EUR}{m^2}\right]$
Floor	39.39
Roof	75.61
Exterior walls	70.34
Windows, double glazing	180.08
Windows, tripple glazing	225

3.3 Storylines & Modeling Scenarios

To align with current policy guidelines and explore pathways to achieve the EU's ambitious decarbonization goals, the analysis begins with a business-as-usual scenario. All future projections and pathways are based on this initial scenario, with variations depending on assumptions related to building renovation depth and invoked flexibility measures (as detailed in Section 3.2). For longer-term planning horizons, the carbon budget becomes increasingly stringent, compelling the transport and industry sectors to phase out fossil processes wherever feasible.

3.3.1 Benchmark scenario

The **2023 scenario benchmark** scenario models the current situation with existing infrastructure as of 2024 without new interventions. This scenario serves as a benchmark for comparing scenarios. The following assumptions are made to model the 2023 scenario benchmark:

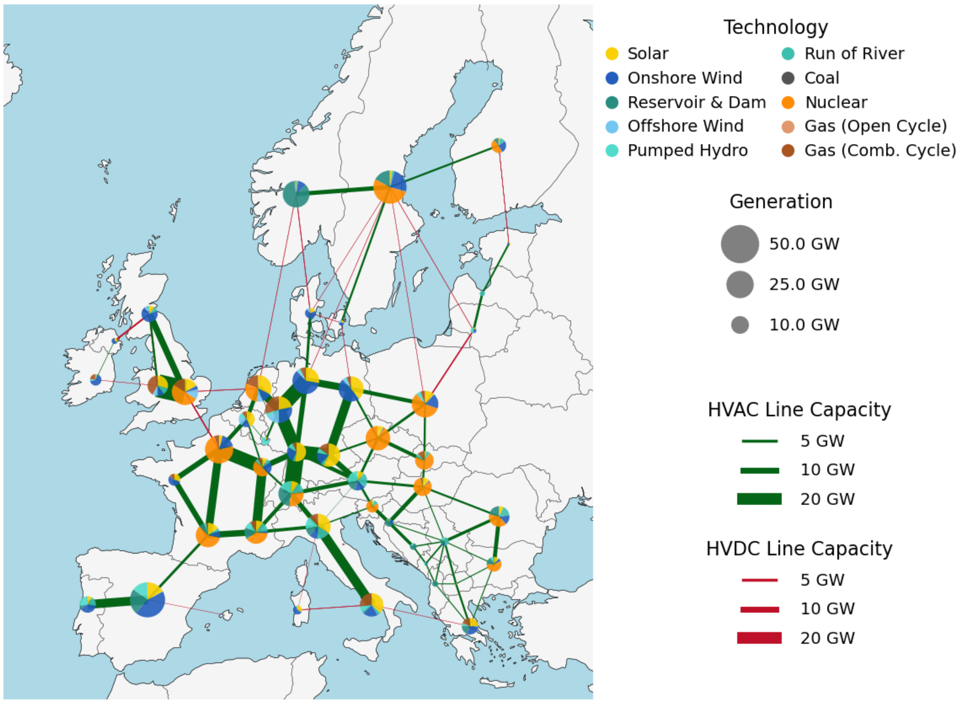


Figure 2: A representation of the power sector assumed for optimisation runs.

- No progress on electrification of transport or industry sectors.
- No advancements in district heating networks.
- Approximately 30% reduction in GHG emissions compared to 1990s levels.
- Includes existing capacities for nuclear and coal plants, solar utility PV, onshore and offshore wind, as well as gas turbines.
- No additional investments in solar, wind, or building renovation.
- No demand-side response for space heating or transport (no ability to shift power demands to times with high renewable penetration).

Existing installations of heat pumps across Europe were not considered due to the lack of available data on them for EU level.

3.3.2 Renovation & efficiency scenarios

Widespread Renovation (WIDE) scenarios enable the model to invest in both supply technologies and building efficiency and flexibility measures to minimise total system costs. This scenario outlines the optimal investments in supply technologies and building renovation strategies.

Widespread Renovation and Electrification (WIDE+ELEC) scenarios are similar to WIDE scenarios, with the exception that investments in individual gas boilers are not permitted and all gas boilers are phased out. This restriction allows for the analysis of the impact of removing fossil heat supply on the energy system.

In the **Limited Renovation** (LIMIT) scenario, the model can invest in all space heating supply technologies to minimize total system costs. However, efficiency and flexibility measures in buildings are limited to half of what was deemed optimal in the WIDE scenarios. This setup exists only for the planning horizon 2030 and is replaced by LIMIT+ELEC for the planning horizons 2040 and 2050 and allows for the analysis of the impact when only a fraction of households implements renovation measures.

Limited Renovation and Electrification (LIMIT+ELEC) is similar to LIMIT, with the exception that investments in individual gas boilers are not permitted and all gas boilers are phased out. This setup replaces LIMIT to align with EU regulations that aim for the complete phase of of gas boilers after 2030.

Business as Usual and Electrification (BAU+ELEC) scenarios allow the model to invest in space heating supply technologies without incorporating thermal energy storage. In this scenario, individual gas boilers and extra efficiency measures (building retrofit and DSR) are not permitted. This setup highlights the impact on the energy system when buildings are renovated only to maintain the current level of thermal quality and serves as an additional benchmark compared to the 2023 scenario benchmark.

All renovation and efficiency scenarios are summarised in Table 2. Additional assumptions apply depending on the planning horizon.

Table 2: Definitions of renovation scenarios. Efficiency in buildings spans building renovation measures and energy management systems. Both a tick and a cross indicate that the parameter is set exogenously to match 50% of the WIDE scenario result.

	efficiency in buildings	individual gas boilers	thermal energy storage
WIDE	✓	✓	✓
WIDE+ELEC	✓	✗	✓
LIMIT	✓ (✗)	✓	✓
LIMIT+ELEC	✓ (✗)	✗	✓
BAU+ELEC	✗	✗	✗

3.3.3 Scenario assumptions by planning horizon

In addition to the differences in energy efficiency measures across scenarios, there are varying emission targets and exogenously set parameters for the transport and industry sectors, while the space heating sector is optimised endogenously.

For the **2030** planning horizon, the following assumptions are made (for all scenarios):

- 55% net reduction in GHG emissions compared to 1990 levels
- transmission grid can expand by up to 15% in volume (measured in MWkm)
- 65,5 million EVs, possible to charge smartly in WIDE, WIDE+ELEC and LIMIT, and and bidirectional EV charging (60% of land transport)
- smart space heating in WIDE, WIDE+ELEC (27% of peak demand can be shifted) and LIMIT (13.5% of peak demand can be shifted)
- technology cost assumptions of 2025
- DHs networks progress by 30% (of urban demand not covered by district heating).

For the **2040** planning horizon, the following assumptions are made (for all scenarios):

- 90% net reduction in GHG emissions compared to 1990 levels
- transmission grid can expand by up to 30% in volume (measured in MWkm)
- 157,2 million EVs, possible to charge smartly in WIDE, WIDE+ELEC and LIMIT, and and bidirectional EV charging (60% of land transport)
- smart space heating in WIDE, WIDE+ELEC (43.5% of peak demand can be shifted) and LIMIT (21.75% of peak demand can be shifted)
- technology cost assumptions of 2035
- DHs networks: progress by 60% (of urban demand not covered by district heating).

For the **2050** planning horizon, the following assumptions are made (for all scenarios):

- 100% net reduction in GHG emissions compared to 1990 levels
- transmission grid can expand by up to 50% in volume (measured in MWkm)
- 222,6 million EVs, possible to charge smartly in WIDE, WIDE+ELEC and LIMIT, and and bidirectional EV charging (85% of land transport)
- smart space heating in WIDE, WIDE+ELEC (60% of peak demand can be shifted) and LIMIT (30% of peak demand can be shifted)
- technology cost assumptions of 2045
- DHs networks: progress by 100% (of urban demand not covered by district heating).

3.4 Modeling advances introduced by the study

For this study, the PyPSA-Eur model has been enhanced to accurately represent current energy policies. The most dominant novelties are outlined below.

3.4.1 Advanced efficiency methods in buildings

Originally, PyPSA-Eur's representation of building efficiency focused solely on improvements of the thermal quality of the building envelope, as outlined in Section 3.2.2. This study introduces two significant enhancements: incorporating energy management system to the space heating sector and adding an option for waste water heat recovery at the building level.

3.4.2 Improve representation of conventional power plants

The model capabilities have been enhanced to provide a detailed representation of conventional generation capacities, in particular nuclear, in the European cross-sectoral model. Specifically, an updated dataset has been implemented to account for existing conventional generation capacities, including future development plans for nuclear expansion for the respective planning horizons [21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40]. In addition, the most recent EU coal and lignite generation capacities have been sourced from an up-to-date dataset as referenced in [41]. Those capacities are set exogenously and are not part of siting and capacity expansion.

Additionally, fuel costs for coal, lignite, gas and uranium have been revised to reflect today's prices [42], [43], [44] or projections as proposed in RePowerEU initiative [45].

3.4.3 Representation of heat pumps and solar thermal units

Heat pumps are anticipated to play an increasingly important role in future heat supply, necessitating a more detailed representation in the model. In the context of buildings renovation, the sink temperature of the heat pumps is influenced by improvements in the thermal quality of buildings. To account for this effect, an iterative solving procedure has been developed and implemented. In this modification, the heat sink temperature reduces depending on the depth of renovation, and δH represents the share of saved heat demand, obtained from the first iteration of the optimisation:

$$T_{\text{heat sink}} = (55 - 21) \cdot (1 - \delta H) + 21 \tag{1}$$

Different estimates for heat pump and solar thermal units exist depending on the level of details considered. A review of cost inputs and technical parameters for heat pumps and solar thermal units has been conducted to align the cost inputs with available data, including technology learning effects.

3.4.4 Review assumptions for distribution grids

Electrification of heating will lead to an increased load to distribution networks and require additional costs. To account for these effects in a more accurate way, the costs of distribution grid assumptions have been revised. The values assumed for the simulation are presented in 17.

4 Results

With the assumptions provided in section 3, modelling results are presented as follows:

A general overview of the modelling results is provided by presenting the total system costs in Section 4.1 for all scenarios and planning horizons, including the business as usual case (2023 scenario benchmark). The analysis includes the shares of building stock renovation, and the share of direct system response (DSR) measures.

In Section 4.2, the impacts of efficiency measures in buildings, namely retrofitting the building envelope and DSR, are analysed with a focus on the effect of these measures on heat demand savings and flattening the peak demand. The demand flattening is obtained as a modeling output and is a combined result both of smoothing a seasonal pattern through improving building insulation and managing the daily variations using DSR. Reduced heating demands affect the size of heat pumps required to cover the remaining heating demands, which is accounted in an optimisation run in an iterative way by adjusting the sink temperature. The analysis further investigates results of the optimisation runs for CO_2 emissions in the system, total electricity demands and the electricity mix. Impacts on infrastructure and grids are discussed, too, highlighting the implications of building renovation and DSR on investments and the need for expanding the variable renewable energy sources (VRES) fleet, storage options (battery and H_2), congestion rent, and distribution grids.

The section concludes in 4.3, with a discussion on implications for electricity prices and approximations for operational expenses in the industry sector and energy bills for private households.

4.1 Effects of the efficiency measures on the system

This section first analyses the impact of efficiency measures on total system costs, proving a metric for the overall cost savings achieved through renovations of the building envelope and the implementation of DSR. Next, it details the share of buildings that must be renovated to realize the projected savings. Finally, the section presents the extent of active DSR measures in the heating sector necessary to achieve these savings.

4.1.1 Total system costs

Figure 3 illustrates the cumulative expenses associated with the entire energy system by the considered time horizons for each technology included into the model for all the considered sectors. These expenses comprise investment costs for new infrastructure, fixed operational costs, including regular maintenance and administrative expenses, and variable operational costs, such as fuels costs for conventional power plants). Collectively, these components provide a measure of the financial requirements for creating, operating and maintaining a future energy system which satisfies the particular emissions targets. The overall objective of the PyPSA-Eur model is to minimise these costs while accounting for the most relevant technical and socioeconomic constraints.

Several observations can be made: (i) When **efficiency measures in buildings are implemented** (scenarios WIDE, WIDE+ELEC, LIMIT+ELEC), the projected total system costs for any future planning horizon are lower than the expenses for the 2023 scenario benchmark and for a projected future system with no efficiency measures and electrified heating (BAU+ELEC). (ii) Implementing the most cost-optimal renovation strategy (WIDE) can result in significant cost savings **compared to the 2023 scenario benchmark**. For example, 27% can be saved by 2030, and 31% can be saved by 2050. The WIDE+ELEC and LIMIT+ELEC also demonstrate significant cost savings, though slightly lower than WIDE. These savings remain within the same order of magnitude. (iii) Compared to BAU+ELEC, 23-27% costs can be saved by 2030, with savings increasing up to 31% by

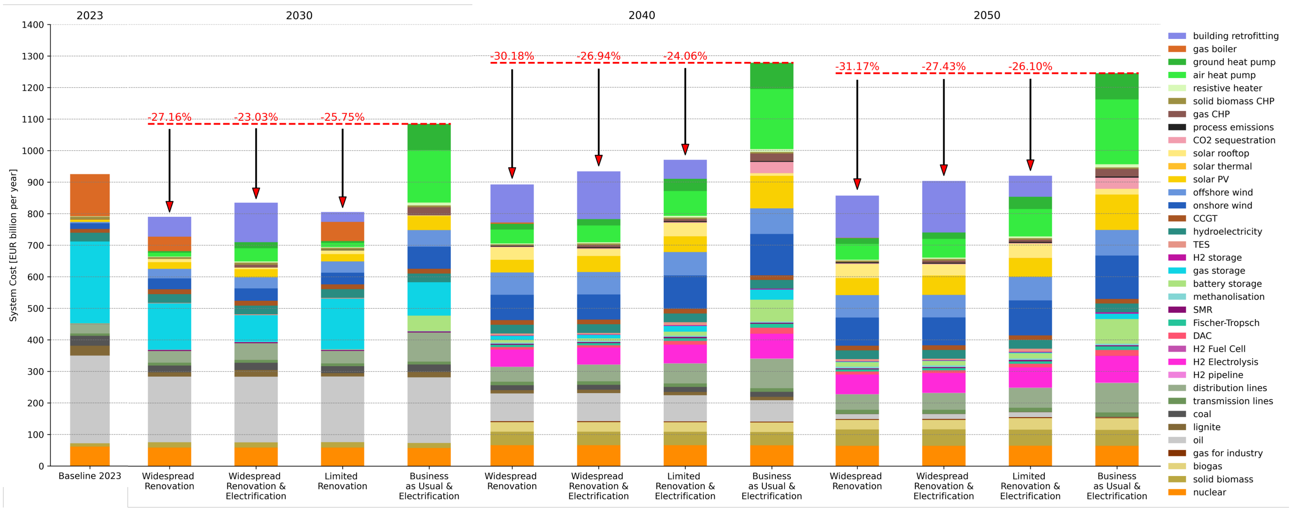


Figure 3: Total system costs per scenario

2050 if the most cost-optimal strategy is followed. Even if no gas boilers are used in Europe by 2050, costs savings can still reach 27% , or 26% if energy efficiency measures are less ambitious. Table 3 provides the detailed magnitudes of the total system costs and renovation costs. The investment and operational costs for each scenario can be found in Fig. 16 and Fig. 17 in Appendix A.

