Building and Environment 269 (2025) 112408

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Decarbonisation scenarios for the European residential sector

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ARTICLE INFO

Keywords:
Climate change
EU Green Deal
Residential sector
Energy efficiency
TIMES-Europe model

ABSTRACT

The urgency to combat global climate change has prompted the implementation of many regional and national policies, with the European Green Deal standing out as one of the most significant initiatives. We use the recently developed TIMES-Europe energy system model to study the pivotal role of the residential sector in achieving the ambitious energy savings goal formulated by the EU in the broad framework of its Fit-for-55 policy package. We observe improved energy efficiency in households across a set of scenarios that differ in terms of climate policy ambition and level of collaboration between European countries. We find that, by 2030, residential buildings can realize up to 3000 PJ in overall energy savings. Cross-country collaboration may yield an additional 11% reduction in residential energy consumption, which could increase to 18% when combined with dwelling retrofitting subsidies. Our analysis of the transformation of the residential fuel mix, particularly the interplay between biomass and natural gas usage, reveals a trade-off between short-term energy efficiency gains and long-term CO_2 reduction goals. In the short run, scenarios lacking stringent climate control measures exhibit higher energy savings in comparison to those embracing ambitious climate targets. This initial difference, however, diminishes over time: energy savings from climate-compliant scenarios nearly align with those in scenarios without strict climate compliance around 2040. Scenarios lacking effective climate policy result in significant delays in decarbonizing the European residential sector. Our findings underscore the critical role of ambitious climate targets and accelerated retrofitting rates, highlighting the necessity to imminently and proactively implement directed policy interventions.

1. Introduction

The increasing severity of the climate crisis in the current era is undeniable [1–3]. In response, the European Green Deal [4] was announced in 2019 with the ambitious goal of transforming Europe into the first continent to achieve a net-zero emissions economy, thereby confirming the EU's commitment to strongly contribute to the Paris Agreement target of limiting global temperature rise to well below 2 °Celsius above pre-industrial levels [5]. One instrumental component of the EU's transformative agenda is the Fit-for-55 policy package [6], a comprehensive set of measures aimed at realizing the objectives of the European Green Deal. In its latest update, it includes a renewed focus on energy efficiency through the revised Energy Efficiency Directive (EED) [7]. This directive targets a reduction in overall energy consumption, setting an ambitious goal to collectively achieve approximately 6700 PJ in energy savings by 2030, equating to an 11.7% reduction relative to the 2020 baseline.

In its recent revision, the EED pinpointed the building sector (including both residential and commercial buildings) as a primary contributor to energy consumption. Eurostat data from 2021 reveal that European households alone accounted for nearly 30% of final energy consumption, amounting to approximately 11 EJ [8]. This shows the critical need for targeted measures and studies to enhance the contribution of the European residential sector towards achieving the EU climate and energy efficiency goals. A multitude of policies and strategies have been formulated to enhance the energy efficiency of EU dwellings. These initiatives encompass, for instance, the EU Renovation Wave [9], the EU Energy Performance of Buildings Directive (EPBD) [10], and the EU Long-Term Renovation Strategies [11]. As we approach the milestone year of 2030 for the climate and energy efficiency targets, there is an urgent need to create new and more stringent climate policies while scrutinizing the adequacy of existing ones.

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https://doi.org/10.1016/j.buildenv.2024.112408
Received 31 May 2024; Received in revised form 14 November 2024; Accepted 2 December 2024
Available online 4 December 2024

Numerous studies have explored the energy transition of the European residential sector [12–25]. For example, our own examination of space-heating decarbonization pathways reveals the importance of implementing EU climate policies, and of quantifying the positive impact of collaboration between European countries [12]. Maduta et al. highlight the importance of compliance with EPBD in order to make progress towards climate-neutral European dwellings [13]. Existing research on residential sector energy efficiency predominantly focuses on individual countries. For instance, Bianco and Marmori conduct examinations of energy efficiency measures in the Italian residential sector, utilizing a bottom-up approach to estimate future energy savings across various scenarios [14]. Peñasco and Anadón conduct similar case studies for England and Wales, using microdata to assess the effects of energy efficiency measures [15]. A significant research gap remains in the literature with regard to analyses of the effects of energy efficiency measures at the supra-national and regional levels. Addressing this gap is crucial for identifying the role of European households in the EED initiative, and for gaining a comprehensive understanding of the broader dynamics shaping the energy efficiency landscape in Europe as it strives to meet its climate targets.

The present paper addresses this gap by using TIMES-Europe, a recently developed European energy system model, which allows for quantifying the effectiveness of EU energy and climate policies. In comparison with the modelling tools used in the studies cited above, TIMES-Europe possesses the unique capability to provide a detailed simultaneous assessment of both the pan-European and the member-state perspective. Our objective is to leverage this particular ability of TIMES-Europe to evaluate the implementation of EU policies and explore the potential advantages of full collaboration between European countries (so as to jointly share the cost burden), relative to partial collaboration (in which each individual country focuses merely on its own target). We present an analysis of the intricate relationship between policies, technologies, and investments needed to achieve the climate goal and energy efficiency target of the EU. In Section 2, we elaborate on our modelling methodology, providing additional justification for the selection of the TIMES-Europe model for this study, along with detailed explanations of relevant assumptions, terminologies, and scenario descriptions. In Section 3, we present our findings, followed by a discussion of insights from our results in Section 4. In Section 5, we draw some overall conclusions that derive from our study and provide recommendations for future research.

2. Methodology, terminology, and description of scenarios

2.1. TIMES-Europe residential module

We here provide a short description of the TIMES-Europe model and discuss its residential module, which is particularly pertinent to our present study. Detailed information about TIMES-Europe, including all modelling parameters, can be found in the work of Luxembourg et al., 2024 [26]. TIMES-Europe utilizes a linear programming (LP) framework to determine the least-cost solution of the European energy system, considering various exogenous constraints and conditions. These include, for instance, the availability of energy supplies, energy demand projections, and targets for emission reduction. The geographic scope of TIMES-Europe currently covers the 27 member states of the European Union and the United Kingdom. The model encompasses energy use across all major supply sectors, i.e. power, heat, and fuel production. Likewise, it does so for all main demand sectors, i.e. the residential and commercial sector, agriculture, transport, and industry.

TIMES-Europe is based on the TIMES model generator [27], which has been successfully used to examine long-term energy transition scenarios across diverse domains and geographies. Some examples – drawn from our own work as well as studies from other researchers – include assessments of enhanced electricity access in Africa [28], the implications for Europe of large-scale renewable energy imports from North Africa [29,30], the achievement of Fit-for-55 targets in Wallonia, Belgium [31], and on the accessibility of clean cooking to align with climate goals [32].

The TIMES-Europe residential sector module is described in detail in Salim et al., 2024 [12]. In summary, this module identifies a cost-optimal portfolio that fulfils the required energy service demand by combining home renovation with the deployment of suitable end-use technologies. Residential energy demand is split into five categories: space heating, space cooling, water heating, cooking, and electric appliances. Residential energy demand data for each of these categories are sourced from [33] for the model base year (2015). The methodology for the calculation of space heating demand in TIMES-Europe is presented in detail in Salim et al., 2024 [12]. The space cooling, water heating, and cooking demands per dwelling in each European country are determined by dividing the end-use demand for each by the total number of dwellings equipped with the corresponding end-use technologies [34]. Demands are then projected to future years using dwelling stock data [35] and population growth data from Eurostat [36], as described in [12,26]. A limitation of this approach is that it assumes no changes in heating or cooling demand resulting from the effects of climate change, which may impact future energy needs.

