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Pathways for Pan-European Energy System Decarbonization: The Effect of Emission Policies on Target Alignment

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Abstract

Decarbonization of the energy system is a major challenge for today's energy system to combat climate change. This challenge is addressed in the EU through different political strategies and plans such as the European Green Deal, Fit-for-55, and REPowerEU, which set specific emission reduction goals for 2030 and 2050. Different mechanisms are in place to achieve these goals, such as the system-wide ETS and the country-level National Energy and Climate Plans. However, there is a difference in the enforcement level between European countries, despite their connection to the same integrated energy system. Hence, there might be discrepancies between the effectiveness of the EU system-level target and the achievements of national goals and plans.

To understand and address these discrepancies, we utilize the open-source, sector-coupled energy system optimization model Balmorel to analyze the impact of different decarbonization methods in a fully interconnected, pan-European energy system. In three scenarios, we consider 1) the use of only a system-level carbon budget in line with Fit-for-55 and the European Green Deal, 2) the application of a carbon budget at the country level, and 3) the use of a carbon tax instead of a budget on all production of electricity, heat, and hydrogen. The novelty of this paper lies in the first comparison of these three decarbonization mechanisms and their impact on alignment with policy targets.

We demonstrate that the pan-European energy system can reach decarbonization targets across all scenarios. Still, diving from the system perspective into the country level, challenges appear, causing nations to overshoot their allocated budgets. Country-level emission targets are more effective with little cost increase compared to the only system-level target scenario but also cause cross-border effects of fossil fuel based energy production. The carbon tax scenario is the most effective at decarbonizing but comes at up to 27 % higher costs in intermediary years, requiring more early investments.

Keywords: Energy policy, Energy Transition Pathway, Decarbonization Strategies, Balmorel, Energy System Modeling

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1. Introduction

Global warming is a well-documented global challenge establishing the global goal of reducing our emissions of greenhouse gases (GHG) to combat climate change [1]. In the EU, several large strategies have been born and enforced through the European Climate Law [2]. The European Green Deal sets climate neutrality goals for 2050 [3], and through Fit for 55 and REPowerEU [4, 5], ambitious intermediary goals are set for 2030 to reach a 55% reduction in GHG emissions compared to 1990. The two main tools utilized by the EU to achieve the decarbonization targets are the EU Emission Trading System (ETS) [6] and Effort Sharing Regulation (ESR) [7] (as well as the EU ETS 2 launching in 2027 [8]).

The policy landscape expands if we consider pan-European non-EU countries. The United Kingdom and Switzerland have created an ETS of their own for the same sectors [9, 10], while Norway integrates into the EU ETS, but not the ESR system. Countries have also created national energy and climate plans (NECPS) [11], including the non-EU Balkan countries. While these countries are not under the Climate Law, hopes of achieving membership status [12] and integration into the interconnected energy system [13] make them important considerations. The circumstances beg the question of how pan-European decarbonization is affected by these kinds of emission policies, what the interactions are between countries, and what the consequent impact is on alignment with policy targets such as Fit-for-55.

The topic of decarbonization pathways in Europe is an area that has already been widely studied. Lotze et al. [14] investigate European decarbonization pathways in a pan-European energy system, focusing on the aggregate system perspective and assuming a decreasing system-level carbon budget. They reach a system heavily relying on variable renewable energy (VRE) from solar and wind, as well as electrified hydrogen and heating from electrolysis and heat pumps. Rodrigues et al. [15] also investigate European decarbonization pathways at the aggregate level, but in the context of suggesting interim 2040 targets beyond Fit-for-55 and focusing on EU-27. They also reach a high degree of electrification from VRE expansion enabled by electrolysis, heat pumps, and electric vehicles (EVs). Both Tsiropoulos et al. and Capros et al. [16, 17] review multiple

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scenarios and models, comparing multiple studies with varying degrees of decarbonization. These studies generally show similar findings about a future energy system with large amounts of VRE. In Tsiropoulos et al. [16], the focus is to investigate the similarities and differences between decarbonization scenarios in 2030 and 2050 from other reports, while Capros et al. [17] focus on the differences between various models, assessing the robustness of policies from a technology-driven perspective, such as the use of nuclear and carbon capture and storage (CCS). These studies apply a variety of models and decarbonization drivers (budget/target or price). A shortcoming of these studies is that the country-level representation is limited.