Table 3: Total system cost and cost for renovation (in bn EUR)

		2024	2030	2040	2050
Total system cost	BASE 2023	926	-	-	-
	WIDE	-	790	892	851
	WIDE+ELEC	-	835	934	903
	LIMIT	-	806	-	-
	LIMIT+ELEC	-	-	970	920
	BAU+ELEC	-	1085	1278	1245
Renovation cost	WIDE	-	63	120	133
	WIDE+ELEC	-	125	151	163
	LIMIT	-	32	-	-
	LIMIT+ELEC	-	-	60	67
	BAU+ELEC	-	-	-	-

These results indicate that the cost variations associated with building renovations are decreasing, once the most inefficient buildings have been renovated. However,retrofitting buildings consistently proves beneficial from a total system cost perspective. This demonstrates that investments in building retrofitting and energy management systems lead to overall cost savings for the energy system, making it a no-regret strategy from the point of view of the complete system.

4.1.2 Amount of building envelope renovation

The share of buildings which the envelope should be renovated has been estimated using a share for an optimal utilisation of the heat savings potential. The results are presented in Table 4 and 5. The number of buildings which need to be renovated for each scenario has been calculated using an estimation of the overall European building stock of 156 millions. This estimation was evaluated using hotmaps database [46] with the latest updates from 2023. The database contains both residential and non-residential buildings, including health and education facilities, trade buildings, offices and industrial facilities. The results are presented in Table 5, distinguishing between different depth of the renovation.

Table 4: Share of buildings to be renovated (%)

	2030	2040	2050
WIDE	44	71	71
WIDE+ELEC	65	72	72
LIMIT	22	-	-
LIMIT+ELEC	-	37	40
BAU+ELEC	-	-	-

Table 5: Amount of buildings to be renovated [millions of buildings (% of the overall building stock)]

		2030	2040	2050
Moderate depth	WIDE	53 (34%)	82 (53%)	82 (53%)
	WIDE+ELEC	76 (49%)	85 (54%)	85 (54%)
	LIMIT	26 (17%)	-	-
	LIMIT+ELEC	-	43 (28%)	47 (30%)
	BAU+ELEC	-	-	-
Ambitious depth	WIDE	16	28	28
	WIDE+ELEC	25 (10%)	28 (18%)	28 (18%)
	LIMIT	8 (5%)	-	-
	LIMIT+ELEC	-	15 (10%)	15 (10%)
	BAU+ELEC	-	-	-

4.1.3 Amount of active demand-side measures in the space heating sector

Tables 6 and 7 present the usage of the active upward and downward DSR facilitated by energy management systems for the space heating and transport sectors, respectively, for each considered scenario (WIDE, WIDE+ELEC, LIMIT, LIMIT+ELEC, BAU+ELEC) and time horizon. In this context, upward DSR refers to a decrease in demand, while downward DSR refers to an increase in demand. It is evident from the tables that the majority of DSR activity occurs in the transport sector, where electric vehicle charging can be shifted without incurring efficiency losses. However, significant DSR measures are also active in the space heating sector.

Another observation is that usage of the active DSR measures increase with later planning horizons. In the space heating, the overall load shifted by active DSR measures increases by a factor of 4 in every scenario. When the space heating is fully electrified, more active usage of DSR measures are needed. For example, in 2030, the WIDE+ELEC scenario, which excludes gas boilers, has twice as much usage DSR for space heating compared to the WIDE scenario where gas boilers still play a significant role. By 2040, DSR is nearly the same in both scnenarios as gas boilers decline to a small share in the WIDE scenario.

Table 6: Active upward and downward DSR in the space heating sector [TWh_{th}]

	2030	2040	2050
WIDE upward DSR	14	41	61
WIDE downward DSR	15	44	65
WIDE+ELEC upward DSR	32	45	
WIDE+ELEC downward DSR	34	47	
LIMIT upward DSR	9	-	-
LIMIT downward DSR	9	-	-
LIMIT+ELEC upward DSR	-	31	36
LIMIT+ELEC downward DSR	-	32	37
BAU+ELEC upward DSR	-	-	-
BAU+ELEC downward DSR	-	-	-

Table 7: Active DSR in the transport sector [TWh]. As there are no losses assumed, upward and downward DSR are equal.

	2030	2040	2050
WIDE DSR	185	403	496
WIDE+ELEC DSR	200	392	
LIMIT DSR	197	-	-
LIMIT+ELEC DSR	-	441	592
BAU+ELEC DSR	-	-	-

4.2 Impact of efficiency measures in buildings

This section analyses the impacts of efficiency measures implemented in buildings on peak demand, examining both daily and seasonal patterns. It evaluates the implications of reduced space heating demands on the size of heat pumps, the resulting CO_2 emissions and electricity demands due to efficiency improvements, as well as the electricity mix. Finally, the section outlines the necessary investments and infrastructure requirements for VRES and the grids.

4.2.1 Impact of efficiency measures on peak demand

Space heating demands are affected by retrofitting of building envelope and the usage of flexibility measures (DSR). This effect depends on the depth of retrofitting for every scenario and planning horizon.Figure 4 shows seasonal variations of the space heating demand during a year for each of the modeling scenarios. The actual value of the space heating demand represents the remaining space heating demand after building renovation. To make the seasonal dynamics more clear, daily aggregation is applied. Additionally, the demand profile is supplemented by the area which represents the respective savings with respect to the 2023 scenario benchmark / BAU+ELEC scenario. DSR measures are not visible in 4 due to the daily aggregation, but can be seen from the annex in Figure 18, which outlines same variations of the space heating demand but depicted with hourly resolution and for two weeks only. Moreover, Figure 5 details how the space heating demand is satisfied for an exemplary time-horizon at hourly resolution, considering a limited set of technologies, which contribute most in covering the space heating demand peaks. The considered period for Figure 5 spanns approximately two weeks, and an effect of the DSR measures is also visible as smoothing of the daily demand peaks during morning and evening hours.

The first plot 5a shows the results for all scenarios in the planning horizon 2030. It can be seen that, from a cost-optimal perspective (WIDE), space heating demands should be reduced. Quantitatively, this reduction comprises 22% compared to BAU+ELEC and 2015 levels with a remaining share of 65% that is covered by utilising gas boilers. As has been shown in section 4.1.1, gas boilers can be fully phased out from the space heating sector at 4% more costs, further decreasing space heating demands by 17% (WIDE), totalling 39% compared to BAU+ELEC and 2015 levels. In this scenario, additional investments into building insulation are required, as well as an increased number of heat pumps and resistive heaters to cover the remaining space heating demands. Finally, with a restricted share of building efficiency measures (LIMIT), space heating demands are reduced by 12% compared to 2015. To cover the remaining space heating demand, an increased number of heat pumps and gas boilers is needed. As space heating demands are not reduced in the BAU+ELEC scenario, and can not be shifted according to availability of variable re-

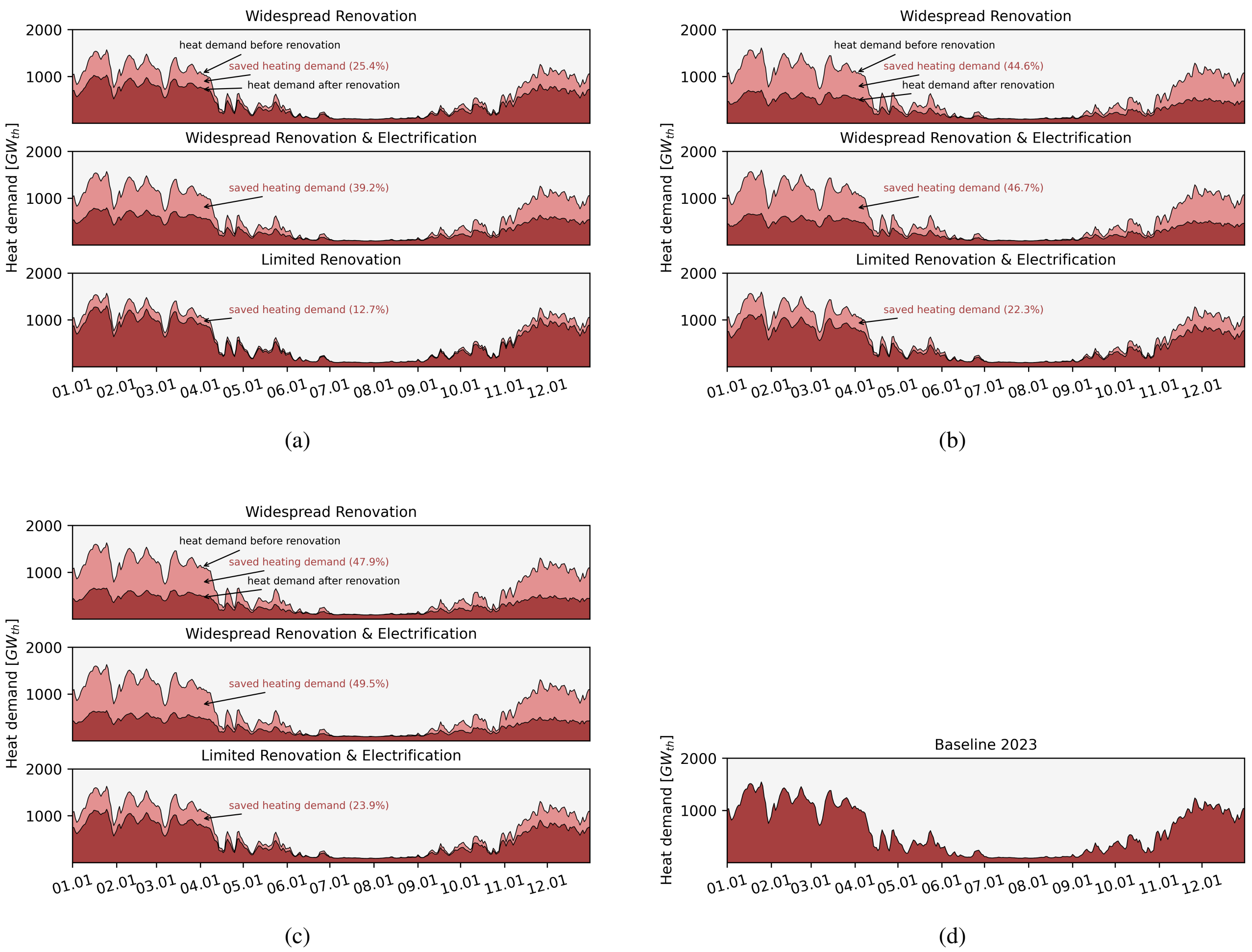


Figure 4: Space heating demand before and after renovation for the full year for each scenario over different horizons: (a) 2030, (b) 2040, (c) 2050, and (d) BASE 2023

sources (no energy management systems are assumed for this scenario), the dispatch of heat pumps and resistive heaters must adjust according to daily demand patterns, totalling a space heat demand of 4242 TWh_{th}, which is 39% more than in WIDE scenario.

Turning to 2040, displayed in Figure 5b, a similar behavior can be seen. From a cost-optimal perspective (WIDE), the space heating demands are now reduced by 44% compared to BAU+ELEC, and the tightened CO_2 budget leads to an almost complete phase-out of gas from the space heating, where only 2% of the remaining space heating demands are covered by gas boilers. Removing gas boilers (WIDE+ELEC) increases total system costs by 3% (c.f. section 4.1.1), and reduces the space heating demands by an additional 2%, totalling a 46% reduction compared to BAU+ELEC. The assumed space heating demand in BAU+ELEC totals 4312 TW_{th}, where the increase of 70 TWh_{th} compared to the 2030 planning horizon is due to the losses from district heating networks, which have a larger share for 2040.

By 2050, see Figure 5c, the total space heat demand can be reduced by up to 50% (WIDE+ELEC), or 48% (WIDE) and 24% (LIMIT+ELEC) respectively, compared to BAU+ELEC. The remaining share of gas contributing to the space heating demands in WIDE decreases to 0.5%, as net emissions are not allowed in the system anymore. The total assumed space heating demands are 4405 TWh_{th}. The behavior of the different scenarios follows the same pattern, as for the previous planning horizons.

4.2.2 Impact of efficiency measures on the number of heat pumps

Efficiency measures in buildings have two different effects on the roll-out of heat pumps. With increased building insulation, it can be expected that the heat pumps of smaller size should be sufficient due to a decrease in the space heating demand. A number of the installed heat pumps can stay aligned with the EU target installed capacity for heat pumps by 2030 which is 60 million pumps. Additionally, demand-side response measures, enabled through smart energy management systems, shift peak load in such a way that heat pumps can continuously operate at a lower base load, instead of continuously ramping up and down. With these two assumptions it is possible to derive from the modelling results an estimate for required installed heat pumps capacity by the different planning horizons, for every scenario, as presented in Table 8.

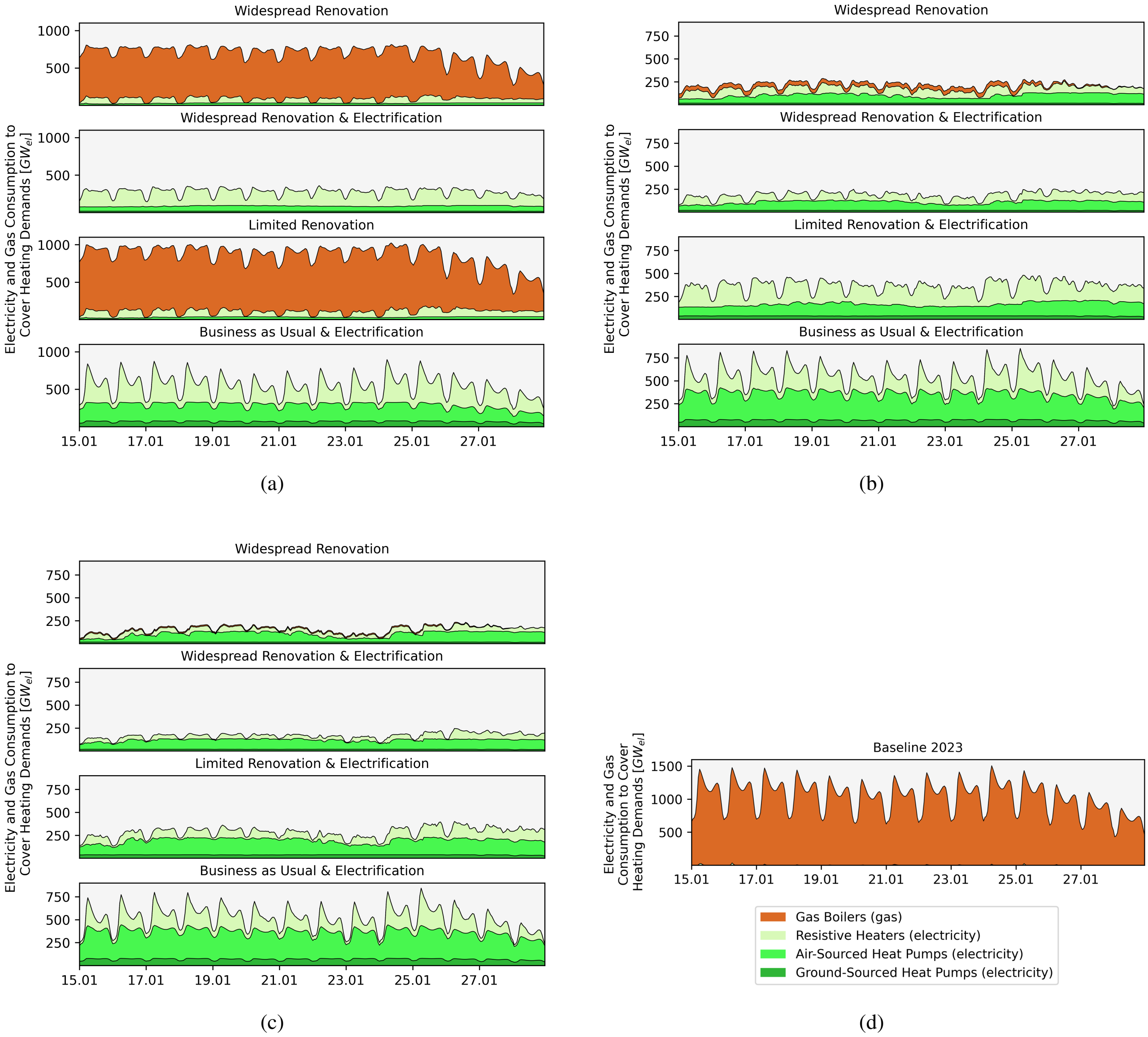


Figure 5: Electricity and gas consumption used to cover space heating demand for each scenario over different horizons: (a) 2030, (b) 2040, (c) 2050, and (d) BASE 2023

It can be seen that, following the cost-optimal approach (WIDE), that an average required size of a heat pump is be up to ten times higher in the scenarios with limited renovation for 2030. This difference is levelled for later time horizons, but still remains as high as 1.5-3 times in 2050.