TIMES-Europe simulates a large set of residential end-use technologies. These include various types of heat pumps, boilers, household appliances, solar thermal water heating devices, and cooking appliances. Depending on the scenario-specific exogenous constraints applied, the model will typically deploy the cheapest technologies with the highest efficiency and lowest CO_2 emissions, using CO_2 factors based on JRC studies [37]. The techno-economic data for the technology parameterization in the model are derived from the JRC database [33] and TNO factsheets [38]. The deployment of heat pumps is limited to dwellings with a minimum energy label of C, which is equivalent to a space heating capacity requirement of less than 12.2 kWth for a dwelling of average size in Europe [38]. This assumption allows us to estimate the dwelling stock that is suitable for heat pump use, based on each construction period and dwelling type. Additionally, we constrain the expansion of fossil-fuel boilers, capping their growth beyond the projected 2035 level, in line with the EU Renewable Energy Directive (RED). Fuel and energy carrier availability originates from other sectors in TIMES-Europe (e.g. the power and upstream sectors) and is determined by exogenous assumptions, including factors such as solar irradiance, wind speed, and natural resources potential. Retrofitting efforts are modelled through three distinct packages—shallow, medium, and deep retrofitting—each offering different levels of insulation improvement depending on the construction period of the dwelling. Shallow retrofitting, characterized by minimal U-value reduction, represents the most cost-effective option, while deep retrofitting, which achieves significant U-value reduction, incurs the highest investment cost. The model estimates energy savings from retrofitting endogenously, taking into account the heating degree days, which vary by country across Europe. This approach allows us to capture the differences in retrofitting impacts due to climatic and housing stock diversity across the region. In this study we assume that each dwelling has only one opportunity for retrofitting during the analysis period, meaning that multiple retrofits for one dwelling are not allowed. This simplification does not fully capture the reality that households might engage in sequential retrofits as their financial situation improves.

Key criteria that justify the selection of TIMES-Europe for this study are: (i) its up-to-date extensive input database, incorporating all the latest technological developments as well as member-state energy statistics; (ii) its comprehensive representation of the energy system across EU member states, allowing for an examination of the interactions between national and European policies; and (iii) its balanced design, which offers sufficient granularity to address our research questions without requiring prohibitively long runtime, thereby allowing the detailed assessment of several scenarios. As already noted in Section 1, one of the main features that make TIMES-Europe stand out among other modelling tools traditionally used to assess energy efficiency policy is its unique ability to capture both the European and the national perspective simultaneously, while maintaining a high level of detail, and without introducing excessive computational complexity. Specifically, TIMES-Europe possesses a robust bottom-up techno-economic characterization of the European energy system at the member-state level, enabling detailed cross-sectoral climate policy analysis. This combination of high techno-economic detail with broad geographical and sectoral coverage enables a comprehensive analysis of interactions across multiple sectors and countries, complementing more specialized models that focus on a narrower set of technologies, applications, and/or regions. By incorporating a building module, our approach captures key decarbonization options for the residential sector (e.g. retrofitting and end-use technology changes), while also providing valuable insights into broader cross-sectoral policy implications and interactions at both the European and national levels.

2.2. Terminology

Throughout this paper, we consistently describe energy conversion processes in the residential sector in terms of ***energy input, energy demand*** and ***energy efficiency***. ***Energy input*** refers to the energy that flows into the residential sector. In this study, it encompasses various sources such as electricity, direct heat (i.e. geothermal heat, district heating, and solar heat), oil, coal, natural gas, and biomass. The energy input required to meet residential demand, including both primary and secondary energy sources, is processed and accounted for within the TIMES-Europe power sector and upstream sector. Ambient heat, while not considered a primary energy source in this study, is estimated using Eq. (1):

$$\text{Heat pump ambient heat input (PJ)} = \text{Heat pump electricity input (PJ)} \times (\text{Heat pump COP} - 1) \quad (1)$$

The Coefficient of Performance (COP) of heat pumps, represents the ratio of heat output to the amount of electricity input for space heating [38]:

$$\text{Heat pump COP} = \frac{\text{Heat pump heat output } (PJ)}{\text{Heat pump electricity input } (PJ)} \quad (2)$$

Heat pump heat output in Eq. (2) is determined by energy conservation as the sum of electricity and ambient heat input:

$$\text{Heat pump heat output (PJ)} = \text{Heat pump electricity input (PJ)} + \text{Heat pump ambient heat input (PJ)} \quad (3)$$

Energy demand is the energy that consumers utilize for various purposes, directly contributing to a specific task or activity. It represents the energy that performs the intended work or provides a desired end-use service, i.e. space heating, space cooling, water heating, cooking, and powering appliances. ***Energy efficiency*** is a metric gauging how effectively energy input is converted into final energy in the residential sector, as expressed in Eq. (4).

$$\text{Energy Efficiency (\%)} = \frac{\text{Energy Demand } (PJ)}{\text{Energy Input } (PJ)} \times 100 \quad (4)$$

High energy efficiency indicates that a relatively small proportion of input energy is wasted. This results in more efficient resource utilization.

2.3. Scenario overview

In this study, TIMES-Europe is utilized to investigate the decarbonization of the European residential sector and to analyse how it may be affected by the synergy between the extent of collaboration among member states and climate ambition. For this purpose, we rely on a set of scenarios originally developed by Salim et al., 2024 [12] for their analysis of European residential space heating. These scenarios, named ***My Delay, Our Delay, My Action***, and ***Our Action***, are each characterized by a unique combination of climate ambition and collaboration level. ***My Delay*** foresees a lack of collaboration, and the EU is set to miss its climate target. ***Our Delay*** envisions cooperation among member states, while the EU is still falling short of its climate goals. ***My Action*** achieves decarbonization targets through a fragmented approach, while ***Our Action*** assumes a collaborative effort among member states leading to the achievement of ambitious climate goals. In this article, we expand the existing set of scenarios by introducing two additional scenario variants: ***My Action*** – ***Subsidy*** and ***Our Action*** – ***Subsidy***. These scenarios are designed to simulate the potential effects of providing subsidies for dwelling retrofitting. By modelling these subsidy-driven scenarios, we aim to explore the extent to which retrofitting incentives may contribute to achieving climate goals within the residential sector, enhancing energy efficiency and reducing overall emissions.

The parameterization of climate targets in terms of modelling constraints is presented in Table 1. These targets are based on either announced or intended European policies, such as the Energy Performance of Buildings Directive (EPBD) for retrofitting targets and the Renewable Energy Directive (RED) for renewable energy generation targets). The climate policies in each scenario are defined by specific conditions in five key areas: (i) fossil fuel deployment in the residential sector, (ii) annual retrofitting rate, (iii) renewable electricity generation, (iv) heat pumps deployment, and (v) subsidy on retrofitting cost. Conditions (i), (ii), and (iii) are applied either to each member state separately or to Europe as a whole, in the partial and full collaboration scenarios, respectively. In the collaborative scenarios, a member state is allowed not to meet its climate targets as long as other member states exceed theirs. Condition (iv) applies to Europe as a whole in all scenarios, given the unavailability of a comprehensive overview of individual country targets for heat pump deployment at the time of writing. Condition (v) is a variant of the Action scenarios, in which countries with retrofitting costs higher than the EU27 + UK average receive a subsidy covering the difference between their actual retrofitting costs and the EU27 + UK average. The average retrofitting costs and the corresponding subsidies are determined separately for different building types and construction periods, as detailed in Appendix 1.

3. Results

In this section, we present the findings of our research, based on model projections designed to determine the least-cost solution that satisfies the constraints of each scenario. The results are organized into two sub-sections: (i) a European perspective, which includes our analysis of the EU27 + UK region as a whole, and (ii) a country-level examination, in which we explore the differences among individual states within our TIMES-Europe model. The results for the year 2020 are based on a calibration process detailed in the work of Salim et al., 2024 [12].

Table 1
Key parameters across all our six scenarios.

Scenario	Space heating fossil fuel supply	Dwelling retrofitting rate	Renewable Energy generation target	Heat pump stock target	Retrofitting cost subsidy
My Delay	No fossil fuel growth in each EU27+UK.	1% / yr dwelling stock retrofit in each EU27+UK.	Minimum 60% renewable electricity generation in each EU27+UK.	7 million additional heat pumps by 2030 within EU27+UK.	No Subsidy.
Our Delay	No fossil fuel growth in EU27+UK as a whole.	1% / yr dwelling stock retrofit aggregated over EU27+UK.	Minimum 60% renewable electricity generation in EU27+UK as a whole.		
My Action	No fossil fuel growth and fossil fuel phase-out by 2040 in each EU27+UK.	3% / yr dwelling stock retrofit in each EU27+UK.	Minimum 60% renewable electricity generation in each EU27+UK.	30 million additional heat pumps by 2030 within EU27+UK.	
Our Action	No fossil fuel growth and fossil fuel phase-out by 2040 in EU27+UK as a whole.	3% / yr dwelling stock retrofit aggregated over EU27+UK.	Minimum 60% renewable electricity generation in EU27+UK as a whole.		
My Action - Subsidy	No fossil fuel growth and fossil fuel phase-out by 2040 in each EU27+UK.	3% / yr dwelling stock retrofit in each EU27+UK.	Minimum 60% renewable electricity generation in each EU27+UK.		Countries with retrofitting costs higher than the EU27 + UK average receive a subsidy that matches the difference between their retrofitting costs and the EU27 + UK average.
Our Action - Subsidy	No fossil fuel growth and fossil fuel phase-out by 2040 in EU27+UK as a whole.	3% / yr dwelling stock retrofit aggregated over EU27+UK.	Minimum 60% renewable electricity generation in EU27+UK as a whole.		