Other studies have investigated European decarbonization, taking into account national perspectives. Hainsch et al. [18] address this topic by adding country-level carbon budgets with different emission distribution scenarios for power, heat, and transport, compared to a system budget. They find that, for a 2 °C temperature target, all investigated scenarios lead to low additional costs. Additionally, Germany and several Eastern European countries are identified as requiring a fast fossil phase-out. Still, a shortcoming of this study is the low temporal resolution (16 yearly time slices) and geographical resolution (17 nodes for Europe). The national perspective is broadened in Pedersen et al. [19] by investigating 30.000 near-optimal configurations for national emission targets, focusing on the power sector and differences in resulting abatement costs. They find that, across the range of possible CO2 reduction targets, a 5% cost increase over system-optimal is almost inevitable.

The use of a carbon tax to put a price on emissions, currently implemented by the various ETSs in Europe, has also been a focus of studies. Zhu et al. [20] advocate for a carbon tax as the necessary tool for decarbonization instead of relying on a carbon budget, and that renewable targets are not enough to achieve low emissions. Papadis et al. and Zhang et al. [21, 22], they also both consider the tool to be an effective mechanism in achieving decarbonization, but that it comes at a higher cost for the energy system. The use of a carbon tax as an effective tool for decarbonizing is a sentiment shared by Penasco et al. and Meckling et al. [23, 24]. They study outcomes and tradeoffs of decarbonization policy instruments and the political challenges of different policies. They mention important considerations of distributional effects and the fact that the price must be paid now while benefits lie in the future. Pedersen et al. [19] also mention the potential increase in social and economic inequality between countries. Aune et al. [25] also argue that they are redundant. Including both the ETS and non-ETS sectors, they consider the high targets already imposed on renewables and energy efficiency to be sufficient, disputing the findings of Zhu et al.

To the best of these authors' knowledge, no previous study has compared the utilization of system-level emission targets, nation-level targets, and carbon taxation in a pan-European energy system and studied their impact at the country level for meeting 2030 targets.

In this study, we investigate the decarbonization of the pan-European energy system under both a system budget, national budgets, and carbon taxes. We generate decarbonization pathways with a brownfield approach utilizing the Balmorel open-source energy system model [26] and study how the different scenarios impact the total system production pathways, as well as how decarbonization performance for each country is impacted. We highlight the year 2030 as an important year for current emission policies (e.g., Fit-for-55 and NECPs) and assess performances for that year in particular. Recognizing that the distribution of the carbon budget and the size of the carbon tax are uncertain parameters, we perform sensitivities on both to assess the robustness of the results. The goal of this study is to provide a more comprehensive perspective on how carbon budgets and taxes impact pan-European decarbonization and assess mismatches that lead to potential differences in some locations.

2. Method

2.1. Balmorel

We utilize the open-source and sector-coupled energy system model Balmorel [26] to study European decarbonization. Balmorel has been built through many years of research and applied to a large variety of topics. Kountouris et al. [27] investigates hydrogen infrastructure in a unified Europe, while Gea-Bermudez et al. [28] investigate the potential future role of sector coupling. In conjunction with other models, Lester et al. and Bramstoft et al. [29, 30] combine Balmorel with the OptiFlow network model to study alternative fuels and renewable gas & liquids.

2.1.1. General description

Balmorel is a bottom-up partial equilibrium energy system optimization with the objective of minimizing the total energy system costs. The model extensively covers the power and district heating sectors. To fully capture the sector coupling synergies of the future European system, the model has been extensively developed and expanded to incorporate further heating in the housing sector, heating in the industrial sector, electrified transportation, and hydrogen penetration for both industry and transport. The model covers the full pan-European energy system at a one-node per country level for all mentioned sectors.

Balmorel is a technology-rich energy system model in which diverse energy sources are turned into energy vectors that can be used to meet demand in various sectors. Simultaneously, the model optimizes both investments and operational dispatching. Furthermore, the model quantifies the optimal cross-border network expansion and trading for electricity and hydrogen energy vectors between countries.

The temporal resolution of Balmorel includes seasons (i.e., 52) and terms (i.e., 168) within a year, representing weeks and hours, allowing for simulating both seasonal and hourly behavior. Due to tractability and computational efficiency considerations, fewer time steps and seasons are attentively selected. Each year is optimized sequentially, with technology investments carrying over from year to year, giving the option of modeling pathways. In this study, we model every five years (myopic approach) using 2050 as the final horizon.