Table 8: Total installed capacity of heat pumps (in GW_{el}).

	2030	2040	2050
WIDE	34.21	132.92	157.55
WIDE+ELEC	94.81	142.20	168.11
LIMIT	39.39	-	-
LIMIT+ELEC	-	214.81	249.06
BAU+ELEC	331.68	430.17	492.67

4.2.3 Impact of efficiency measures on CO_2 emissions

Figure 6 shows the CO_2 emissions by technology for each scenario across all horizons (2030, 2040, and 2050). The positive part of the bar diagram details different sources of the emissions, while the negative values represent different sinks of CO_2. In particular, a pink color bar denotes the overall amount of CO_2 emitted to atmosphere.

The comparison demonstrates that the scenarios where gas boilers are phased out WIDE+ELEC and BAU+ELEC tend to have lower CO_2 emissions than allowed for 2030, compared to the scenarios where gas boilers are still part of the system composition. Gas boilers provids some benefits to the total system costs (see Figure 3), but remain a significant contributor to CO_2 emissions, especially for the planning horizon of 2030. In scenarios where gas boilers are removed from the system (WIDE+ELEC and

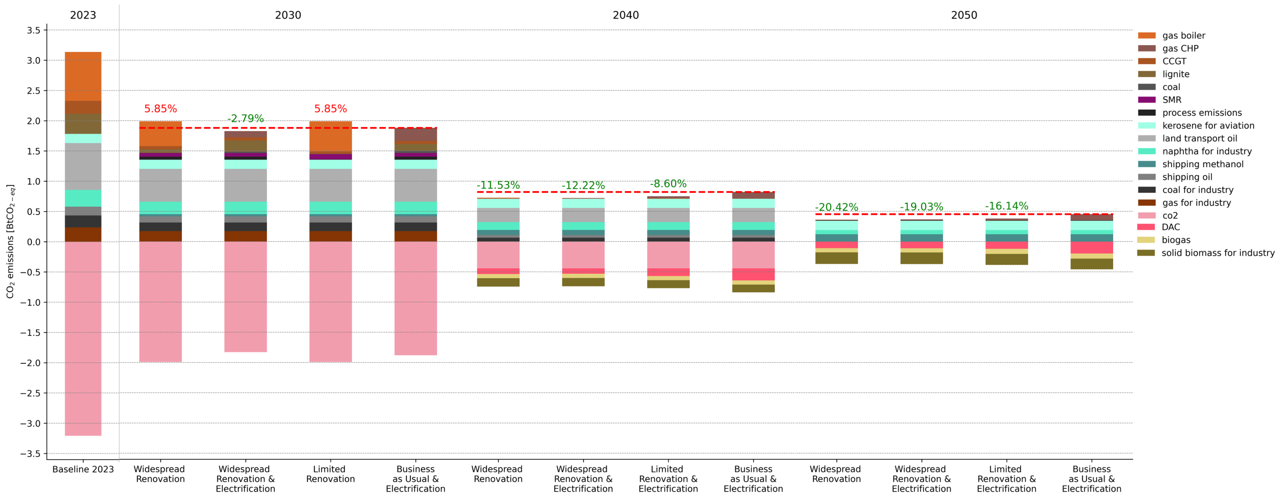


Figure 6: Total CO_2 emissions per scenario

BAU+ELEC), space heating demands are purely covered by electricity, while gas remains a part of the electricity mix but is consumed by CHP plants or gas turbines. Additionally, replacing heating gas boiler with heat pumps leads to a decrease of the emissions from the space heating sector, which allows a share of coal remains part of the emissions.

Total CO_2 emitted in each scenario is illustrated in Table 9 for all horizons in billion tons of CO_2 equivalent. Table 10 presents the equivalent gas savings, measured in trillion cubic meters, for various scenarios compared to the 2023 scenario benchmark BASE 2023) over different planning horizons.

Table 9: Total CO_2 emissions (in B$tCO_{2-\mathrm{eq}}$).

		2030	2040	2050
BASE 2023	3.21	-	-	-
WIDE	-	1.99	0.44	0
WIDE+ELEC	-	1.83	0.44	0
LIMIT	-	1.99	-	-
LIMIT+ELEC	-	-	0.44	0
BAU+ELEC	-	1.88	0.44	0

Table 10: Equivalent gas savings (in trillion m^3).

	2030	2040	2050
WIDE	0.64	1.45	1.69
WIDE+ELEC	0.73	1.45	1.69
LIMIT	0.64	-	-
LIMIT+ELEC	-	1.45	1.69
BAU+ELEC	0.70	1.45	1.69

4.2.4 Impact of efficiency measures on the electricity mix

The resulting electricity generation mix is shown in Figures 7 and 8. The simulation results for the 2023 scenario benchmark are compared with the historical electricity generation mix from 2022 as reported in [47], and the results for generation shares are presented across all scenarios and planning horizons.

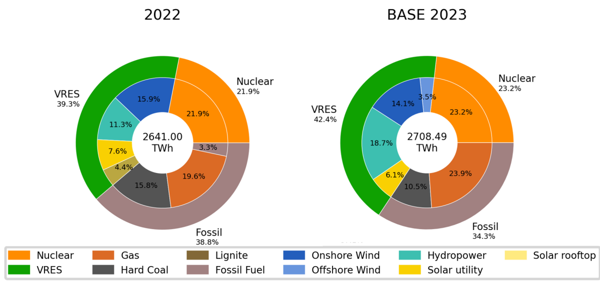


Figure 7: Electricity generation mix for 2023 scenario benchmark compared with historic generation

The comparison of the 2023 scenario benchmark against historically reported numbers shows that the proportion of electricity derived from variable renewable energy sources (VRES), nuclear power, and fossil fuels in the modelled 2023 scenario benchmark closely aligns with the reported historical generation mix with an error of below 5%.

When moving to the projected planning horizons, model results indicate that the overall share of fossil fuel-based electricity decreases over time for each scenario. When focusing on 2030, Figure 8a shows that (i) the total electricity demand increased compared to the 2023 scenario benchmark due to electrification rates in all sectors and (ii) the share of coal and gas reduces from 34.4% to 5.5% - 13.3%, compared to 2023 scenario benchmark. An increase in the electricity demand depends on the rate of electrification in the space heating sector which is a modelling result and not set exogenously, in contrast to the transport and industry sectors. The overall demand increase varies between the scenarios.

While the total electricity demand is relatively similar in all scenarios that allow for efficiency improvements in

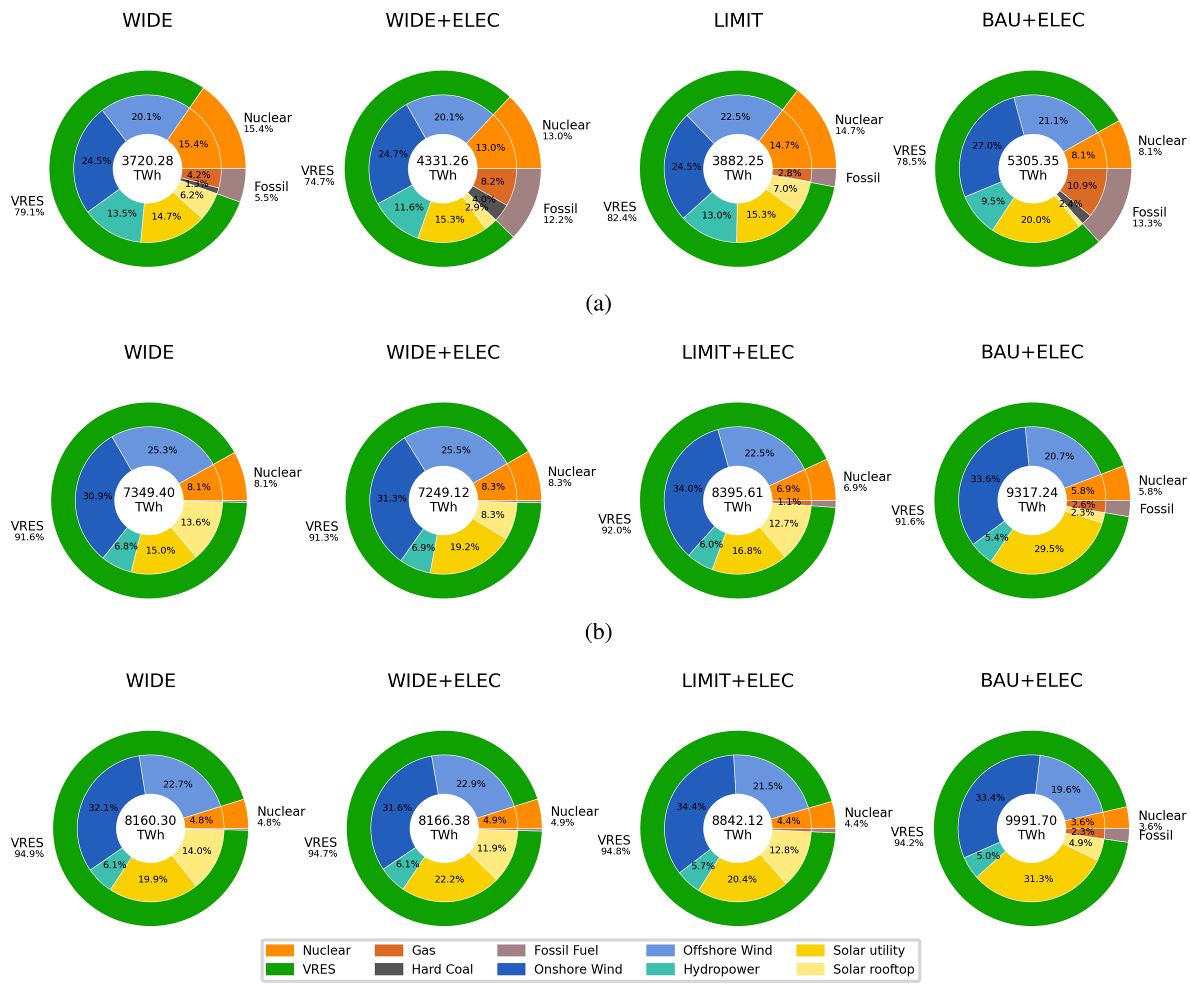


Figure 8: Electricity generation mix for scenarios in (a) 2030, (b) 2040, and (c) 2050

buildings (WIDE, WIDE+ELEC, LIMIT), the total amount of electricity demand is significantly higher in the BAU+ELEC scenario. A primary reason for that is the absence of building renovation resulting in higher space heating demand with reliance on electric heating technologies. In scenarios where space heating is fully electrified (WIDE+ELEC, BAU+ELEC), the share of fossil fuels is typically higher compared to those scenarios where gas boilers are allowed. But in those scenarios, where gas boilers are considered (WIDE for all horizons and LIMIT for 2030), more gas is utilized at worse efficiency through gas boilers, as we have seen in the previous Section (see also Figure 6). The high electricity demands in the BAU+ELEC scenario also require more expensive gas utilization, compared to WIDE+ELEC, where a small share of coal (4%) can remain in the mix.

Moving to 2040 and 2050 (Figures 8b and 8c), the aforementioned trend remains the same. The BAU+ELEC scenario always has the highest electricity demand and the highest share of remaining fossil fuels. In all other scenarios, coal and gas can be phased out almost completely already by 2040.

Figure 9 demonstrates the level of curtailment for every scenario, showcasing the efficiency on the generation side of VRES. Curtailment is the amount of VRE that is not fed into the grid due to congestion or overproduction. The Figure 9 demonstrates that the total amount of curtailment increases for all scenarios when moving forward in time, with the highest rates being observed in the BAU+ELEC scenario, peaking at approximately 690 TWh annually in 2040, almost 8% of annual demand. Curtailment for all other scenarios is always lower by approximately 400 TWh, approximately the annual electricity demand of France in 2022. The BASE 2023 scenario stands out with nearly 0% curtailment, primarily due to the relatively low penetration of VRES and its limited spatial scale.

4.2.5 Impact of efficiency measures on the energy infrastructure

An increased electricity demands requires additional investments in energy infrastructure. Figure 10 illustrates the projected infrastructure expansion of technologies across

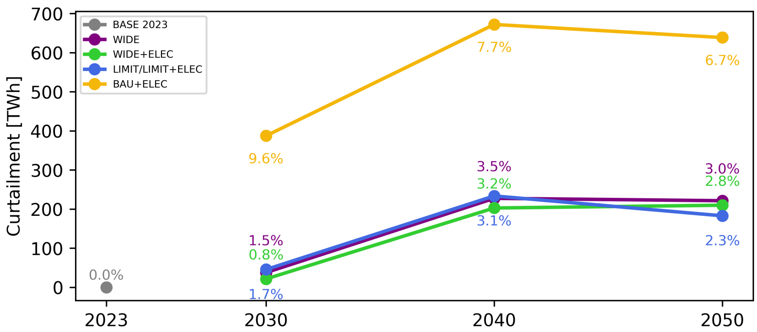


Figure 9: Curtailment of RES (in TWh and % of total RES generation for give scenario)

all scenarios and planning horizons.

Focusing on 2030, it can be seen that there is a trend towards increased infrastructure expansion for VRES generation, power grids and storage technologies. Solar technologies, which include both solar rooftop PV and solar utility PV, experience significant growth in all the scenarios.

For 2040 and 2050, solar PV expansion accelerates, profiting from the reduced costs. In case of solar rooftop PV, the assumed upper limit for expansion in Europe covering all available roofs is met. Ramping up to meet the CO_2 targets, it can also be seen that energy storage experiences a significant growth. The share of battery storage increases proportional to solar PV infrastructure buildout, and H_2 electrolysis increases proportional to onshore and offshore wind installations. These trends can be observed for all scenarios, with increased investments in the BAU+ELEC and LIMIT scenarios. Table 11 shows required capacity for wind turbines and solar PV panels for the different scenarios, and how that translates into capital expenditure and land usage. Estimation of land usage for wind turbines and PV panels are based on the typical land requirements per megawatt (MW) of nameplate capacity. Specifically, wind turbines require approximately 0.345 km^2 per MW [48], while solar utility installations require about 0.02 km^2 per MW [49].

Overall, the results underscore the critical role of solar technologies in the future energy mix, reflecting a transition towards more sustainable and renewable energy sources.

The total installed capacities for each scenario are shown in Figure 11 across all scenarios and planning horizons.

Table 11: Optimal installed capacity (in GW), capital expenditure (in bn EUR), and land usage (in thousands km^2) for solar PV panels and wind turbines.