3.1. European level insights

Fig. 1 presents the annual energy input mix into the residential sector, measured in PJ, in our six scenarios. In the short term (i.e. until 2030), our first two scenarios exhibit lower total energy input requirements compared to scenarios that meet climate targets. However, in the long term (i.e. in 2050), scenarios achieving climate control demonstrate lower energy input levels than our first two scenarios. The attainment of climate targets alongside subsidising retrofitting efforts (i.e. in both subsidy scenarios) showcases a lower energy input requirement compared to climate-compliance scenarios without such subsidies, with this contrast becoming more pronounced over the long term. Across all scenarios, direct heat usage is relatively consistent until 2050. At the same time, there is an increase in the utilisation of ambient heat and electricity. Conversely, the reliance on fossil fuels and biomass demonstrates a consistent decline over time. In all scenarios, the phase-out of oil and coal is realised by 2035, whereas the phase-out of natural gas is contingent on achieving climate targets (attained in 2040 for scenarios with a climate constraint). The use of natural gas persists until 2050 in scenarios falling short of climate targets.

Fig. 2 illustrates the projected disaggregation of annual residential energy demand into the distinct energy services modelled in TIMES-Europe: space heating, space cooling, water heating, cooking, and appliances. Our projections indicate a minor increase in total residential energy demand in scenarios without a stringent climate target. Conversely, we observe a decline in energy demand in scenarios aligned with climate targets, with this decline being more pronounced in scenarios that also incorporate retrofitting subsidies. The decline in energy demand is observed in space heating demand, while other residential end-use demands show relatively small increases until 2050.

Fig. 3 depicts the annual reduction in residential energy input relative to the 2020 level (bars), juxtaposed to the 2030 EU energy savings target (line) for the entire energy sector. This illustrates the potential contribution of the residential sector to achieving the energy-saving target outlined by the EED. Scenarios involving full collaboration consistently exhibit higher energy savings in comparison to partial collaboration scenarios. In 2030, in the stringent climate target scenarios, collaboration among countries has a positive effect, resulting in an approximately 11% larger reduction in residential energy input than under the assumption of partial collaboration. This reduction increases to 18% when collaboration is complemented with dwelling retrofitting subsidies. In the short term, up to 2030, both non-climate-compliant scenarios exhibit greater energy savings than scenarios implementing strict climate targets. However, this disparity diminishes in the long term, with energy savings from attained climate control scenarios aligning closely with those in scenarios that lack ambitious climate control measures by around 2040. Also in the long term, in our subsidy scenario variants, significantly higher energy savings are observed compared to scenarios without subsidies under climate control measures.

Fig. 4 illustrates the annual CO_2 emissions from the European residential sector. In all scenarios, there is a consistent decline in annual emissions. This decline is notably more pronounced in scenarios with stringent climate targets. While scenarios with ambitious climate goals

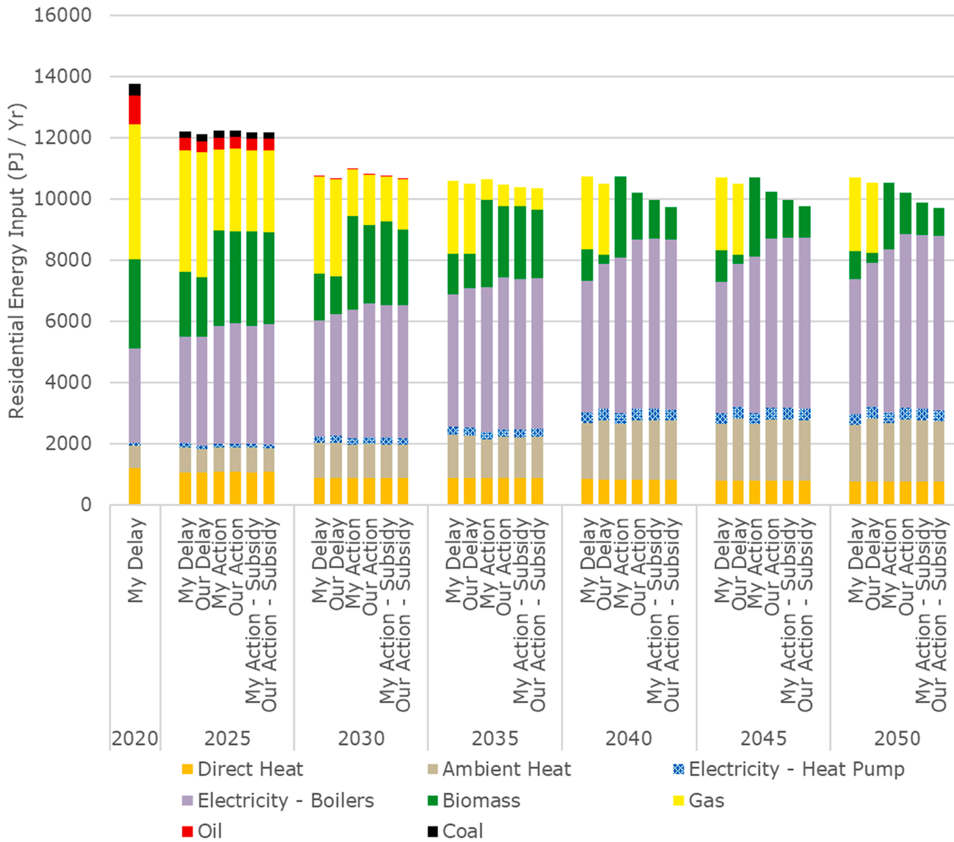

Fig. 1. European residential sector energy input.

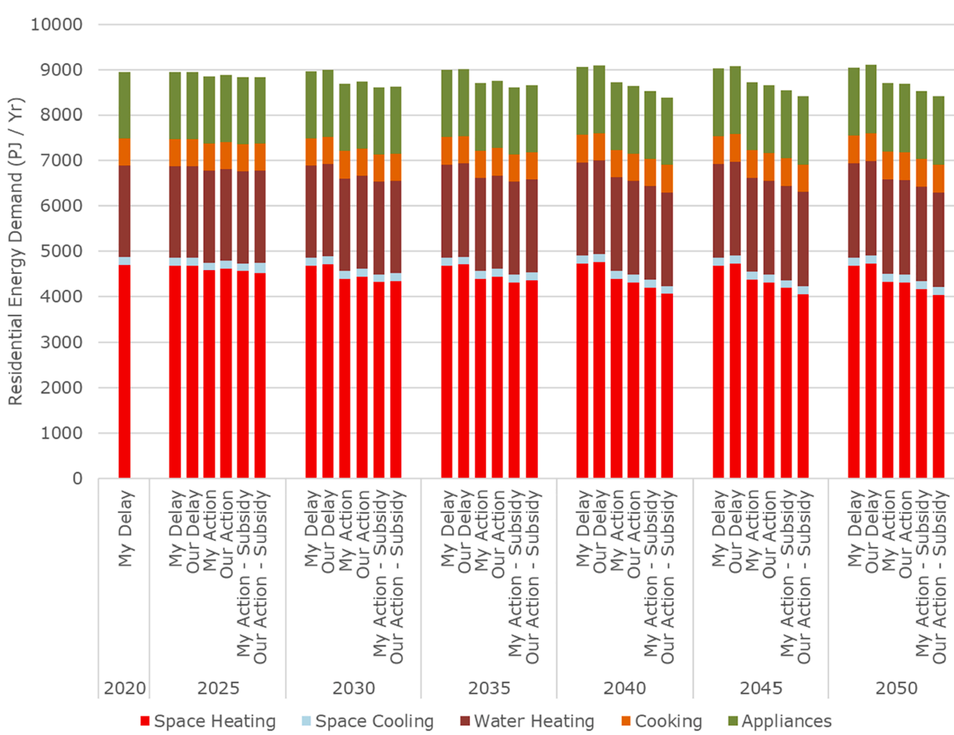

Fig. 2. European residential sector energy demand.

achieve zero emissions by 2040, less stringent climate control measures result in residual emissions persisting in the residential sector until 2050.