2.1.2. *Objective function*

The objective of Balmorel is to minimize total system costs, following the generalized objective function in Equation (1).

$$\min \sum_{y} DF_y \, (c_y^{INV} + c_y^{FOM} + c_y^{VOM} + c_y^{TAX}) \tag{1}$$

The costs are a combination of investment costs (c_y^{INV}) for generating technologies, storage, and transmission, operation costs from fuel use and maintenance (c_y^{FOM}, c_y^{VOM}), and potential taxes applied to emissions (c_y^{TAX}), summed over all years and discounted. While taxes are not costs from a socioeconomic perspective, we include the cost of carbon as a way of internalizing the externalities resulting from GHG emissions.

2.1.3. *Energy balances*

The production of electricity, heat, and hydrogen are balanced by Equations (2) to (4).

$$\begin{aligned} g^E_{y,r,s,t} &= d^E_{y,r,s,t} \\ &+ \sum_{r'} \left(x^E_{y,r,r',s,t} - x^E_{y,r',r,s,t} \cdot (1 - X^{E,LOSS}_{r,r'}) \right) \forall y, r, s, t \end{aligned} \tag{2}$$

$$\begin{aligned} g^H_{y,a,s,t} &= d^H_{y,a,s,t} \\ &+ \sum_{a'} \left(x^H_{y,a,a',s,t} - x^H_{y,a',a,s,t} \cdot (1 - X^{H,LOSS}_{a,a'}) \right) \forall y, a, s, t \end{aligned} \tag{3}$$

$$\begin{aligned} g^{H2}_{y,r,s,t} &= d^{H2}_{y,r,s,t} \\ &+ \sum_{r'} \left(x^{H2}_{y,r,r',s,t} - x^{H2}_{y,r',r,s,t} \cdot (1 - X^{H2,LOSS}_{r,r'}) \right) \forall y, r, s, t \end{aligned} \tag{4}$$

All equations follow the same general structure where generation (g) equals demand (d), accounting for transmission (x) and transmission losses (X^{LOSS}). For electricity and hydrogen (Equations (2) and (4)), transmission refers to cables and pipelines between regions of countries, allowing neighboring countries to cover and balance each other's demands through trade. '*Transmission*' of heat also exists to a smaller extent within a country, where, e.g., heat from an industrial area connected to district heating can contribute to covering residential heat demand in the district heating system.

2.1.4. *Emission constraints*

Emission target policies are implemented through emission constraints (Equations (5) and (6)). Depending on whether the limit is applied nationally or at the system level, these constraints place a limit on emissions from all fuel consumption in either the aggregate system or nationally.

$$\sum_{c,g} f_{y,c,g} \cdot E_g \leq LIM_y^{SYS} \; \forall y \tag{5}$$

$$\sum_{g} f_{y,c,g} \cdot E_g \leq LIM_{y,c} \; \forall y, c \tag{6}$$

Fuel consumption ($f_{c,g}$) from the generation of technologies burning non-sustainable fuels and the corresponding emission factor (E_g) is restricted to being below a limit (LIM). Equation (5) represents the system-level constraint where the emissions and limits are summed for all countries, and Equation (6) the nation-level constraint where the limit applies for each country.

3. Data & assumptions

3.1. *Carbon budget & tax*

The core objective of the European Green Deal and Fit-for-55 is to decarbonize the European Union and reach climate goals. By extension, to ensure alignment with policies, the carbon budget applied is a main parameter in this study. The majority of the budget comes from the EU, UK, and Swiss ETS [6, 9, 10], slightly reduced to account for aviation and some industrial demand not included in the model, such as non-process heat emissions. Of the ESR sectors, the only sector included is the building sector, as future electrified transportation falls under the ETS. Historically, this share of the non-ETS has been 25%, so only this share of the ESR budgets is considered [7, 31]. For national allocation, the distribution to the ESR has been applied. Lastly, for countries not included in these budgets, GDP-adjusted values have been added from other countries. Table 1 shows the aggregate CO2 budget considered, with a linear decrease between the listed years.

Table 1: Carbon budget considered in MtCO2, linearly decreasing between the stated years.