			2030	2040	2050
Optimal capacities	PV panels	WIDE	647	1859	2405
		WIDE+ELEC	655	1758	2403
		LIMIT	722	-	-
		LIMIT+ELEC	-	2176	2536
		BAU+ELEC	1014	2746	3275
	Wind turbines	WIDE	537	1319	1431
		WIDE+ELEC	617	1305	1414
		LIMIT	596	-	-
		LIMIT+ELEC	-	1633	1692
		BAU+ELEC	1049	1936	2014
Capital cost	PV panels	WIDE	31.4	73.2	84.1
		WIDE+ELEC	30.8	67.6	83.5
		LIMIT	35.1	-	-
		LIMIT+ELEC	-	85.2	88.4
		BAU+ELEC	46.5	102.7	111.7
	Wind turbines	WIDE	64.5	146.1	149.8
		WIDE+ELEC	74.2	144.9	148.4
		LIMIT	72.4	-	-
		LIMIT+ELEC	-	174.2	172.4
		BAU+ELEC	122.4	202.7	201.4
Land usage	PV panels	WIDE	12.9	37.2	48.1
		WIDE+ELEC	13.1	35.2	48.1
		LIMIT	14.4	-	-
		LIMIT+ELEC	-	43.5	50.7
		BAU+ELEC	20.3	54.9	65.5
	Wind turbines	WIDE	185.4	454.9	493.6
		WIDE+ELEC	212.8	450.2	487.7
		LIMIT	205.7	-	-
		LIMIT+ELEC	-	563.2	583.9
		BAU+ELEC	361.8	667.9	694.8

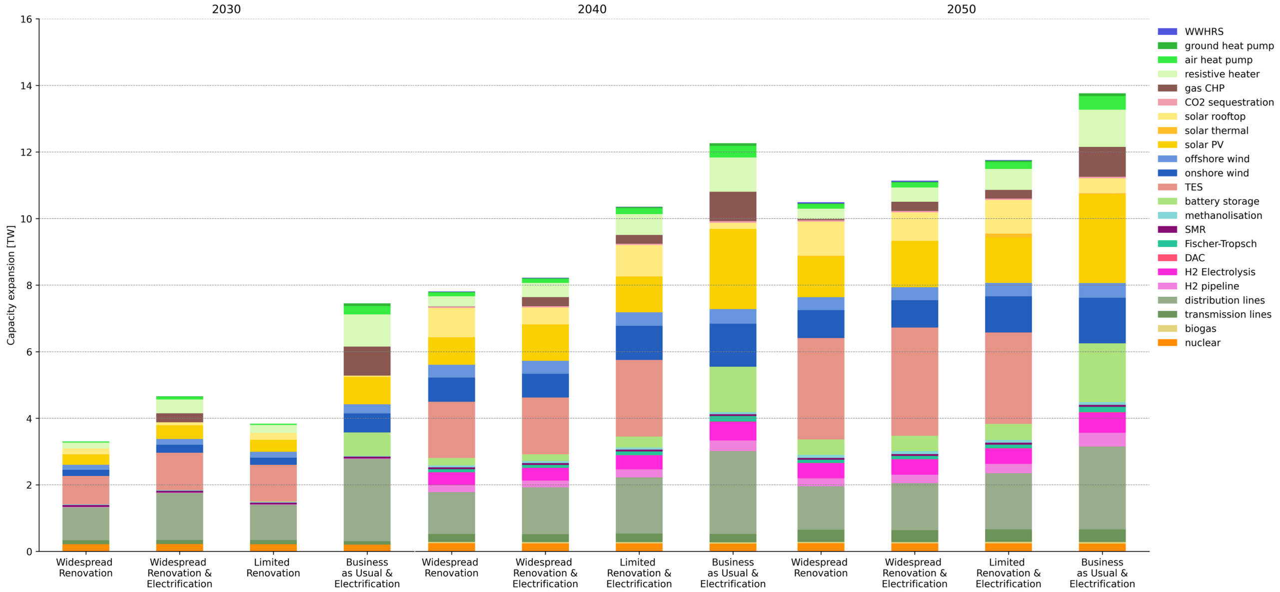


Figure 10: Capacity expansion per scenario

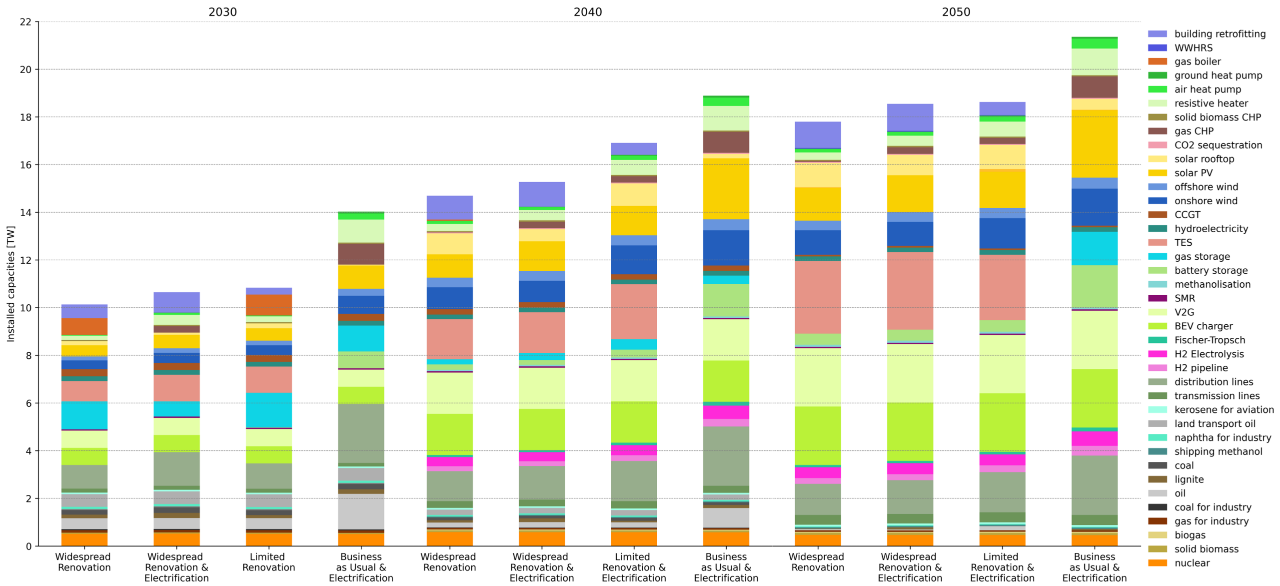


Figure 11: Total installed capacities per scenario

4.2.6 Impact of efficiency measures on the grids

Turning to the grid infrastructure, modeling results are examined for both transmission and distribution grids. Table 12 presents the annual investments into the distribution grids for each scenario and planning horizon. Focusing on 2030, the WIDE and LIMIT scenarios, where gas boilers still play a significant role in covering space heating demands, require the lowest immediate investments in the distribution grid, amounting to 37-39 billion EUR annually. In contrast, the WIDE+ELEC scenario, which involves electrifying the space heating completely, necessitates 33% more investment, reaching 52 billion EUR annually. If no efficiency measures are implemented but space heating is electrified (BAU+ELEC scenario), the grid requires 150% more investments compared to WIDE, or 92 billion EUR annually.

Moving to the 2040 planning horizon, distribution grid investments become more closely linked to efficiency measures rather than the availability of gas boilers. The WIDE and WIDE+ELEC scenarios require the lowest investments in the distribution grid, ranging from 46.9 to 52.7 billion EUR annually. In the WIDE+ELEC scenario, the investment levels remain consistent with the 2030 planning horizon, while the WIDE scenario sees delayed investments into the distribution grids, eventually reaching similar amounts by 2040. In scenarios with fewer or no efficiency measures (LIMIT+ELEC and BAU+ELEC), stricter requirements for enhancing the distribution network are evident, with 20% more investments for LIMIT+ELEC and 75% more for BAU+ELEC compared to the WIDE+ELEC scenario. For the BAU+ELEC scenario, the improvement compared to the 2030 horizon is minimal.

Compared to the 2040 planning horizon, the 2050 projections show minimal increases in the distribution gird investments across all scenarios. This suggests that the bulk of the necessary enhancements and investments will have already been made by 2040, resulting in only slight adjustments needed to maintain or marginally improve the distribution grid infrastructure by 2050.

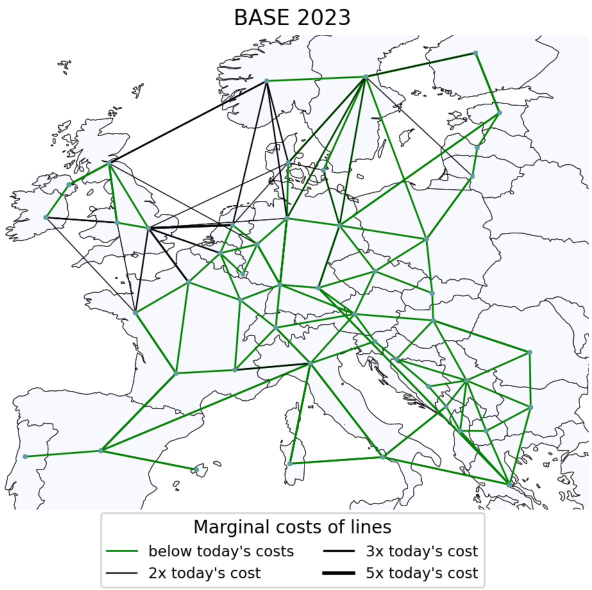
While the model can expand the distribution grids without limits, transmission grid expansion is capped in line with the projected TYNDP scenarios. Therefore, a congestion analysis is performed to understand the impact of efficiency measures in buildings on the operation of the transmission grids. Transmission line congestion occurs when the demand for electricity transfer across a specific transmission line meets its capacity creating inefficiencies in the power grid. In technical terms, it is often quantified using the shadow price of the line capacity constraint. The shadow price is a value which represents the marginal cost of alleviating the congestion. A high shadow price indicates a significant congestion, as it reflects the additional cost of supplying one more unit of electricity through the congested line. This situation can arise due to an increased electricity consumption, unexpected power plant outages, or the integration of distant renewable energy sources. High shadow prices signal that the grid is operating near its limits, leading to higher electricity prices and increased operational costs as grid operators may need to re-route power or curtail generation to maintain reliability. Addressing congestion and its associated costs often involves infrastructure upgrades, improved grid management, and the use of advanced technologies to increase capacity and efficiency.

Table 12: Annual distribution grid investments in bn EUR.

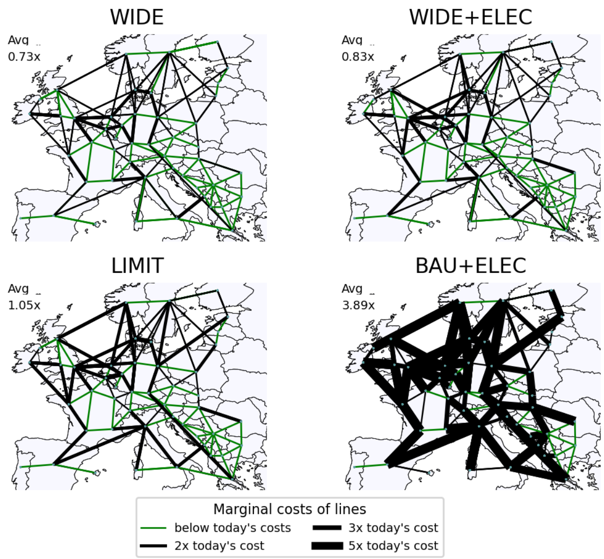
	2030	2040	2050
WIDE	37.0	46.9	48.8
WIDE+ELEC	52.7	52.7	52.8
LIMIT	39.6	-	-
LIMIT+ELEC	-	63.0	63.0
BAU+ELEC	92.4	92.9	93.0

The congestion cost measured in EUR/MW/km are visually represented for each line in Figure 12, displaying the per MWkm average across the hourly resolved timeseries of the shadow prices. This approach provides a standardised measure of congestion alleviation per kilometer. The cost of building or expanding transmission lines is set at 200 EUR/MW/km for AC lines, and 100 EUR/MW/km for DC lines [50]. The plots provide a relative increase in the congestion alleviation cost as compared to the current costs of building or upgrading the infrastructure. The displayed metric compares the averaged cost of the alleviation of congestion with the construction costs. The overall average congestion costs are then calculated by averaging these values across all lines in the network and presented as a single value at each map. This approach helps to identify the most congested parts of the grid and prioritize investments for upgrades to improve efficiency and reliability.

When examining at the current situation (Figure 12a), the model results indicate that the system is not heavily stressed. Most of the infrastructure operates well within existing capacity constraints, suggesting that enhancing the transmission grid would not yield significant economic benefit. However, as electrification rates rise to improve system efficiency and meet 2030 emission targets (Figure 12b), the system becomes more stressed and average congestion increases, varying by scenario.



(a)



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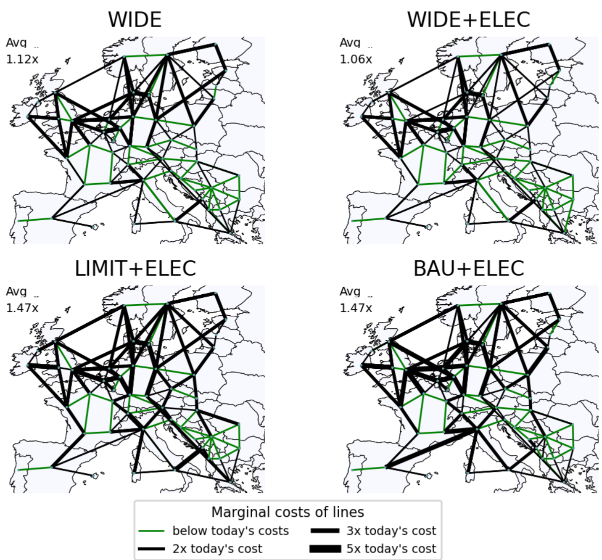

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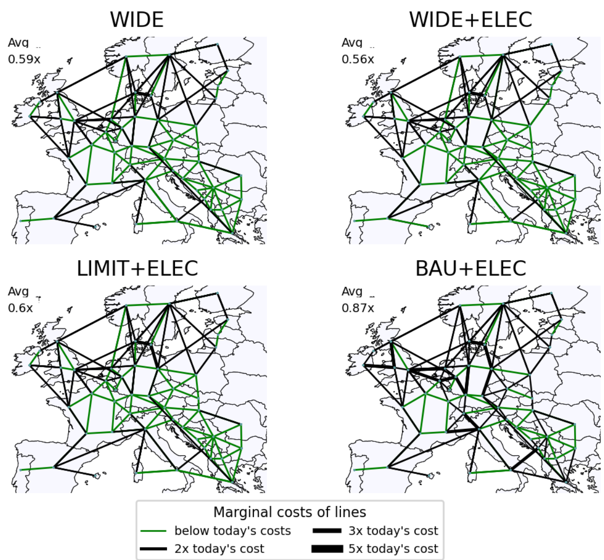


(d)

Figure 12: Transmission line congestion for each scenario over different horizons: (a) BASE 2023, (b) 2030, (c) 2040, and (d) 2050

For the WIDE and WIDE+ELEC scenarios, the system manages to operate within the 30% enhancement of the transmission grid assumed according to TYND. Some congestion is present, but remains economically balanced, as the projected shadow price constraint is below the threshold for further capacity increases. In the LIMIT scenario, congestion rates rise to a level where additional enhancements could provide economic benefits, with the average shadow price constraint exceeding today's transmission infrastructure enhancement costs by 5%. Without any efficiency measures at the building level (BAU+ELEC scenario), the grid becomes heavily stressed, with the shadow price constraint reaching up to 3.89 times of the current per-MWkm transmission infrastructure enhancement costs.