The box plots in Fig. 5 visualize the distribution of residential sector energy efficiency across European countries, showcasing the first quartiles (the lower bound of the box), the median (centre line), the third

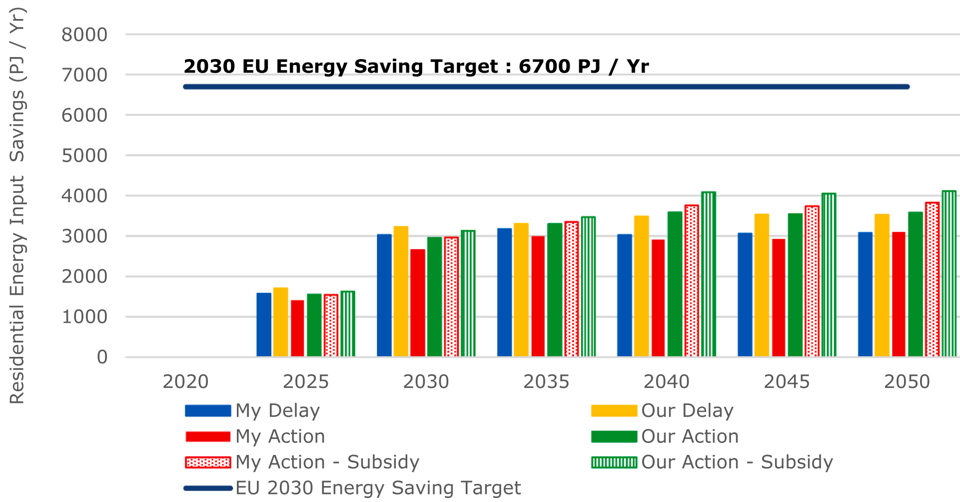

Fig. 3. Residential energy input savings relative to the 2020 level.

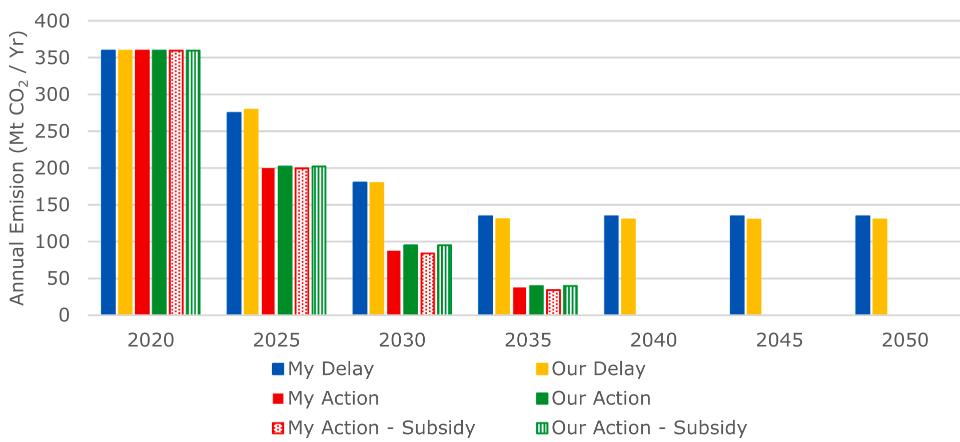

Fig. 4. Annual European household CO_2 emission.

quartiles (the upper bound of the box), the mean (the cross), the outlier boundary i.e. 1.5 times the interquartile range (the whiskers), and any outliers (data points outside the whiskers). A consistent increase in overall energy efficiency can be observed, with comparable averages and ranges in all scenarios. In partial collaboration scenarios, no outliers are observed, whereas, in full collaboration scenarios, we see outliers in the short term (i.e. until 2035). During this period, the energy efficiency profiles of the residential sector are spread more widely in full collaboration scenarios, suggesting significant changes in efficiency profiles for a few countries.

3.2. Country-level insights

The maps in Fig. 6 illustrate the energy input reduction for each member state, expressed as a percentage relative to the 2020 level. East European countries and the Baltics exhibit substantial reductions in energy input across all scenarios. In the scenarios aimed at achieving climate targets (depicted in panels (c) and (d)), countries like the UK, Italy, and Spain exhibit higher reductions in emissions compared to when they fall short of climate targets (illustrated in panels (a) and (b)). This difference is particularly noticeable in scenarios involving full collaboration. By comparing panels (c) and (d) vs. panels (e) and (f), respectively, we can observe that the inclusion of dwelling retrofitting subsidies is effective in stimulating energy input reductions in central European countries (i.e. The Netherlands, Belgium, France, and Germany).

The maps in Fig. 7 show the retrofitting subsidy allocated in each country, cumulated over the entire modelling horizon (2020–2050, and normalized to the total cumulative renovated dwelling stock per country for both subsidy scenario variants. In both cases, the subsidy is primarily allocated to the same set of member states, i.e. countries in central and northern Europe, as well as Romania. In the partial collaboration scenario, however, subsidy levels are generally higher than in the full collaboration scenario.

4. Discussion

Our model projections show a decrease in European residential energy input in all scenarios (see Fig. 1). This projected decline is attributed partially to the improvement in end-use technology efficiency, and partly to the implementation of energy-saving measures (i.e. dwelling renovation to reduce space heating demand), as evidenced by the larger energy input reductions in scenarios that explicitly simulate a retrofitting subsidy. In scenarios achieving climate targets, we project a complete phase-out of fossil fuel consumption in the European residential sector by 2040, in line with the target announced in the EPBD. Biomass becomes the predominant substitute for fossil fuels in scenarios achieving climate control targets, while in scenarios falling short of climate targets, the use of natural gas persists until 2050. This is due to the fact that natural gas has a higher merit order than biomass, that is, the levelized cost of a unit of energy for technologies fuelled with natural gas is lower than that for biomass-based technologies, hence natural