(MtCO2)	2021	2030	2050
ETS (EU, UK, & Swiss)	1 543	1 163	-
ESR, buildings	557	449	-
Additional GDP adjusted	288	269	-
Total	2 388	1 880	-

Complementary to the carbon budget, another core decarbonization mechanism is using a carbon tax to provide market-based incentives. The level of the ETS price in the future is uncertain, so as a proxy, we consider the carbon price from the World Energy Outlook 2022 (WEO) [32] Net Zero Emissions (NZE) scenario. The carbon tax is presented in Table 2 where 2030, 2040, and 2050 represent WEO2022 values, and 2021 represents the average ETS price of that year. A linear change is assumed between stated years.

Table 2: Carbon price in EUR/tCO2.

(EUR/tCO2)	2021	2030	2040	2050
Carbon price	48.2	108.6	159.0	193.9

The uncertainty connected to the carbon budget national distribution and level of carbon tax motivates reflection on the robustness of the results. To address this, a sensitivity is conducted in Section 5.5.

Further details on the makeup of the carbon budget and tax can be found in Appendix C.1, including the national-level allocation of the budget.

3.2. *Energy demands*

A driving model parameter is the exogenously defined energy demands for electricity, heat, and hydrogen applied in the model to the balancing equation (Equations (2) to (4)). The demand for electricity consists of a conventional demand that is constant for all years and an increasing demand for e-mobility. Additional demand from electrified heating and electrolysis may arise endogenously. The demand for heat consists of constant residential and commercial heating, split between district heating and non-district heating-connected users, and industrial demand for space and process heating. Demand for hydrogen is assumed for both heavy transport and industrial applications. This demand increases greatly towards 2050, displacing some industrial heat demands. The aggregate demands are displayed in Table 3, while the disaggregated demands can be found in Appendix B (See Tables B.6 to B.8).

Table 3: Exogenous energy demands

(TWh)	2020	2030	2040	2050
Electricity	3 370	3 606	3 880	4 299
Heat	6 261	6 125	5 811	5 613
Hydrogen	33	366	1 142	1 713

Information on data and assumptions not mentioned here can be found either in the appendix for modeling work done in relation to this study or in Kountouris et al. [27] and Gea-Bermúdez et al. [28]. New modeling work includes heat savings as an investment option and new projected demand for EVs.

4. Scenarios

The scenarios are designed to provide insight into the impact of different decarbonization mechanisms. The first scenario, labeled the '*system*', applies only a system-level budget, utilizing Equation (5) to constrain emissions. The second scenario, labeled '*national*', splits the budget from the system scenario to apply nationally, utilizing Equation (6). Lastly, the third scenario, labeled '*carbon tax*', takes out any limit on emissions and instead applies a carbon tax to the objective function (Equation (1)) based on the WEO NZE scenario. Table 4 shows an overview of the scenarios.

Table 4: The three scenarios considered in the study for different implementation methods of decarbonization mechanisms.

Name	Description
system cap	A carbon budget is implemented at an aggregate system level, allowing for optimal allocation of emissions by the model.
national cap	The carbon budget implemented in scenario 1 is implemented at national level. The ETS allowances are allocated similarly to the ESR budget distribution.
carbon tax	Instead of the carbon budget, this scenario uses a carbon tax to simulate the price currently paid in the ETS sectors.

5. Results & discussion

To assess the impacts and mechanisms of the decarbonization scenarios, we investigate the aggregate system production pathways before diving into the country-level perspective.

5.1. Extensive renewable expansion & fossil phase-out

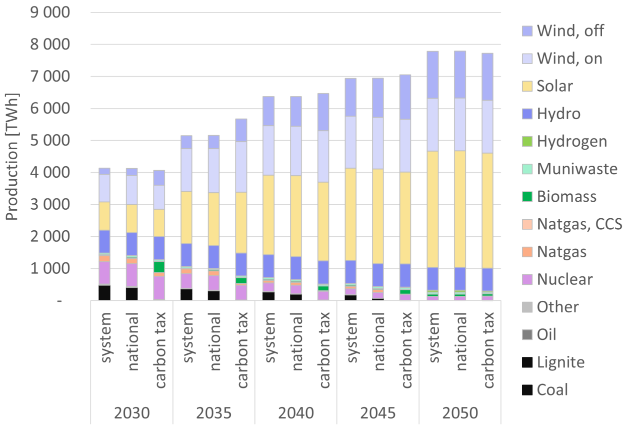
The general transition towards a decarbonized energy system is shown in Figure 1 for electricity, heat, and hydrogen. The overarching trend is the transition towards a power sector reliant on wind & solar, an electrified heating sector dominated by heat pumps (ambient heat and partly electricity), and a large amount of electrolysis capacity for hydrogen production. All three scenarios end up in near-identical energy-system configurations with a final power production of around 7 700 to 7 800 TWh. Solar PV and wind (onshore & offshore) become the dominant sources of electricity (Figure 1a), producing 86-87 % across the scenarios in 2050.