For the projected planning horizon of 2040, the overall behavior remains consistent with the trends identified for 2030. The WIDE and WIDE+ELEC scenarios exhibit the lowest transmission congestion levels, with the shadow price constraint staying below the current per-MWkm transmission infrastrucutre enhancement cost. In contrast, the LIMIT+ELEC and BAU+ELEC scenarios place greater stress on the system. This increased congestion suggests that enhancing the transmission infrastructure in these scenarios could provide economic benefits, adding substantial value to the energy system.

Reaching the planning horizon of 2050, the assumed significant improvements of the transmission infrastructure by 50% ensure that all scenarios can operate well within the grid capacity constraints. However, the WIDE and WIDE+ELEC scenarios result in much lower average shadow price constraints, as compared to the LIMIT+ELEC and BAU+ELEC scenarios. This indicates that the WIDE and WIDE+ELEC settings could provide greater system stability and reduce the need for extensive re-dispatch measures, increasing the overall economic efficiency and reliability of the energy system.

4.3 Private sector perspective

This section delves into the implications of reduced heat demand peaks for the private sector, including private households and industry. First, it outlines endogenously derived electricity prices, which form the basis for subsequent calculations on household energy bills and operational expenses (OPEX) in the industrial sector.

4.3.1 Electricity prices

Electricity prices per MWh are determined by taking into account the hourly electricity price and the demand at each node of the model, and are presented in Figure 13 for each scenario in different horizons.

In the 2023 scenario benchmark (Figure 13a), average electricity prices in central Europe remain relatively stable, showing only slight variations between countries. However, notable differences can be observed in other regions: Nordic countries, such as Norway, Sweden and Finland, experience lower prices, with reductions of approximately 18%, while Great Britain and Ireland see increased prices. Although the exact margins differ from historically observed costs in 2023, the overall trend aligns closely, reflecting the recent market dynamics effectively.

According the the modeling results, the electricity prices can differ significantly from the current level and the value of this difference remarkably depends on the depth of efficiency measures applied to buildings. In the absence of efficiency measures, the average electricity price for Europe is projected to be 155.27 EUR/MWh by 2030, while in scenarios with active efficiency measures, the average price is substantially lower (63.77 EUR/MWh). Variations from country to country can be even more pronounced, with the largest reductions in electricity prices observed in Belgium, Germany, Romania and Hungary, comparing BAU+ELEC to situations when efficiency measures are applied. In these countries, prices significantly exceeds an annual average of 200 EUR/MWh for BAU+ELEC scenarion with an average increase of approx. 210% compared to scenarios where efficiency measures are active. Notably, in scenarios with active efficiency measures, the electricity costs show minimal deviations between countries, indicating a more equitable distribution of electricity costs across Europe. In Nordic countries such as Denmark and Norway, electricity costs remain lower compared to mainland Europe. While some countries may experience slightly higher costs, the cross-national differences are much lower compared to those corresponding to the scenarios without efficiency measures. The electricity costs are not significantly impacted by the availability of gas boilers or the depth of renovation, if the most inefficient buildings has been already renovated. The costs are similar for the WIDE, WIDE+ELEC and LIMIT scenarios, highlighting that the primary driver for reduced electricity prices is the implementation of efficiency measures rather than the type of space heating technology used.

In 2040 and 2050, the differences between the scenarios become less pronounced due to a massive development of the infrastructure needed to satisfy the decarbonization requirements. While scenarios with more efficiency measures still maintain lower electricity prices compared to scenarios with no or limited efficiency improvements, the benefits are reduced. This is primarily a result of improved transmission infrastructure, which mitigates transmission congestion and allows the model to meet high peak demands at lower costs by sourcing resources from the most cost-effective sites. Nevertheless, a more equitable distribution of electricity costs between countries is observed in the WIDE and WIDE+ELEC scenarios, while the efficiency measures lead to a decrease of the energy prices for the industry and households, as will be shown in the next subsections.

4.3.2 Operating expenses for the industrial sector

The energy prices significantly impact profitability of the industrial sector, especially as electrification rates increase over time. Figure 14 illustrates the projected oper-

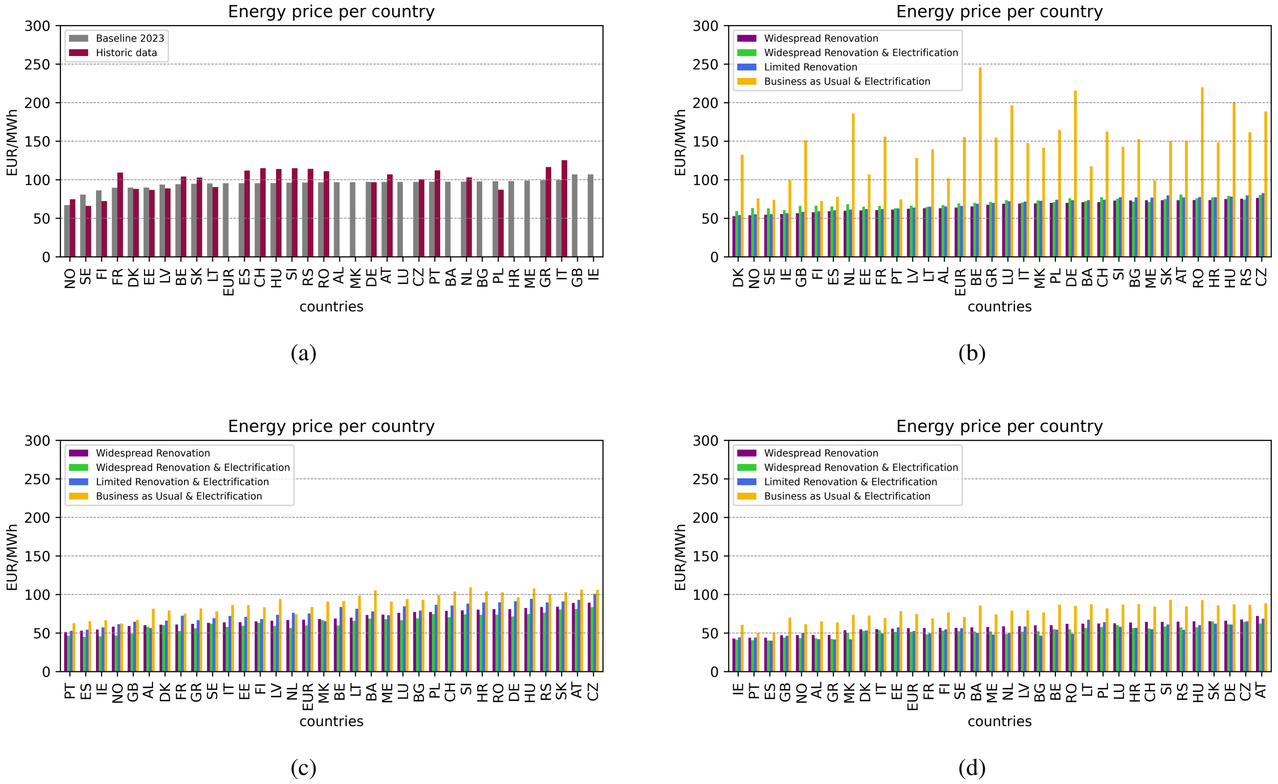


Figure 13: Electricity prices per MWh for each scenario over different horizons: (a) BASE 2023, (b) 2030, (c) 2040, and (d) 2050

ating expenses (OPEX) for the 2023 scenario benchmark all the future planning horizons. Moving from 2023 to 2030, the cumulative operating expenses for the industry sector remain relatively stable with some noticeable changes which can have substantial implications for specific industrial processes, such as pulp and paper production (not discussed here).

In 2030, the depth of efficiency measures in buildings notably affects the share of operating electricity-related expenses for the industry. The OPEX associated with electricity is significantly higher for BAU+ELEC scenario compared to the WIDE and WIDE+ELEC scenarios. Similarly, for LIMIT scenario, the OPEX for electricity is also higher than in the optimal space heating scenarios, with increased costs for oil products as well.

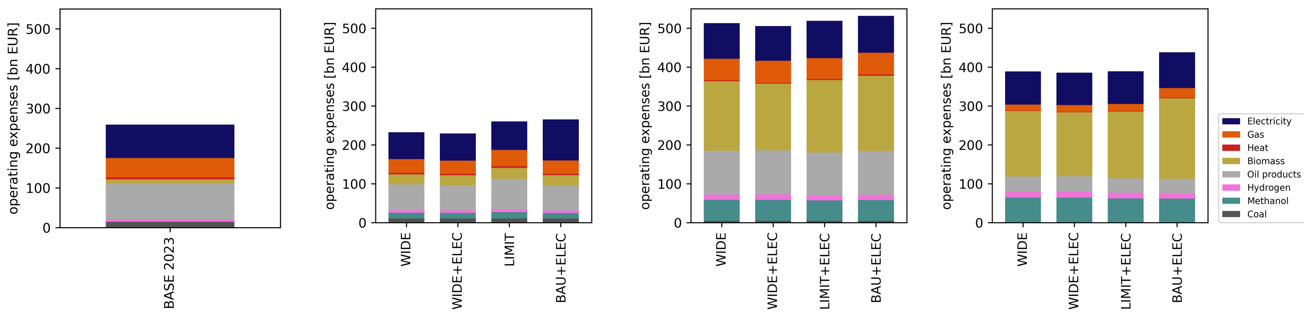
Looking to the 2040 and 2050 planning horizons, the aforementioned trend persists: OPEX related to electricity for the industry sector remains higher in scenarios with lower or no efficiency measures (LIMIT+ELEC, BAU+ELEC). In 2050, the absence of efficiency measures results in higher costs for biomass, as well. This is linked with the increased reliance on biomass as an alternative energy source when efficiency improvements are not implemented, driving up demand and prices.

4.3.3 Energy bills for private households

Finally, the electricity prices for electricity have an impact on the resulting energy bills of private households. Figure 15 shows the average energy bills per country for each scenario and time horizon. The bills are derived as a sum of the households expenses for electricity and gas, where the electricity prices as evaluated as explained previously. This includes accounting for electrical loads for the household and electrified space heating and transport, such as resistive heaters, heat pumps, and electric vehicle (EV) charging. Gas consumption is estimated from usage of residential gas boilers, central gas combined heat and power (CHP) systems, and micro-CHPs used for space heating.

In the 2023 scenario benchmark, substantial cross-national variations in energy bills are already evident. The most extreme disparities can be observed between Albania and Norway for which average energy bills are different by several times. This variation is primarily driven by the demands for electricity and gas for space heating.

Moving to 2030, the general trend is kept with the energy bills higher in colder countries, which is not changed significantly if efficiency measures are implemented. Scenarios WIDE and WIDE+ELEC result in very similar average energy bills, while LIMIT scenario leads to only a slightly higher bills. Phasing-out gas boilers has different impacts on the energy bills, depending on the country, while implementation of the efficiency measures has a pronounced effect in this case. For example, the energy bill could more than double of the average by all European countries (the EUR bar in Figure 15b for individual countries such as Germany, France, the Netherlands or Sweden.



(a) (b) (c) (d)

Figure 14: Operating expenses for the industry sector for each scenario over different horizons: (a) BASE 2023, (b) 2030, (c) 2040, and (d) 2050

For the 2040 and 2050 planning horizons, the results are similar, although the very extreme overhead costs in the BAU+ELEC scenario come down, and lower renovation rates (LIMIT+ELEC) mostly perform worse than WIDE and WIDE+ELEC.

5 Summary and Conclusions

Based on the results presented in Section 4, several conclusions can be drawn regarding the role of building renovation and energy management systems in achieving a cost-effective transition to a 100% renewable energy system. Implementing the energy efficiency measures in builbings can significantly reduce the energy transition costs, saving over 250 billion annually which corresponds to approximately 25% costs of the scenarios without efficiency improvements. The exact savings depend on the extent of the applied efficiency measures and the availability of gas boilers. These findings were observed across all planning horizons from today through 2050, making the entire energy system cheaper to build, maintain and operate. To achieve the most cost-effective benefits, up to 70% of the building stock must be renovated by 2050, with significant progress required still by 2030. Additionally, energy management systems are crucial to achieve these cost reductions which implies substantial adjustments in energy use, both upward and downward.

Renovating the buildings envelope can reduce seasonal peak demand by up to 49.5% by 2050. Even with a less ambitious renovation strategy, it is possible to reach at least 12.7% peak reduction for the space heat demand in 2030. This substantial reduction in peak demand has several implications for the remaining energy system:

- Renovation allows the EU to achieve its climate targets more affordably.
- Widespread renovations, combined with decarbonised heating systems, substantially reduce peak and overall heat and electricity demand. This means lower electricity costs, reduced carbon emissions, and a more efficient investment strategy for energy generation and grid infrastructure.
- Renovation provides the highest savings in electricity price, household bills, and energy infrastructure investments over the next decade. Delaying or opting for less ambitious renovations can lock Europe into financial and environmental losses.
- Widespread renovation provides greater grid stability, enhancing the overall economic efficiency and reliability of the energy system.
- Renovations increase the equality in electricity prices between countries, promoting a more balanced energy market across regions.
- By bringing about significant energy system savings, widespread renovations can significantly reduce household electricity bills. This makes European households more resilient to energy price shocks. Additionally, improved system efficiency and increased flexibility, driven by energy efficiency improvements, can empower European consumers to become more energy independent and encourage the creation of energy communities.
- Building renovation enables local European economies to be more competitive and lower carbon at the same time.

6 Limitations and further work

The study highlight relevance of efficiency measures for achievement decarbonization goals thanks to smoothing demand peaks for the electricity and space heat. That implies a need for incorporation of such peak effects into power and energy system models which are used to provide modelling evidence for decision-making.

The outputs of this study are available publicity as code and data under licences which allow modification and re-distributions to anyone. The current study has

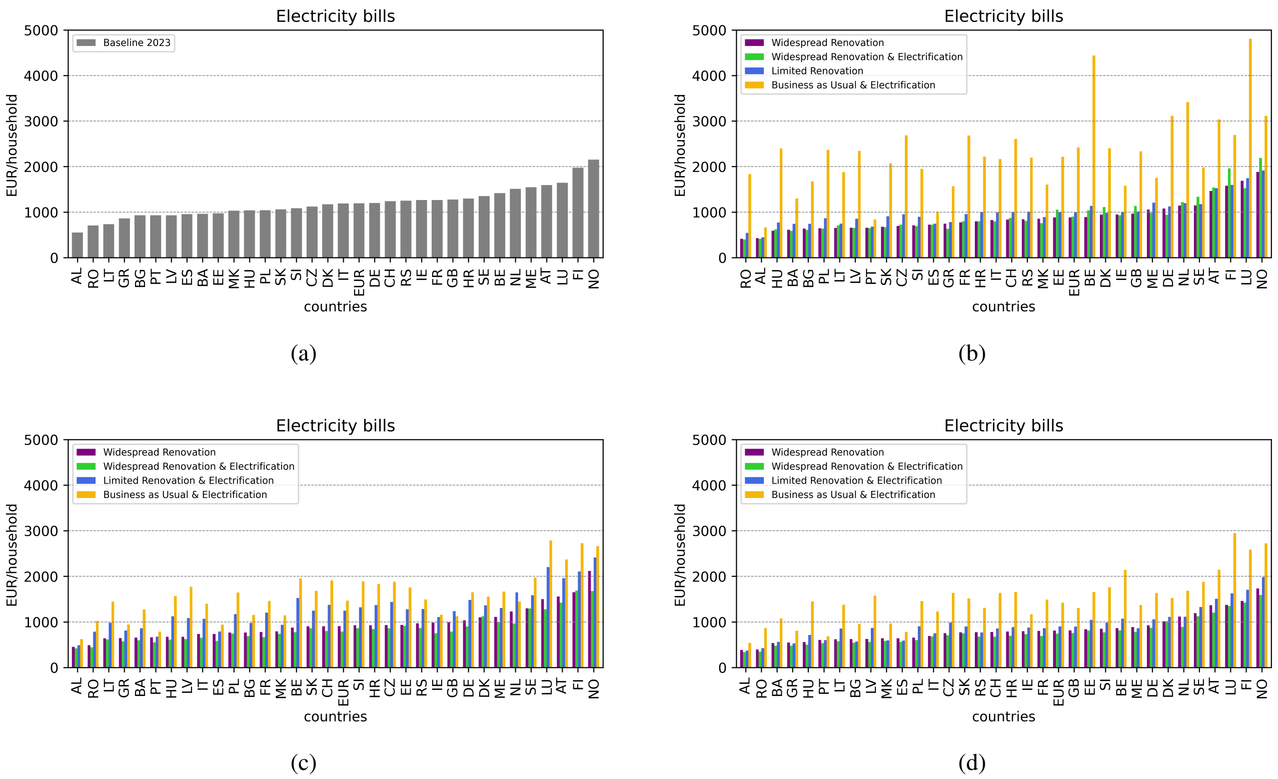


Figure 15: Energy bills per household for each scenario over different horizons: (a) BASE 2023, (b) 2030, (c) 2040, and (d) 2050

the following limitations which are mainly connected with availability of the data and can be improved in the future.