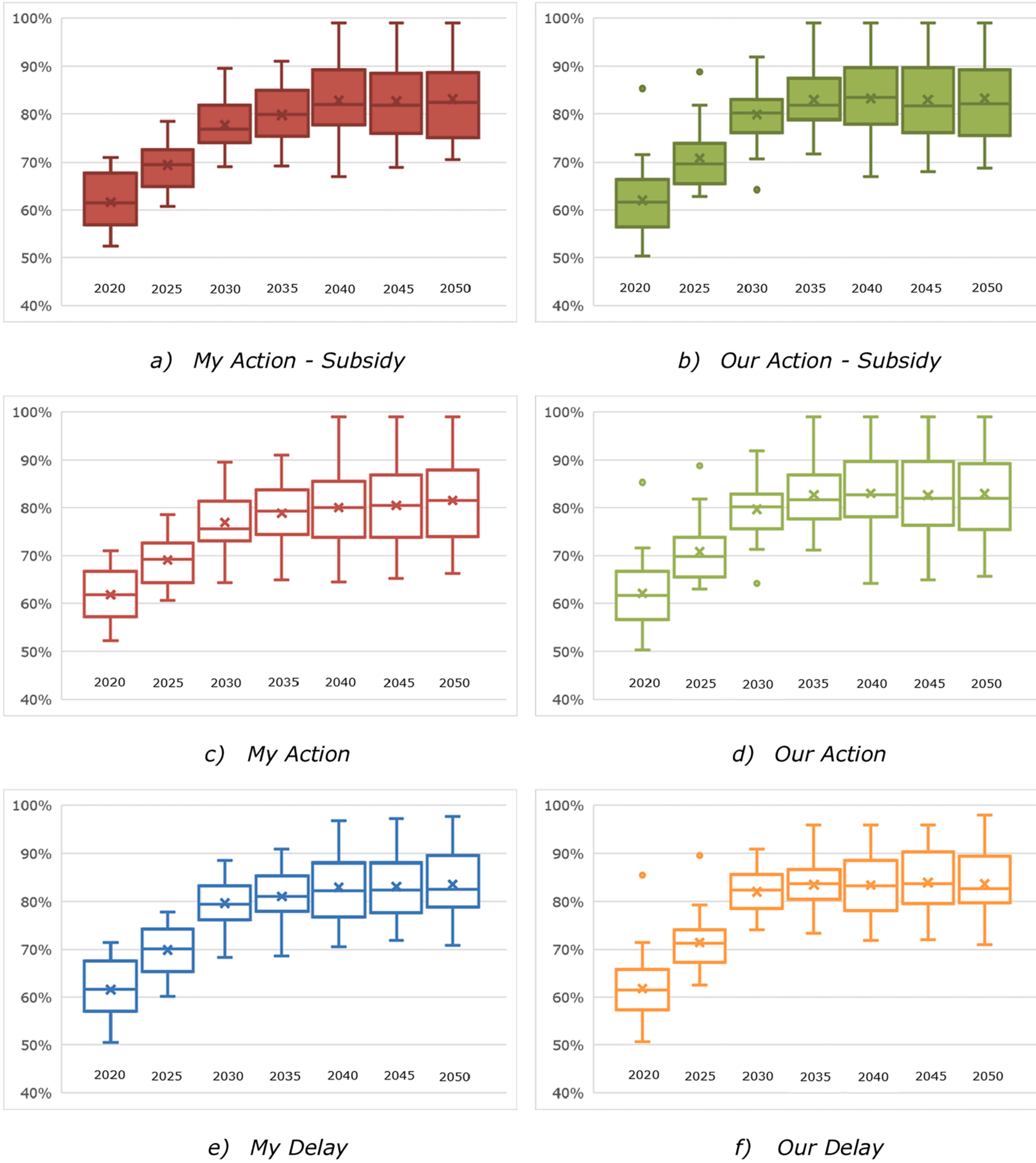

Fig. 5. EU27+UK residential sector energy efficiency.

gas is generally the cost-optimal choice when climate objectives are neglected. Supply of direct heat (e.g. geothermal or solar heat, for instance through district heating) remains consistent in all scenarios throughout the modelling horizon since it is partially driven by a model constraint that specifies that direct heat supply is not allowed to decrease below the 2015 level. This specific condition is intended to stylistically take into account the renewable heating target as announced under the RED framework.

In Fig. 2, we observe two different trajectories for the European household energy demand projection. Under the scenarios achieving the climate target, we see a decreasing trend in energy demand while, conversely, in scenarios falling short of the climate target, we see a slight increase in annual energy demand. Population growth contributes to higher energy demand in the residential sector while retrofitting efforts help reduce space heating demand. The ambitious climate scenarios, which align with the annual dwelling retrofitting rate target announced in the EPBD recast (3%/yr), demonstrate more significant reductions in space heating demand, leading to a decoupling of population growth from residential energy demand. In the delayed climate scenarios, in which a continuation of the current retrofitting rate trend is assumed (of 1%/yr), the results of energy savings are insufficient to decouple energy demand from population growth. Under subsidy scenario variants, in which we artificially lower the retrofitting cost for countries where it is higher than the regional average, we observe even lower energy demand than in scenarios achieving the climate target without subsidies. Independently of climate target attainment, full collaboration scenarios show lower energy demand in the long term (i.e. 2040 and beyond), in comparison to scenarios in which member states operate in isolation. In the former scenarios, the model can achieve a more cost-effective resource allocation, i.e. prioritizing dwelling retrofitting in countries where renovation can be done at relatively low costs while yielding large savings. Nevertheless, we observe outliers in the low-end tail of the distribution of energy efficiency levels in full collaboration scenarios (Fig. 5, panels (b), (d), and (f)) in the short term. This suggests that some countries lag behind in their renovation efforts, compared to the rest of Europe. However, in the long run, post-2030, the distribution shrinks,

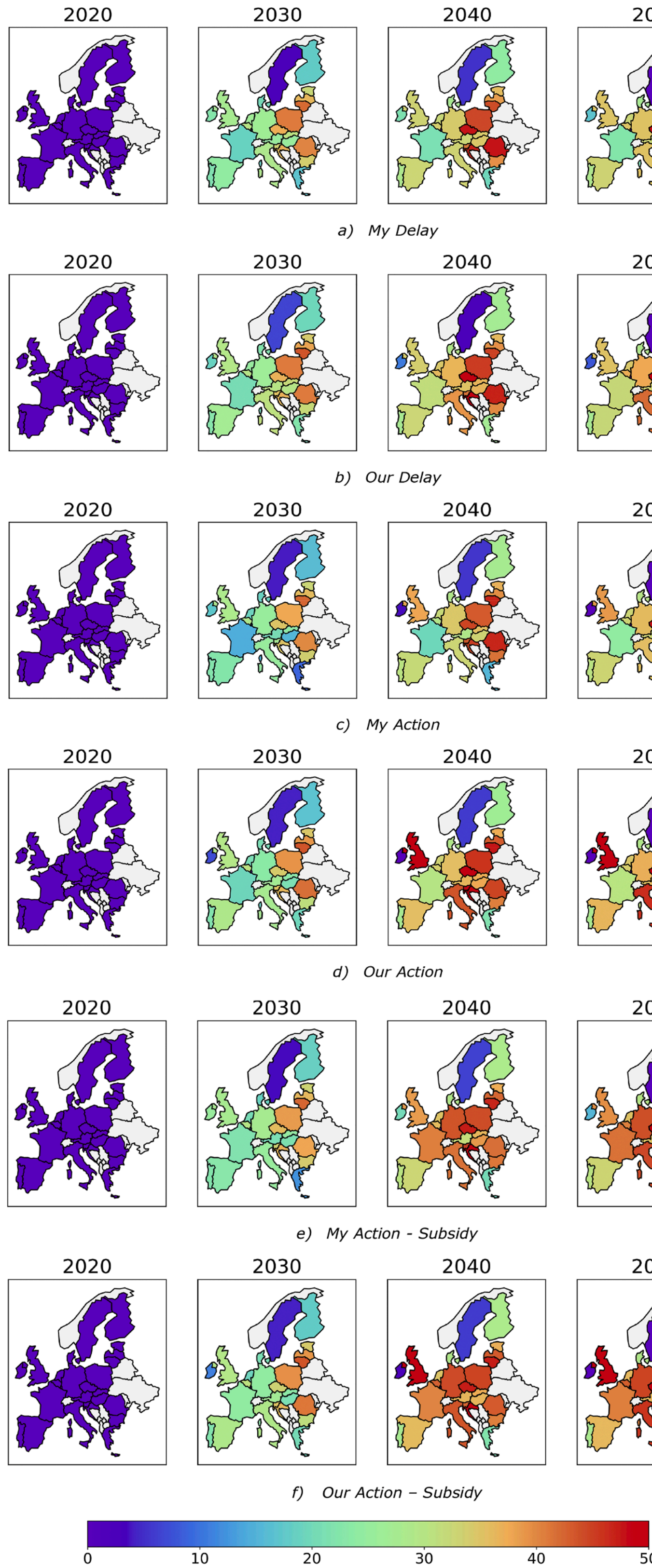

Fig. 6. Residential sector energy input reduction relative to the 2020 level.

with the outliers disappearing, indicating a converging trend in efficiency levels among countries.

Fig. 3 shows that in 2030 (the milestone year of the EU energy reduction target), the delayed climate target scenarios have higher energy savings than the attained climate target scenarios. Although the latter scenarios have a higher yield of energy savings from retrofitting, the use of biomass as a substitute for natural gas results in lower overall residential sector efficiency, i.e. higher losses from biomass conversion

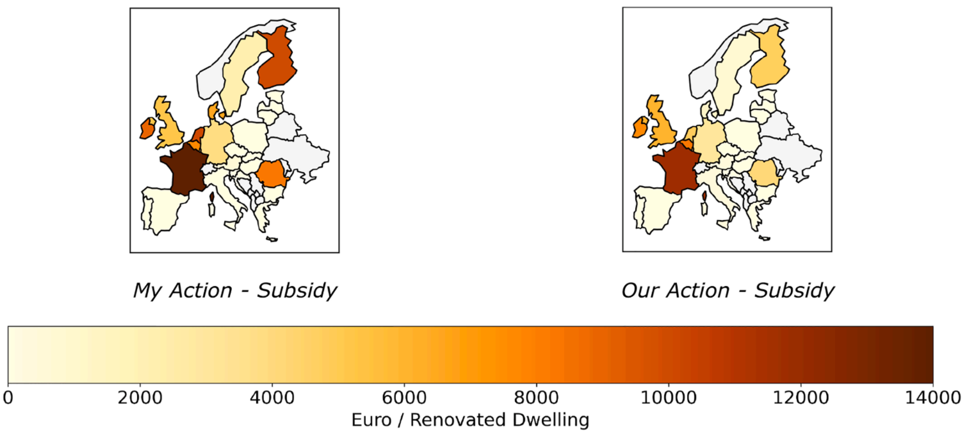

Fig. 7. Cumulative subsidy level normalized with the dwelling stock in each member state.

from energy input to energy demand (see Appendix 2). Conversely, under less stringent climate control, the use of biomass is avoided in exchange for the use of natural gas. As a result, the delayed climate action scenarios yield 8% to 17% more energy savings. On the other hand, as illustrated in Fig. 4, under the fall-short climate target scenarios, we observe CO_2 emission levels twice as high as those in the attained climate target scenarios. Our results provide insight into the contribution of the residential sector to the EU energy efficiency target (see Fig. 3). However, our projections of regional aggregated energy savings are not directly comparable to the EU energy efficiency target due to the inclusion of the UK in our calculations.

In Fig. 6, which illustrates the energy input reduction relative to the 2020 level, we observe that in both delay scenarios, Eastern European countries contribute more significantly to energy savings than the rest of Europe. This is mainly due to efficiency improvements through end-use technology changes, which vary by country according to technology potentials, efficiency, and capacity factors. For instance, direct heat is prominent in Northern Europe, heat pumps are common in Central and Northern Europe, and electric boilers are used primarily in Eastern Europe (see Salim et al., 2024 [12], where we also quantify the amount of energy savings in each country from retrofitting). In the climate-compliant scenarios, along with East European countries, several other countries (e.g. the UK, Italy, and Spain) show more significant reductions in energy input, predominantly driven by retrofitting efforts. In the subsidy scenarios, the number of countries that have significant energy savings increases, as we can see with France, the Netherlands, Belgium, and Germany. Hence, those countries are the ones that receive the highest amount of subsidy per renovated dwelling (see Fig. 7). Under full collaboration assumptions, these countries receive less subsidy per dwelling than in the partial collaboration case due to strategic retrofitting allocation, wherein retrofitting resources are distributed to optimize energy efficiency improvements in the whole of Europe. Not all countries reach significant energy savings, mainly because they already have an efficient fuel mix which leaves little room for improvement. For instance, in the case of Sweden, 90% of the energy input in the base year is already supplied by a combination of direct heat, heat pumps, and direct electricity.

5. Conclusion and outlook

Our study presents insights into possible decarbonization trajectories until 2050 of the European residential sector under a set of scenarios with varying levels of climate ambition, collaboration among European countries, and retrofitting subsidies. We highlight the importance of end-use technology efficiency improvements and energy-saving measures, particularly through retrofitting initiatives, for driving down energy demand in this sector. The substitution dynamics between biomass and natural gas yield differences in fuel mix deployment across scenarios, with implications for overall sectoral efficiency. While natural gas persists in scenarios falling short of climate change control targets, biomass emerges as a substitute in scenarios in which these targets are attained. This reflects a transitory short-term trade-off between pursuing energy efficiency gains and CO_2 emission reductions.

The interplay between population growth and retrofitting efforts shows divergent energy demand projections across scenarios. Ambitious climate targets, coupled with accelerated retrofitting rates, demonstrate the potential for decoupling population growth from energy demand, which underscores the critical importance of imminent and proactive policy interventions. Subsidies and collaboration between countries offer promising pathways for enhancing energy savings. Our analysis reveals a complex interplay between subsidization and collaboration, highlighting regional disparities in energy-saving contributions. These disparities are driven by differences in technological advancement and policy incentives across countries. In particular, East European countries, along with several Central European countries, emerge as frontrunners in energy efficiency gains, with varying degrees of success influenced by factors such as the base-year technology mix and retrofitting costs. Future policies should carefully consider these regional and national differences when designing targets for residential energy consumption, and possible schemes for subsidizing buildings retrofit.

The findings of our study highlight the critical importance of policy coherence, technological efficiency improvements, and regional collaboration to achieve the ambitious climate targets set by the EU. The insights gained from our research can provide a valuable guide for policymakers and stakeholders at both the EU and national levels as they navigate the path toward a sustainable future. At the EU level, our findings may provide valuable insights into the effectiveness and costs of energy efficiency policies, helping policymakers assess impacts and make informed decisions. For national policymakers, the results can assist in tailoring energy efficiency measures to align with both EU-wide targets and national priorities.

Our analysis suggests the need for further exploration in several key areas. First, we recommend conducting more in-depth studies to cover other facets of EU regulation, notably the second and expanded version of the EU Emissions Trading Scheme (ETS 2) and the (partly overlapping) EU Effort Sharing Regulation (ESR). These policies, currently excluded from our study, aim to address CO_2 emissions from various sectors, including European dwellings. Incorporating these policies into future research could provide deeper insights into the interaction between the residential sector and other greenhouse gas-emitting sectors, contributing to pathways that meet the EU's energy efficiency and emission reduction targets. EU climate policies often have cross-sectoral implications; for example, the Energy Efficiency Directive (EED) targets energy savings not only within individual sectors but across the entire energy system. Our study suggests that the energy savings target set by the EED cannot be fully achieved by focusing solely on the European residential sector. This underscores the need for a broader perspective that includes all relevant energy sectors. By analysing the interactions among sectors, policymakers can better understand how to align and coordinate efforts across the entire energy system to meet overall targets.

Second, we emphasize the importance of considering the socio-economic factor and an energy justice approach, for instance with regard to the distribution of dwelling retrofitting subsidies. While this study primarily focused on identifying the least-cost solutions for the EU energy system using the TIMES-Europe linear programming framework, it did not explicitly incorporate considerations of economic welfare and socio-economic factors. The TIMES-Europe model optimizes for cost efficiency rather than equity or justice. Consequently, although the model offers valuable insights into cost-effective strategies, it does not address how these strategies might impact different socio-economic groups or ensure a just transition. Future refinements could include incorporating varying economic conditions of households, socio-economic factors (e.g. behavioural aspects), or even human migration within Europe through sets of scenarios. Such refinements could help align the sector's transformation with the European Green Deal's goal of a *just* transition.

Dedications

S.S.S. dedicates this work to the memory of L.S.C. (1973–2024), whose radiant joy and unyielding resilience throughout her battle with cancer have been a profound source of inspiration. Her unwavering ability to find hope in the face of adversity continually motivates S.S.S. to remain resolute. *Aut viam inveniam aut faciam.*

CRediT authorship contribution statement

Steven S. Salim: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Stefan L. Luxembourg:** Methodology, Conceptualization. **Francesco Dalla Longa:** Writing – review & editing, Visualization, Methodology, Conceptualization. **Bob van der Zwaan:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no competing financial interests or personal relationships that could influence in any way the work reported in this paper.

Acknowledgements

S.S.S., S.L.L., F.D.L., and B.v.d.Z. thank the Ministry of Economic Affairs and Climate Policy of the Netherlands for its financial support of research on the international dimensions of the energy transition. The views expressed in this paper are exclusively those of the authors.

Appendix 1. Retrofitting Cost and Subsidy Level

Retrofitting costs in our study vary by country and are influenced by dwelling type, age, and renovation depth (i.e., shallow, medium, or deep renovation). The assumptions regarding retrofitting costs are detailed in Appendix 1 of Salim et al., 2024 [12], based on cost data from sources [39] and [40], which are normalised using Eurostat construction cost indices [41]. Fig. 8 through Fig. 13 illustrate a few examples of retrofitting costs for all countries, showcasing different dwelling types and construction periods. Subsidies received for renovation efforts in our Subsidy scenarios are determined for each country relative to the regional average, for each unique combination of dwelling type, age, and renovation depth. Only countries for which renovation costs are above the regional average (green bars and red horizontal lines in Figs. 10-15) receive a subsidy, and this is estimated as the difference between the actual costs and the regional average. The full set of cost data is provided as supplementary material. Fig. 9

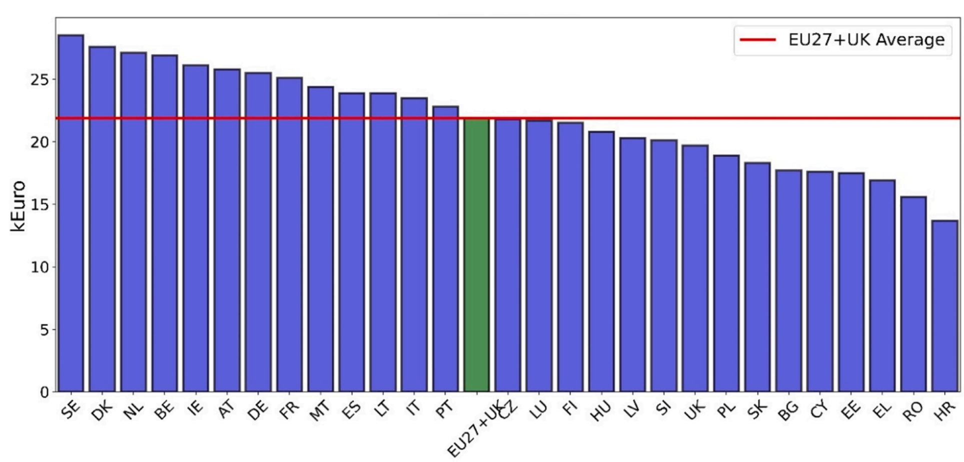

Fig. 8. Deep retrofitting cost per country relative to the EU27+UK average for pre-45 detached dwellings.