1. The still existing heat pumps are not included into the simulation due to the lack of statistical data on them.

2. The retrofitting costs are assumed as an average value across all types of buildings, e.g. between single-family houses and apartment blocks.

3. Regional-specific space heating technologies are not taken into account. That relates in particular to wooden pellets.

4. The expansion of transmission grids is set exogenously to comply with the existing plans for grid development.

5. Transmission capacity of the distribution grids is taking into account using a bulk approach, without considering the detailed topology.

List of Figures

List of Tables

Nomenclature

AC	Alternating Current
BDEW	Bundesverband der Energie- und Wasserwirtschaft
DC	Direct Current
DSR	Demand Side Response
EMI	Electromagnetic Interference
EV	Electric Vehicle
FCS	Fast Charging Station
HDD	Heating degree-day
IGBT	Insulated-gate Bipolar Transistor
NUTS	Nomenclature of Territorial Units for Statistics
PMU	Phase Measurement Unit
PV	Photovoltaics
RMS	Root Mean Square
THD	Total Harmonic Distortion
TYNDP	Ten-year network development plan
VRES	Variable Renewable Energy Sources

References

[1] "Heat demand peaks: An modeling study on flattening the peak demand curve through energy efficient buildings," 2024.

[2] European Environment Agency, "National emissions reported to the unfccc and to the eu greenhouse gas monitoring mechanism," 2019.

[3] E. Papadis and G. Tsatsaronis, "Challenges in the decarbonization of the energy sector," *Energy*, vol. 205, p. 118025, Aug 2020.

[4] E. Zeyen, V. Hagenmeyer, and T. Brown, "Mitigating heat demand peaks in buildings in a highly renewable european energy system," *Energy*, vol. 231, p. 120784, 2021.

[5] European Commission, "Making our homes and buildings fit for a greener future," 2021.

[6] E. Union, "Directive (eu) 2024/1275 of the european parliament and of the council of 24 april 2024 on the energy performance of buildings (recast) (text with eea relevance)." `https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32024L1275`, 2024.

[7] E. Union, "Directive (eu) 2023/1791 of the european parliament and of the council of 13 september 2023 on energy efficiency and amending regulation (eu) 2023/955 (recast) (text with eea relevance)." https://eur-lex.europa.eu-/eli/dir/2023/1791/oj, 2023.

[8] C. M. Baker and J. W. Coleman, "Paying for energy peaks: Learning from texas february 2021 power crisis," 2022.

[9] T. Brown, D. Schlachtberger, A. Kies, S. Schramm, and M. Greiner, "Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable european energy system," *Energy*, vol. 160, pp. 720–739, 2018.

[10] M. Child, C. Kemfert, D. Bogdanov, and C. Breyer, "Flexible electricity generation, grid exchange and storage for the transition to a 100

[11] M. Kendziorski, L. Göke, C. von Hirschhausen, C. Kemfert, and E. Zozmann, "Centralized and decentral approaches to succeed the 100

[12] A. Palzer and H.-M. Henning, "A comprehensive model for the german electricity and heat sector in a future energy system with a dominant contribution from renewable energy technologies part ii: Results," *Renewable and Sustainable Energy Reviews*, vol. 30, p. 10191034, Feb 2014.

[13] E. Ó Broin, Mata, A. Göransson, and F. Johnsson, "The effect of improved efficiency on energy savings in eu-27 buildings," *Energy*, vol. 57, p. 134148, Aug 2013.

[14] E. Union, "Regulation (eu) 2024/1747 of the european parliament and of the council of 13 june 2024 amending regulations (eu) 2019/942 and (eu) 2019/943 as regards improving the unions electricity market design (text with eea relevance)." https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202401747, 2024.

[15] "Pypsa-eur: A sector-coupled open optimisation model of the european energy system," 2024.

[16] F. Neumann, E. Zeyen, M. Victoria, and T. Brown, "The potential role of a hydrogen network in europe," *Joule*, vol. 7, no. 8, pp. 1793–1817, 2023.

[17] ENTSO-E Transparency, "Open power system data time series," 2020.

[18] M. Hellwig, *Entwicklung und Anwendung parametrisierter Standard-Lastprofile*. PhD thesis, Techinical University of Munich, 2003.

[19] ENTSO-E, "Grid map," Mar. 2024.

[20] ENTSO-E, "Tyndp 2022 projects sheets," Mar. 2024.

[21] Balkan Green Energy News, "France boosts its nuclear energy plan with eight more large reactors," 2023.

[22] TF1 INFO, "Nucléaire : la france a-t-elle les moyens de construire 14 nouveaux réacteurs ?," 2023.

[23] TF1 INFO, "Nucléaire : ce que l'on sait sur les futurs réacteurs epr2," 2023.

[24] Reuters, "Three companies vie to build new czech nuclear plant," 2023.

[25] AP News, "Czech government now seeks to build up to 4 nuclear reactors instead 1 to reduce price," 2023.

[26] World Nuclear Association, "Nuclear power in the czech republic," 2023.

[27] Anadolu Agency, "Russia, hungary sign schedule for construction of paks-2 nuclear power plant," 2023.

[28] World Nuclear Association, "Nuclear power in hungary," 2023.

[29] EL PAÍS English, "Plans for polands first nuclear power plant move ahead as us and polish officials sign an agreement," 2023.

[30] World Nuclear Association, "Nuclear power in poland," 2023.

[31] World Nuclear News, "Second large polish nuclear plant gets approval : New nuclear," 2023.

[32] Enerdata, "The netherlands plans to build two new nuclear reactors by 2035," 2023.

[33] World Nuclear Association, "Nuclear power in romania," 2023.

[34] World Nuclear Association, "Nuclear energy in sweden," 2023.

[35] IAEA, "Slovakia 2022," 2022.

[36] World Nuclear Association, "Nuclear power in slovenia," 2023.

[37] World Nuclear Association, "Nuclear power in the united kingdom," 2023.

[38] Wikipedia, "Nuclear power in the united kingdom," 2023.

[39] Le Monde, "France chooses third location for next-generation nuclear reactors," 2023.

[40] World Nuclear News, "Second large polish nuclear plant gets approval : New nuclear," 2023.

[41] Beyond Fossil Fuels, "Beyond fossil fuels europe coal plants database," 2024.

[42] Business Analytiq, "Subbituminous coal price index," 2024.

[43] Business Analytiq, "Lignite coal price index," 2024. Accessed: 2024-07-15.

[44] Business Insider, "Uranium price," 2024. Accessed: 2024-07-15.

[45] European Commission, "Commission staff working document accompanying the proposal for a regulation of the european parliament and of the council establishing a social climate fund," 2022.

[46] Simon, S. Pezzutto, S. Zambotti, P. Croce, G. Zambelli, C. Garegnani, R. Scaramuzzino, A. Pascual Pascuas, F. Zubaryeva, D. Haas, A. Exner, M. Muller, T. Hartner, A. Fleiter, M. Klingler, P. Kuhnbach, S. Manz, M. Marwitz, J. Rehfeldt, E. Steinbach, and Popovski, "Hotmaps project, d2.3 wp2 report open data set for the eu28," 2018.

[47] European Council (Consilium), "How is eu electricity produced and sold?," Year of access.

[48] M. J. Paul Denholm, Maureen Hand and S. Ong, "Land-use requirements of modern wind power plants in the united states," 2009.

[49] Amplus Solar, "1 mw solar power plant: All costs installation guide," 2024.

[50] D. DeSantis, B. D. James, C. Houchins, G. Saur, and M. Lyubovsky, "Cost of long-distance energy transmission by different carriers," *iScience*, vol. 24, p. 103495, Dec 2021.

[51] Lazard, "Levelized cost of energy analysis - version 13.0," 2019.

[52] D. E. Agency, "Technology data for electricity and district heating, 2022," 2022.

[53] lisazeyen, euronion, F. Neumann, M. Millinger, M. Parzen, aalamia, L. Franken, T. Brown, J. Geis, martavp, P. Glaum, K. van Greevenbroek, lukasnacken, s8au, and T. Seibold, "Pypsa/technology-data: v0.9.0," May 2024.

[54] International Energy Agency, "Renewable energy essentials: Hydropower," 2010.

[55] A. Schröder, F. Kunz, J. Meiss, R. Mendelevitch, and C. von Hirschhausen, "Current and prospective costs of electricity generation until 2050," Jan 1970.

[56] D. E. Agency, "Technology data for heating installations," 2018.

[57] K. Schaber, *Integration of variable renewable energies in the European power system a model-based analysis of transmission grid extensions and Energy Sector coupling Katrin Schaber*. PhD thesis, 2013.

[58] D. E. Agency, "Technology data for energy storage, 2020," 2020.

[59] F. IEE, "Interaktion ee-strom, wärme und verkehr: Endbericht," 2015.

[60] D. E. Agency, "Technology data for renewable fuels, 2022," 2022.

[61] K. Lauri, R. Jouko, N. Nicklas, and T. Sebastian, "Scenarios and new technologies for a north-european co2 transport infrastructure in 2050," *Energy Procedia*, vol. 63, p. 27382756, 2014.

[62] D. E. Agency, "Technology data for carbon capture, transport and storage, 2021," 2021.

[63] D. E. Agency, "Projections and models: Technology data," 2022.

[64] International Energy Agency, "The role of e-fuels in decarbonising transport," 2022.

[65] A. Energiewende, "The future cost of electricity-based synthetic fuels," 2018.

[66] I. R. E. A. (IRENA), "Global hydrogen trade to meet the 1.5řc climate goal: Part ii technology review of hydrogen carriers," 2022.

[67] M. ReuSS, T. Grube, M. Robinius, P. Preuster, P. Wasserscheid, and D. Stolten, "Seasonal storage and alternative carriers: A flexible hydrogen supply chain model," *Applied Energy*, vol. 200, p. 290302, Aug 2017.

[68] D. GL, "Study gle: Technologies and costs analysis on imports of liquid renewable energy," 2020.

[69] D. E. Agency, "Technology data for transport of energy, 2021," 2021.

[70] European Hydrogen Backbone (EHB), "European hydrogen backbone 2023," 2023.

[71] Energy Watch Group (EWG) and Lappeenranta-Lahti University of Technology (LUT), "Global energy system based on 100% renewable energy," 2019.

[72] S. Hagspiel, C. Jägemann, D. Lindenberger, T. Brown, S. Cherevatskiy, and E. Tröster, "Cost-optimal power system extension under flow-based market coupling," *Energy*, vol. 66, pp. 654–666, 2014.

[73] A. Palzer, "Sektorübergreifende modellierung und optimierung eines zukünftigen deutschen energiesystems unter berücksichtigung von energieeffizienzmaSSnahmen im gebäudesektor," 2016.

[74] International Energy Agency (IEA), "Global average levelised cost of hydrogen production by energy source and technology (2019 and 2050)," 2020.

[75] B. Analytiq, "Subbituminous coal price index." `https://businessanalytiq.com/procurementanalytics/index/subbituminous-coal-price-index/`, 2024.

[76] E. Commission, "Commission staff working document - implementing the repower eu action plan: Investment needs, hydrogen accelerator and achieving the bio-methane targets." `https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52022SC0230`, 2022.

[77] B. Analytiq, "Lignite coal price index." `https://businessanalytiq.com/procurementanalytics/index/lignite-coal-price-index/`, 2024.

[78] B. Insider, "Uranium price today | uranium spot price chart." `https://markets.businessinsider.com/commodities/uranium-price`, 2024.

A Assumptions

Table 13: Increase in thermal quality of building envelope elements assumed for moderate renovation.

	$U\left[\frac{W}{m^2 \cdot K}\right]$	$l[cm]$
Walls	0.31	11.6
Roof	0.23	15.7
Floor	0.46	7.8

Moderate renovation is characterised by the use thermal insulation which provides moderate thermal transmittance U-values, as listed in Table 13. Additionally, this renovation depth involves replacing all windows with a higher transmittance than 3.5 $W/(m^2 * K)$ with double-glazing windows.

Table 14: Increase in thermal quality of building envelope elements assumed for the ambitious renovation.

	$U\left[\frac{W}{m^2 \cdot K}\right]$	$l[cm]$
Walls	0.124	29.0
Roof	0.094	38.3
Floor	0.184	19.6

Ambitious renovation involves using higher thickness of thermal insulation which ensures lower thermal transmittance U-values, as listed in Table 14, and replacing all windows with the thermal transmittance higher than 1.3 $W/(m^2 * K)$ with triple-glazing windows.