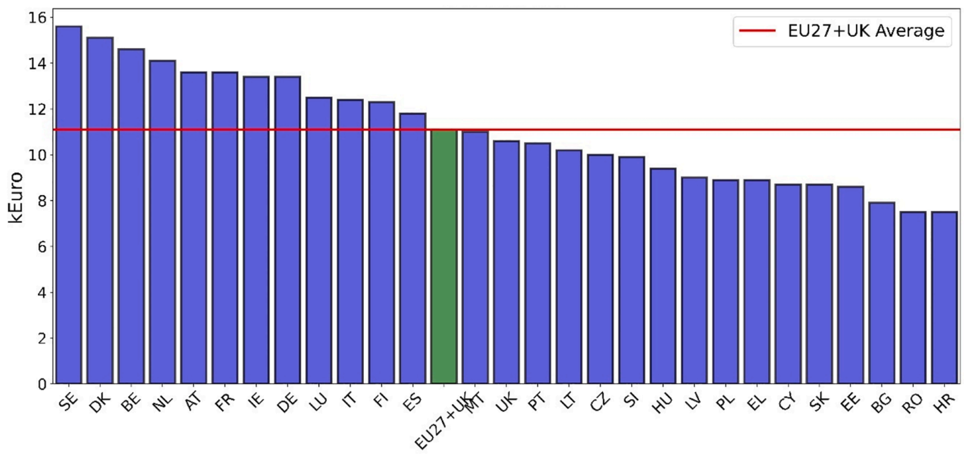

Fig. 9. Medium retrofitting cost per country relative to the EU27+UK average for pre-45 detached dwellings.

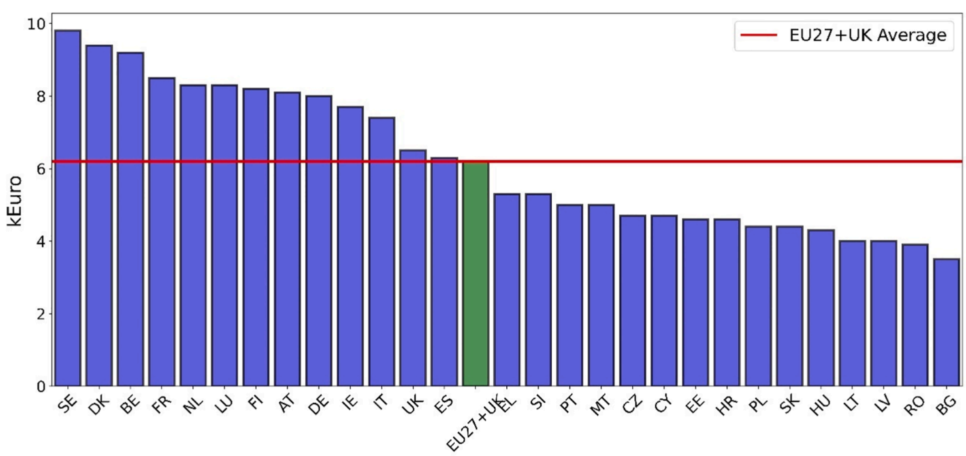

Fig. 10. Shallow retrofitting cost per country relative to the EU27+UK average for pre-45 detached dwellings.

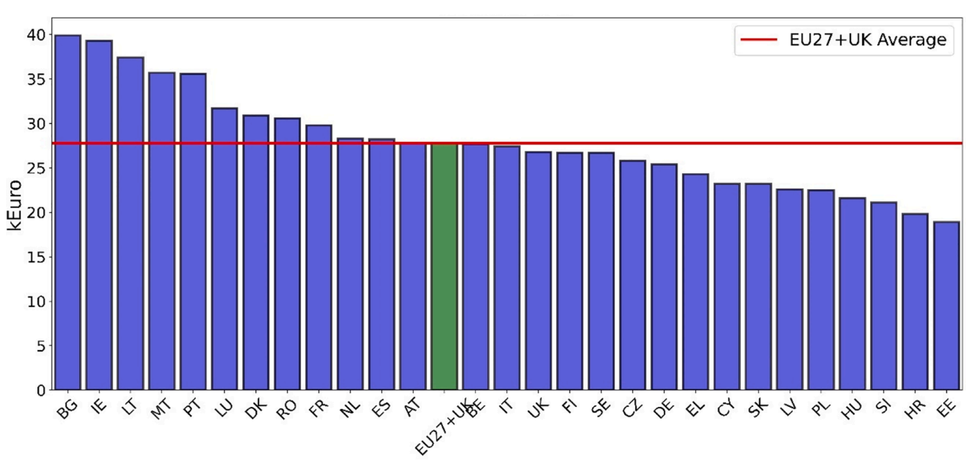

Fig. 11. Deep retrofitting cost per country relative to the EU27+UK average for pre-99 apartment dwellings.

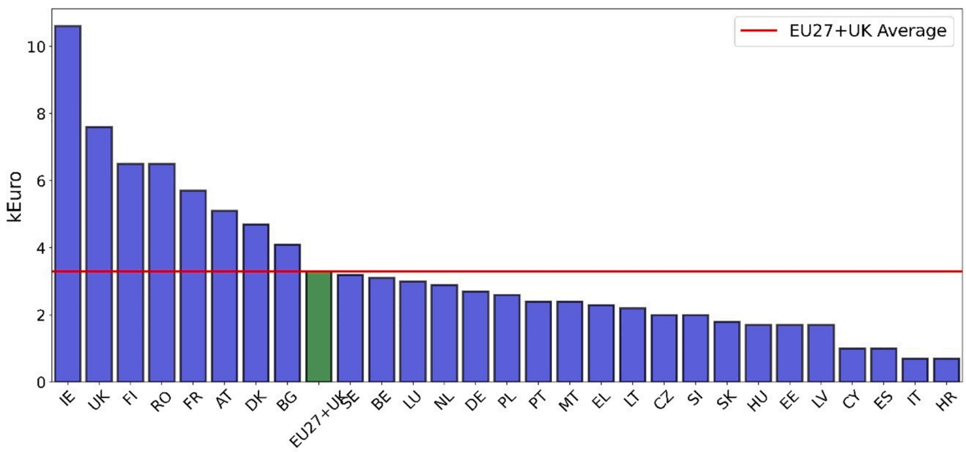

Fig. 12. Medium retrofitting cost per country relative to the EU27+UK average for pre-99 apartment dwellings.

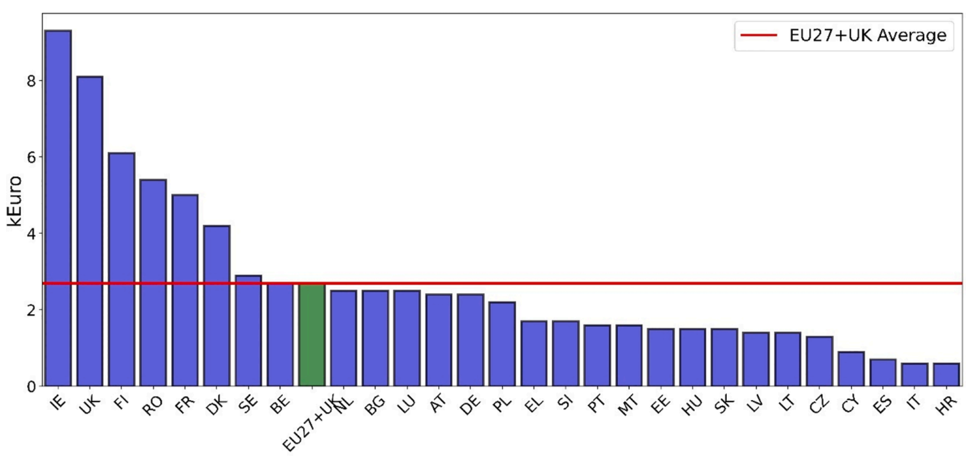

Fig. 13. Shallow retrofitting cost per country relative to the EU27+UK average for pre-99 apartment dwellings.

Appendix 2. Energy Flows in 2030 and 2050

Fig. 14 illustrates the energy flows in the European residential sector in 2030 across all scenarios, while Fig. 15 depicts the corresponding energy flows in 2050.

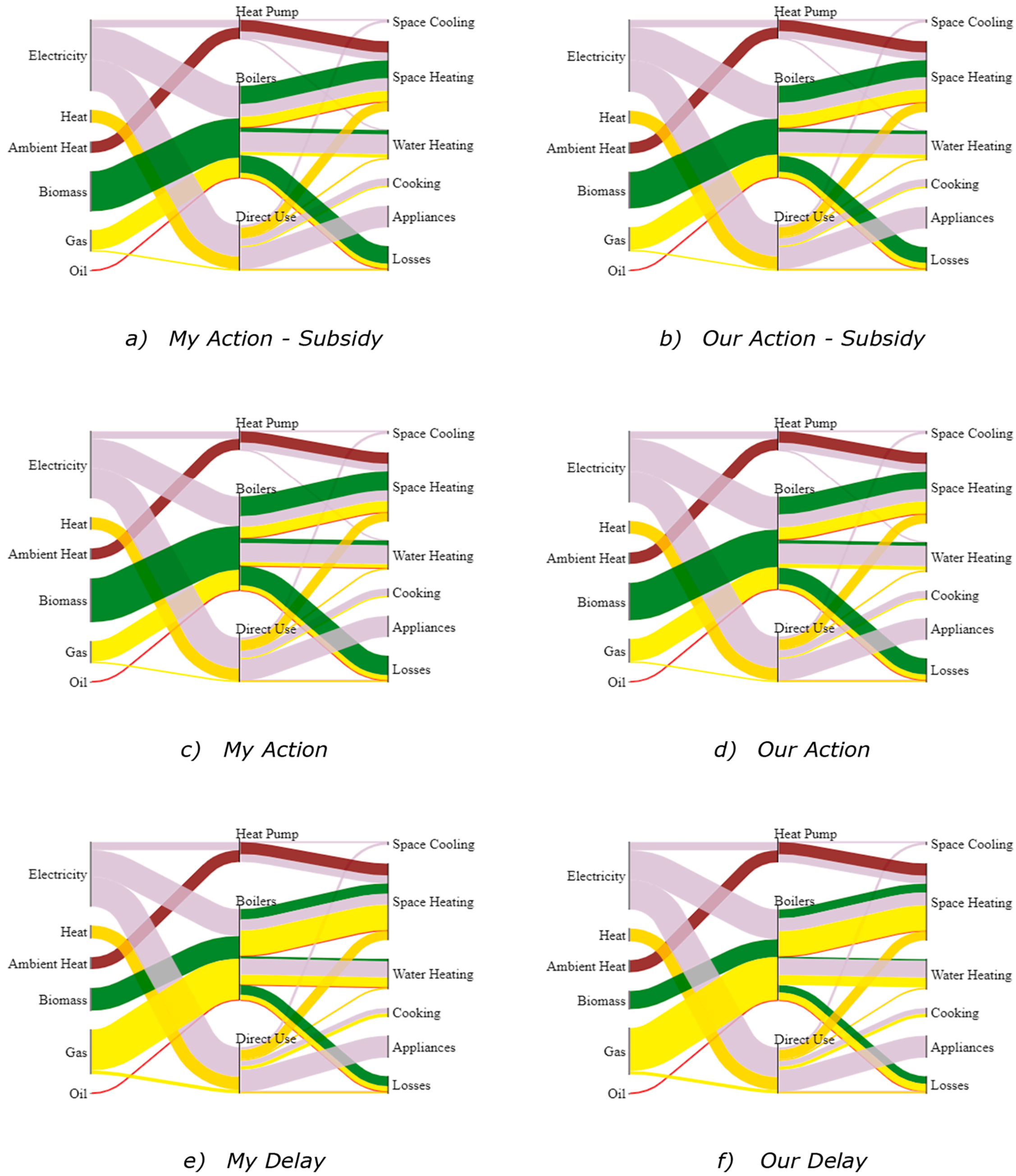

Fig. 14. EU27+UK residential sector energy flow in 2030.

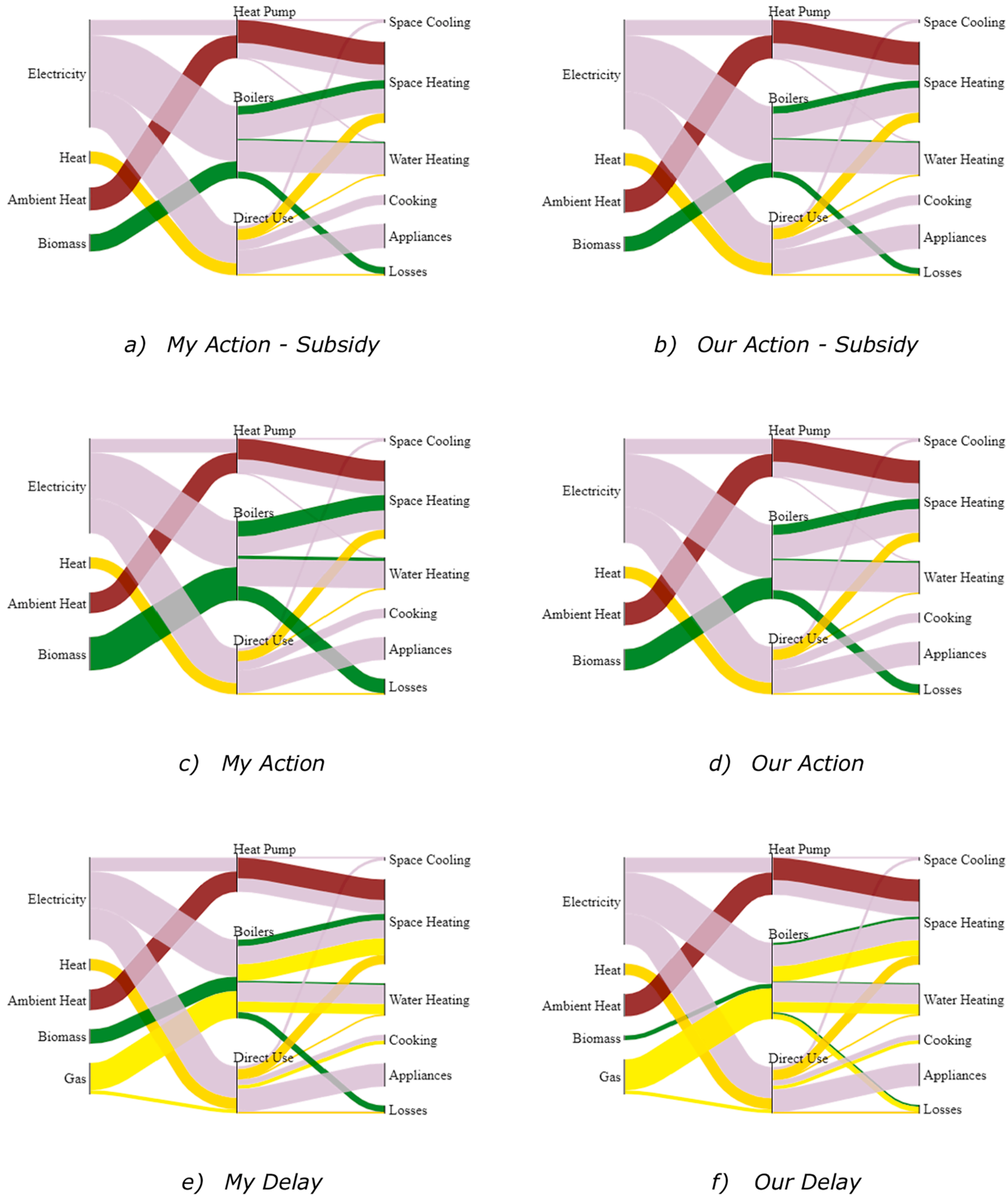

Fig. 15. EU27+UK residential sector energy flows in 2050.

Data availability

Data will be made available on request.

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