Table 15: Cost assumptions for electricity generation technologies

technology	horizon	investment costs	FOM [%/year]	VOM	efficiency [p.u.]	lifetime [years]	source
Coal PP	2030	3827.2 €/kW$_e$	1.31	3.26 €/MWh$_e$	0.33	40	[51]
	2040	3827.2 €/kW$_e$	1.31	3.26 €/MWh$_e$	0.33	40	
	2050	3827.2 €/kW$_e$	1.31	3.26 €/MWh$_e$	0.33	40	
Lignite PP	2030	3827.2 €/kW$_e$	1.31	3.26 €/MWh$_e$	0.33	40	[51]
	2040	3827.2 €/kW$_e$	1.31	3.26 €/MWh$_e$	0.33	40	
	2050	3827.2 €/kW$_e$	1.31	3.26 €/MWh$_e$	0.33	40	
Nuclear PP	2030	8594.1 €/kW$_e$	1.27	3.55 €/MWh$_e$	0.326	40	[51]
	2040	8594.1 €/kW$_e$	1.27	3.55 €/MWh$_e$	0.326	40	
	2050	8594.1 €/kW$_e$	1.27	3.55 €/MWh$_e$	0.326	40	
Offshore wind	2030	1769.1 €/kW$_{e,2020}$	2.3741	0.02 €/MWhel		30	[52], [53]
	2040	1622.2 €/kW$_{e,2020}$	2.25	0.02 €/MWhel		30	
	2050	1543.1 €/kW$_{e,2020}$	2.1709	0.02 €/MWhel		30	
Onshore wind	2030	1139.9 €/kW	1.2347	1.51 €/MWh		28	[52]
	2040	1065.2 €/kW	1.2017	1.37 €/MWh		30	
	2050	1026.8 €/kW	1.1817	1.3 €/MWh		30	
Open cycle gas turbine (OCGT)	2030	470.5 €/kW	1.7784	4.76 €/MWh	0.405	25	[52]
	2040	454.4 €/kW	1.785	4.76 €/MWh	0.415	25	
	2050	442.0 €/kW	1.7964	4.76 €/MWh	0.425	25	
Pumped hydro storage (PHS)	2030	2274.8 €/kWel	1.0		0.75	80	[54], [55]
	2040	2274.8 €/kWel	1.0		0.75	80	
	2050	2274.8 €/kWel	1.0		0.75	80	
Reservior hydro	2030	2274.8 €/kWel	1.0		0.9	80	[54], [55]
	2040	2274.8 €/kWel	1.0		0.9	80	
	2050	2274.8 €/kWel	1.0		0.9	80	
Run of river (ror)	2030	3412.2 €/kWel	2.0		0.9	80	[54], [55]
	2040	3412.2 €/kWel	2.0		0.9	80	
	2050	3412.2 €/kWel	2.0		0.9	80	
Solar utility	2030	676.6 €/kW$_e$	1.7275	0.01 €/MWhel		37	[53]
	2040	496.8 €/kW$_e$	1.9904	0.01 €/MWhel		40	
	2050	429.5 €/kW$_e$	2.0531	0.01 €/MWhel		40	
Solar rooftop	2030	880.0 €/kW$_e$	1.2567			37	[53]
	2040	641.4 €/kW$_e$	1.4828			40	
	2050	552.3 €/kW$_e$	1.5792			40	

Table 16: Cost assumptions for heat technologies

technology	horizon	investment costs	FOM [%/year]	VOM	efficiency [p.u.]	lifetime [years]	source
Air-sourced heat pump central	2030	1006.8 €/kW$_{th}$	0.2102	2.32 €/MWh$_{th}$	3.5	25	[52]
	2040	906.1 €/kW$_{th}$	0.2336	2.49 €/MWh$_{th}$	3.625	25	
	2050	906.1 €/kW$_{th}$	0.2336	2.57 €/MWh$_{th}$	3.675	25	
Air-sourced heat pump decentral	2030	1604.0 €/kW$_{th}$	2.9785		3.5	18	[56]
	2040	1483.0 €/kW$_{th}$	3.0335		3.65	18	
	2050	1402.0 €/kW$_{th}$	3.1033		3.75	18	
Gas boiler central	2030	58.2 €/kW$_{th}$	3.5	1.11 €/MWh$_{th}$	1.035	25	[52]
	2040	52.9 €/kW$_{th}$	3.7	1.06 €/MWh$_{th}$	1.04	25	
	2050	52.9 €/kW$_{th}$	3.5	1.06 €/MWh$_{th}$	1.04	25	
Gas boiler decentral	2030	322.2 €/kW$_{th}$	6.6243		0.975	20	[56]
	2040	306.6 €/kW$_{th}$	6.7009		0.9825	20	
	2050	291.6 €/kW$_{th}$	6.7194		0.9875	20	
Gas CHP central	2030	608.5 €/kW	3.313	4.55 €/MWh	0.405	25	[52]
	2040	582.0 €/kW	3.3545	4.39 €/MWh	0.415	25	
	2050	560.9 €/kW	3.4245	4.29 €/MWh	0.425	25	
Ground-sourced heat pump decentral	2030	2682.0 €/kW$_{th}$	1.8384		3.85	20	[56]
	2040	2497.0 €/kW$_{th}$	1.8594		3.9375	20	
	2050	2312.0 €/kW$_{th}$	1.9426		4.0125	20	
Micro CHP	2030	9224.4 €/kW$_{th}$	6.4286		0.351	20	[56]
	2040	7406.1 €/kW$_{th}$	6.1765		0.351	20	
	2050	6534.8 €/kW$_{th}$	6.3333		0.351	20	
Resistive heater central	2030	68.8 €/kW$_{th}$	1.6077	1.01 €/MWh$_{th}$	0.99	20	[52]
	2040	63.5 €/kW$_{th}$	1.6583	1.06 €/MWh$_{th}$	0.99	20	
	2050	63.5 €/kW$_{th}$	1.575	1.06 €/MWh$_{th}$	0.99	20	
Resistive heater decentral	2030	105.8 €/kWhth	2.0		0.9	20	[57]
	2040	105.8 €/kWhth	2.0		0.9	20	
	2050	105.8 €/kWhth	2.0		0.9	20	
Solar thermal central	2030	280650.0 €/1000m2	1.4			30	[53]
	2040	196455.0 €/1000m2	1.4			30	
	2050	112260.0 €/1000m2	1.4			30	
Solar thermal decentral	2030	428920.0 €/1000m2	1.3			30	[53]
	2040	300245.0 €/1000m2	1.3			30	
	2050	171570.0 €/1000m2	1.3			30	
Solid biomass CHP central	2030	3642.5 €/kW$_e$	2.8762	4.86 €/MWh$_e$	0.2694	25	[52]
	2040	3493.3 €/kW$_e$	2.8627	4.87 €/MWh$_e$	0.2687	25	
	2050	3390.9 €/kW$_e$	2.8555	4.92 €/MWh$_e$	0.2664	25	
Water tank charger/discharger	2030				0.8367		[58]
	2040				0.8367		
	2050				0.8367		
Water tank storage central	2030	0.6 €/kWhCapacity	0.5338			22	[58]
	2040	0.6 €/kWhCapacity	0.5714			25	
	2050	0.5 €/kWhCapacity	0.6171			25	
Water tank storage decentral	2030	19.4 €/kWh	1.0			20	[53], [59]
	2040	19.4 €/kWh	1.0			20	
	2050	19.4 €/kWh	1.0			20	

Table 17: Cost assumptions for the miscellaneous technologies

technology	horizon	investment costs	FOM [%/year]	VOM	efficiency [p.u.]	lifetime [years]	source
Battery inverter	2030	227.5 €/kW	0.2512		0.955	10	[58]
	2040	137.6 €/kW	0.4154		0.96	10	
	2050	84.7 €/kW	0.675		0.96	10	
Battery storage	2030	197.9 €/kWh				22	[58]
	2040	124.9 €/kWh				27	
	2050	89.4 €/kWh				30	
Biogas upgrading	2030	205.2 €/kW	17.0397	4.43 €/MWh output		20	[60]
	2040	153.3 €/kW	17.3842	3.37 €/MWh output		20	
	2050	130.8 €/kW	17.4434	2.89 €/MWh output		20	
CO2 storage tank	2030	2584.3 €/t$_{CO2}$	1.0			25	[61]
	2040	2584.3 €/t$_{CO2}$	1.0			25	
	2050	2584.3 €/t$_{CO2}$	1.0			25	
Direct air capture (DAC)	2030	7000000.0 €/(tCO2/h)	4.95			20	[62]
	2040	5500000.0 €/(tCO2/h)	4.95			20	
	2050	4500000.0 €/(tCO2/h)	4.95			20	
Electricity distribution grid	2030	1058.2 €/kW	2.0			40	[53]
	2040	1058.2 €/kW	2.0			40	
	2050	1058.2 €/kW	2.0			40	
Electricity grid connection	2030	148.2 €/kW	2.0			40	[53], [63]
	2040	148.2 €/kW	2.0			40	
	2050	148.2 €/kW	2.0			40	
Electrolysis	2030	1800.0 €/kW$_e$	4.0		0.5874	25	[64], [60]
	2040	1350.0 €/kW$_e$	4.0		0.6374	25	
	2050	1100.0 €/kW$_e$	4.0		0.6763	25	
Fischer-Tropsch	2030	761417.5 €/MW$_{FT}$	3.0	5.05 €/MWh$_{FT}$	0.799	20	[65], [60]
	2040	657729.6 €/MW$_{FT}$	3.0	3.93 €/MWh$_{FT}$	0.799	20	
	2050	565735.8 €/MW$_{FT}$	3.0	2.82 €/MWh$_{FT}$	0.799	20	
Fuel cell	2030	1269.9 €/kW$_e$	5.0		0.5	10	[52]
	2040	1084.7 €/kW$_e$	5.0		0.5	10	
	2050	925.9 €/kW$_e$	5.0		0.5	10	
Gas pipeline	2030	87.2 €/MW/km	1.5			50	[53]
	2040	87.2 €/MW/km	1.5			50	
	2050	87.2 €/MW/km	1.5			50	
Gas storage	2030	0.0 €/kWh	3.5919			100	[53], [63]
	2040	0.0 €/kWh	3.5919			100	
	2050	0.0 €/kWh	3.5919			100	
H2 liquefaction	2030	889.9 €/kW$_{H2}$	2.5			20	[66], [67], [68]
	2040	800.9 €/kW$_{H2}$	2.5			20	
	2050	623.0 €/kW$_{H2}$	2.5			20	
H2 pipeline	2030	303.7 €/MW/km	3.5833			50	[69], [70]
	2040	303.7 €/MW/km	2.75			50	
	2050	303.7 €/MW/km	1.9167			50	
H2 storage	2030	53.9 €/kWh	1.0794			27	[58]

technology	horizon	investment costs	FOM [%/year]	VOM	efficiency [p.u.]	lifetime [years]	source
tank	2040	38.1 €/kWh	1.3897			30	
	2050	25.4 €/kWh	1.873			30	
H2 storage underground	2030	2.6 €/kWh	0.0	0.0 €/MWh		100	[58]
	2040	1.9 €/kWh	0.0	0.0 €/MWh		100	
	2050	1.4 €/kWh	0.0	0.0 €/MWh		100	
Home battery inverter	2030	321.3 €/kW	0.2512		0.955	10	[71]
	2040	197.4 €/kW	0.4154		0.96	10	
	2050	122.6 €/kW	0.675		0.96	10	
Home battery storage	2030	280.2 €/kWh				22	[71]
	2040	179.6 €/kWh				27	
	2050	129.8 €/kWh				30	
HVAC overhead	2030	442.1 €/MW/km	2.0			40	[72]
	2040	442.1 €/MW/km	2.0			40	
	2050	442.1 €/MW/km	2.0			40	
HVDC inverter pair	2030	165803.0 €/MW	2.0			40	[72]
	2040	165803.0 €/MW	2.0			40	
	2050	165803.0 €/MW	2.0			40	
HVDC overhead	2030	442.1 €/MW/km	2.0			40	[72]
	2040	442.1 €/MW/km	2.0			40	
	2050	442.1 €/MW/km	2.0			40	
Methanolisation	2030	761417.5 €/MW$_{MeOH}$	3.0			20	[65], [60]
	2040	657729.6 €/MW$_{MeOH}$	3.0			20	
	2050	565735.8 €/MW$_{MeOH}$	3.0			20	
Sabatier (methanation)	2030	728.7 €/kW$_{CH4}$	3.0		0.8	20	[65], [53], [73]
	2040	639.8 €/kW$_{CH4}$	3.0		0.8	20	
	2050	559.8 €/kW$_{CH4}$	3.0		0.8	20	
Steam methane reforming (SMR)	2030	522201.0 €/MW$_{CH4}$	5.0		0.76	30	[63], [74]
	2040	522201.0 €/MW$_{CH4}$	5.0		0.76	30	
	2050	522201.0 €/MW$_{CH4}$	5.0		0.76	30	

Table 18: Cost assumptions for fuel

technology	horizon	fuel cost [€/MWh$_{th}$]	source
Biogas	2030, 2040, 2050	62.4351	[53]
Coal	2030, 2040, 2050	24.57	[75]
Gas	2030, 2040	38.84	[76]
	2050	42.08	[76]
Lignite	2030, 2040, 2050	22.11	[77]
Nuclear	2030, 2040, 2050	1.75	[78]
Oil	2030, 2040, 2050	52.9111	[55]

B Modelling of building envelope retrofitting

The approach relays on calculation of heat demand according to the seasonal balance method. The method is adjusted to be used with the data on buildings topology for European building stock prepared in course of TABULA project (Typology Approach for Building Stock Energy Assessment).

The energy needed for space heating E_{space} is calculated as the sum of heat losses H_{losses} and heat gains H_{gains}
$E_{space} = H_{losses} - H_{gains}$.

The heat losses constitute from the losses through heat transmission H_{tr}, which includes heat transfer through building elements and thermal bridges, and ventilation H_{ve}
$H_{losses} = (H_{tr} + H_{ve}) \cdot F_{red} \cdot (T_{threshold} - T_{dh}) \cdot d_{heat} \cdot 1/365$,
where:
F_{red} is the reduction factor which accounts for non-uniform heating demand during the year [C],
$T_{threshold}$ is the heating temperature threshold, assumed to be $15C$
d_{heat} is the length of heating season defined as number of days with daily averaged temperature below $T_{threshold}$
T_{dh} is the mean daily averaged temperature of the days within heating season d_{heat}.

Heat transfer H_{tre} through building element e
$H_{tre} = U_e \cdot A_e / A_{CRef}$,
where:
U_e is the effective transmittance value through the building element,
A_e is the area of heat transfer,
A_{CRef} is the reference area of the building.

Heat transfer by thermal bridges H_{tb}
$H_{tb} = \delta U \cdot A_{envelope} / A_{CRef}$,
where:
δU is the transmittance of thermal bridges,
$A_{envelope}$ is the area of the building envelope.

Heat transfer by ventilation H_{ve}
$H_{ve} = c_p^{(air)} \cdot (n_{au} + n_{ai}) \cdot h_{room}$,
where:
$c_p^{(air)}$ is the thermal capacity of the air,
n_{au} is the average air change rate during heating season,
n_{ai} is the air change rate by infiltration,
h_{room} is the ventilaiton reference room height.

Total annual heat losses Q_{ht} are evaluated as a sum of the transmission heat losses trough building elements H_{tr_e} and thermal bridges H_{tb}, and ventilation heat losses H_{ve}. The sum is weighted by a factor F_{red} which takes into account non-uniform heating and the temperature factor tf of the heating season
$Q_{ht} = (H_{tr_e} + H_{tb} + H_{ve}) \cdot F_{red} \cdot tf$.

The temperature factor F_{red} is calculated as: $tf = (T_{threshold} - T_{dh}) \cdot d_{heat} \cdot 1/365$,
where:
t_{dh} is the average temperature of days within the heating season,
d_{heat} is the length of the heating season.

Heat gains constitute from the gains by solar radiation H_{solar} and internal heat gains (H_{int}) weighted by a gain utilisation factor ν: $H_{gains} = \nu \cdot (H_{solar} + H_{int})$.

Gains by solar radiation H_{solar}
$H_{solar} = R/A_{CRef} \cdot 1\text{e}^3/8760$,
where:

R is the solar radiation gain trough the windows calculated during heating season calculated according to the window area of the building, assuming a equal distributed window orientation (east, south, north, west) .

Internal gains H_{int} are evaluated using an empirical coefficient ϕ:
$H_{int} = \phi \cdot d_{heat} \cdot 1/365$,
where ϕ coefficient represents the average thermal output of internal heat sources.

C Modelling outputs

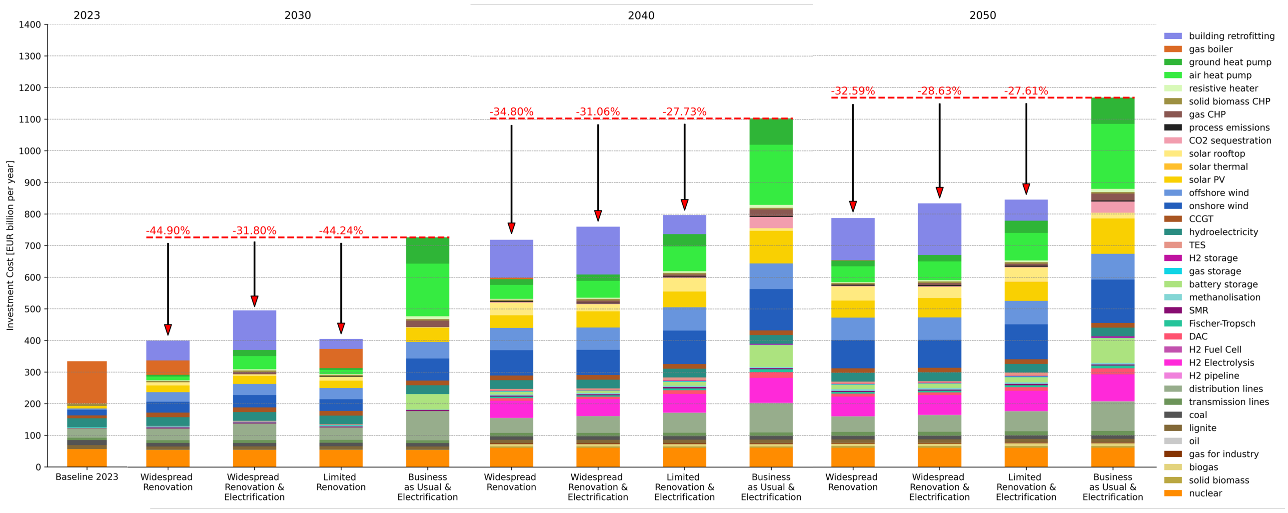


Figure 16: Investment costs per scenario

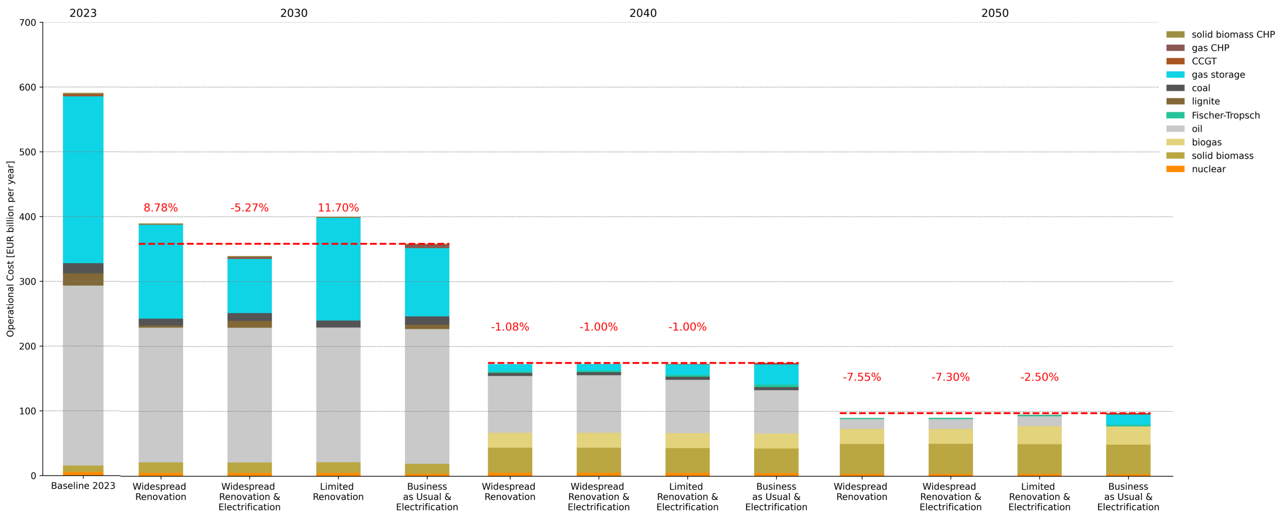


Figure 17: Operational costs per scenario

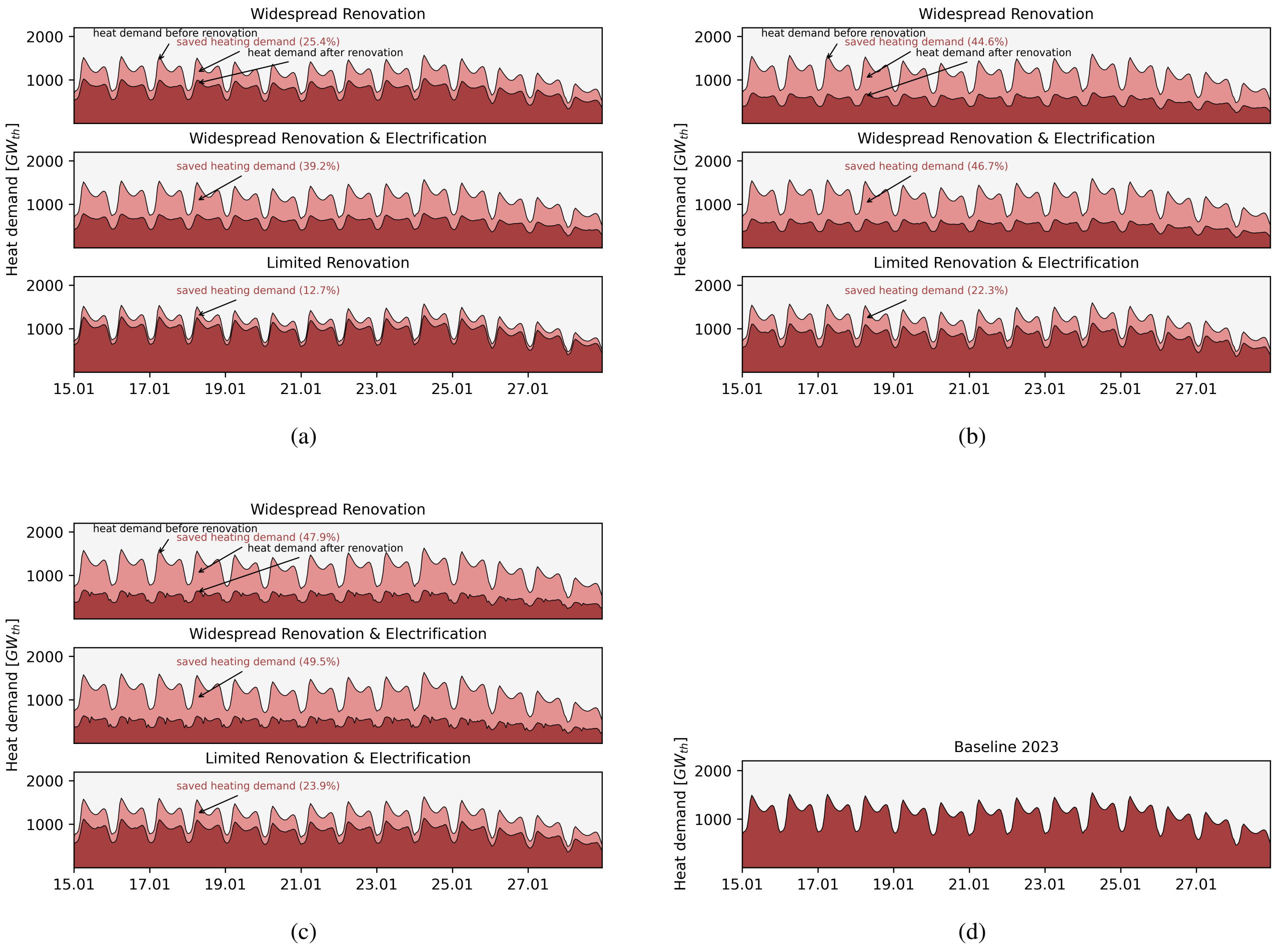


Figure 18: Heat demand before and after renovation and heat flexibility for 2 week period in each scenario over different horizons: (a) 2030, (b) 2040, (c) 2050, and (d) BAU

Table 19: Electricity prices in €/MWh for each scenario over different horizons by countries

	2023	2030				2040				2050			
	BASE	WIDE	WIDE +ELEC	LIMIT	BAU +ELEC	WIDE	WIDE +ELEC	LIMIT +ELEC	BAU +ELEC	WIDE	WIDE +ELEC	LIMIT +ELEC	BAU +ELEC
AL	96.7	63.0	67.0	65.4	101.9	60.2	57.9	56.3	81.4	47.3	43.1	41.9	65.0
AT	97.1	73.4	80.6	77.1	150.2	88.9	81.3	93.0	106.2	72.1	62.4	68.5	88.5
BA	97.4	70.8	72.4	73.6	117.3	73.4	68.5	77.8	105.4	57.4	51.9	49.9	85.6
BE	94.1	65.3	70.0	68.9	245.7	68.7	59.7	83.7	91.6	60.1	54.9	54.3	86.8
BG	97.8	73.0	71.6	77.0	152.8	77.2	68.9	79.0	93.3	59.8	52.3	46.4	76.8
CH	95.4	71.1	77.3	74.1	162.2	78.7	70.4	85.7	103.9	64.4	55.9	55.0	84.1
CZ	97.2	76.3	80.2	82.6	188.4	89.4	83.5	100.8	106.0	67.6	64.4	65.1	86.5
DE	97.1	70.0	76.0	73.3	215.5	80.9	71.4	91.3	96.6	65.9	61.3	61.1	87.1
DK	89.9	52.6	59.3	54.1	132.2	60.8	60.1	66.1	79.2	54.6	52.6	53.1	72.7
EE	89.9	60.2	64.8	61.9	107.0	64.1	59.4	71.0	86.2	55.6	51.2	57.3	78.4
ES	95.4	59.1	65.3	60.2	77.9	53.0	45.0	54.4	65.3	43.9	40.1	40.1	50.6
FI	86.1	57.8	66.2	59.0	72.2	65.0	63.1	68.1	83.3	56.7	53.0	54.8	76.7
FR	89.5	60.6	66.1	61.8	155.8	61.0	52.5	72.4	75.3	56.4	48.1	49.3	69.0
GB	106.9	56.5	66.0	58.2	150.9	59.0	49.1	64.7	67.1	47.1	44.0	46.4	70.0
GR	99.3	67.4	71.2	69.9	154.6	61.8	56.1	66.6	81.8	47.7	42.1	41.6	63.6
HR	98.2	73.5	77.1	77.2	148.4	80.2	73.6	89.6	103.8	63.6	56.4	56.6	87.4
HU	95.7	74.9	78.9	78.0	200.9	82.4	74.6	94.4	107.7	65.1	57.5	60.1	92.6
IE	106.9	55.3	60.7	56.5	99.3	54.5	45.7	57.3	66.5	42.9	41.3	44.2	60.7
IT	99.5	68.9	70.3	71.6	147.8	63.8	58.0	72.0	86.3	54.9	53.6	49.3	69.5
LT	95.2	62.9	64.8	64.9	139.4	70.0	65.7	81.3	98.6	62.1	56.4	67.3	87.5
LU	97.1	68.9	73.3	72.0	196.5	76.1	66.7	84.6	94.2	62.5	60.0	57.9	87.0
LV	93.7	62.3	66.2	63.8	128.2	65.9	59.2	73.5	94.2	58.8	51.6	58.4	79.5
ME	99.0	73.3	71.2	76.8	99.0	73.7	67.9	73.1	90.7	57.7	51.9	48.1	74.3
MK	96.8	69.2	73.2	72.6	141.6	68.2	66.7	65.4	90.9	53.7	50.0	41.7	73.7
NL	97.6	59.7	68.1	61.2	185.7	66.9	56.5	76.1	74.4	58.6	48.6	50.4	78.9
NO	67.1	53.9	63.2	55.1	76.0	58.3	46.8	61.5	62.2	47.3	43.3	49.9	61.4
PL	98.0	69.9	71.0	74.0	164.5	77.3	74.4	86.7	99.1	62.2	57.8	64.0	82.0
PT	97.3	61.3	62.9	62.7	74.4	51.3	46.6	52.8	62.7	43.8	40.7	44.0	49.7
RO	96.5	73.5	75.7	77.4	219.9	80.8	73.7	89.7	102.8	61.8	54.8	48.9	85.0
RS	96.3	75.3	74.2	79.7	161.6	83.8	76.3	89.5	100.5	64.8	57.4	54.2	84.5
SE	80.6	54.5	62.7	55.4	73.9	63.1	62.0	69.2	78.1	56.8	52.4	56.3	71.0
SI	96.1	72.9	75.3	77.2	142.6	79.4	74.1	88.1	109.4	64.4	58.5	60.9	92.8
SK	94.7	73.4	74.8	79.7	150.0	84.2	80.5	90.9	103.0	65.4	64.9	62.2	85.8
EUR	95.4	63.8	69.2	66.0	155.3	67.2	59.7	75.4	83.7	56.3	51.4	52.5	74.5

Table 20: Energy bills in €/household for each scenario over different horizons by countries

	2023	2030				2040				2050			
	BASE	WIDE	WIDE +ELEC	LIMIT	BAU +ELEC	WIDE	WIDE +ELEC	LIMIT +ELEC	BAU +ELEC	WIDE	WIDE +ELEC	LIMIT +ELEC	BAU +ELEC
AL	552	428	416	447	665	454	419	489	623	384	338	372	540
AT	1592	1463	1538	1524	3037	1559	1422	1960	2369	1366	1203	1508	2145
BA	961	611	587	740	1296	655	597	861	1274	537	477	563	1076
BE	1415	890	1039	1136	4439	874	775	1526	1954	865	815	1071	2140
BG	929	639	610	743	1673	769	686	978	1154	625	545	568	957
CH	1240	834	872	1007	2607	905	801	1375	1912	778	679	857	1636
CZ	1121	694	724	952	2685	931	860	1440	1881	754	706	985	1638
DE	1200	1077	940	1123	3115	1034	900	1483	1649	925	872	1057	1633
DK	1171	946	1111	985	2401	1098	1124	1362	1555	1013	1015	1111	1526
EE	974	883	1053	999	2216	935	911	1276	1755	838	811	1044	1655
ES	954	725	725	745	1007	736	582	787	941	641	563	590	781
FI	1974	1578	1961	1596	2693	1652	1687	2107	2725	1459	1424	1706	2586
FR	1267	775	799	956	2682	778	668	1206	1461	803	691	862	1490
GB	1274	965	1135	1014	2333	992	790	1235	1125	813	757	898	1304
GR	862	746	635	780	1569	645	572	812	943	547	479	530	807
HR	1298	795	799	996	2218	927	842	1371	1833	790	696	886	1654
HU	1037	592	620	772	2397	672	611	1125	1570	560	501	714	1448
IE	1266	947	930	1007	1579	982	752	1106	1156	795	730	874	1169
IT	1191	825	795	993	2162	734	651	1066	1398	691	679	751	1228
LT	734	651	707	744	1880	642	617	979	1444	619	578	856	1377
LU	1645	1687	1526	1746	4807	1499	1276	2204	2788	1373	1348	1626	2947
LV	931	654	652	853	2345	673	622	1086	1769	625	561	870	1575
ME	1548	1055	983	1208	1750	1109	991	1304	1666	886	781	861	1371
MK	1030	853	757	890	1603	792	737	937	1143	640	585	593	964
NL	1511	1143	1220	1198	3415	1228	965	1646	1445	1116	888	1115	1683
NO	2153	1883	2189	1913	3115	2115	1678	2413	2662	1733	1590	1982	2724
PL	1041	646	636	866	2365	767	743	1171	1644	656	603	903	1455
PT	929	657	647	679	839	662	551	678	787	605	534	602	684
RO	707	415	400	544	1834	490	443	785	1018	397	349	423	863
RS	1251	843	808	1011	2195	969	868	1282	1492	776	679	769	1310
SE	1353	1146	1338	1174	1981	1299	1292	1587	1971	1194	1123	1328	1877
SI	1083	709	692	896	1950	925	861	1321	1888	851	772	985	1762
SK	1059	676	671	906	2068	905	860	1248	1679	769	751	902	1515
EUR	1192	884	900	991	2420	906	789	1248	1466	810	741	899	1420