In the intermediary years, similarities remain at the aggregate level between the system and national scenarios for renewable expansion. Larger differences appear in the carbon tax scenario, where there is an increase in production from biomass. This increase aligns with a similar increase in biomass-based heating, caused by higher investment in CHP. This increased investment is also evident in heat production (Figure 1b), where the use of biomass is much higher than in the system and national scenarios, as well as a smaller degree of electrification. Investment in heat savings via renovations also provides a significant contribution. Investments reach a peak in 2030, saving 850-860 TWh, corresponding to 22-23 % of heat demand from district heating and non-district-heating connected users, regardless of the decarbonization strategy.

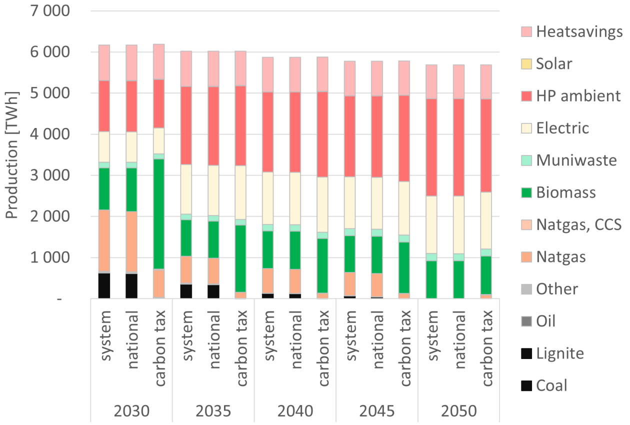
In the initial years until 2030, hydrogen production is predominantly fossil-based, making up a majority of the production either as grey hydrogen in the system and national scenarios or blue hydrogen in the carbon tax scenario. By 2040, production will be fully electrified, with a small amount of green hydrogen imports from Africa and Ukraine, peaking in 2045. The potential of wind and solar is presented in Figure A.7.

The expansion of renewable production displaces the existing fossil energy production from coal, lignite, and natural gas. Generally, the trend shows increased effectiveness in reducing the use of fossil fuels from the system to the national to the carbon tax scenario, although this decarbonization rate is much quicker using the carbon tax. In this scenario, instead of a gradual decrease, the results show a near-complete phase-out of coal & lignite in 2030, displaced by biomass CHP.

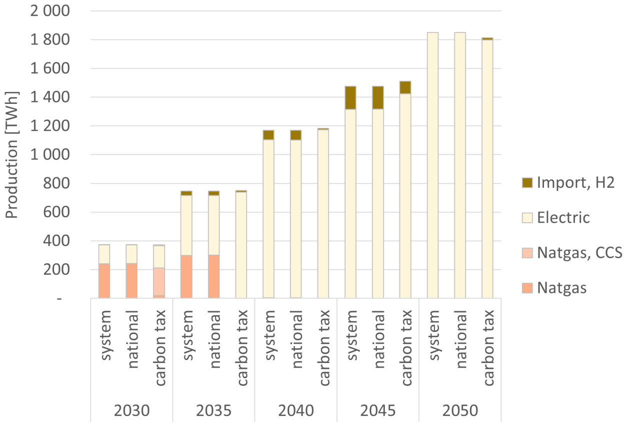
The share of fossil fuels in the energy mix is much larger in the heating sector (Figure 1b), across both district heating, residential, and industry. Industry in particular is hard to abate, as process heating relies heavily on natural gas consumption. As a result, even in 2050, when the carbon price is at its peak in the carbon tax scenario, some level of natural gas consumption remains.



(a) Electricity production



(b) Heat production



(c) Hydrogen production

Figure 1: Yearly production pathways for electricity, heat, and hydrogen towards 2050 across scenarios.

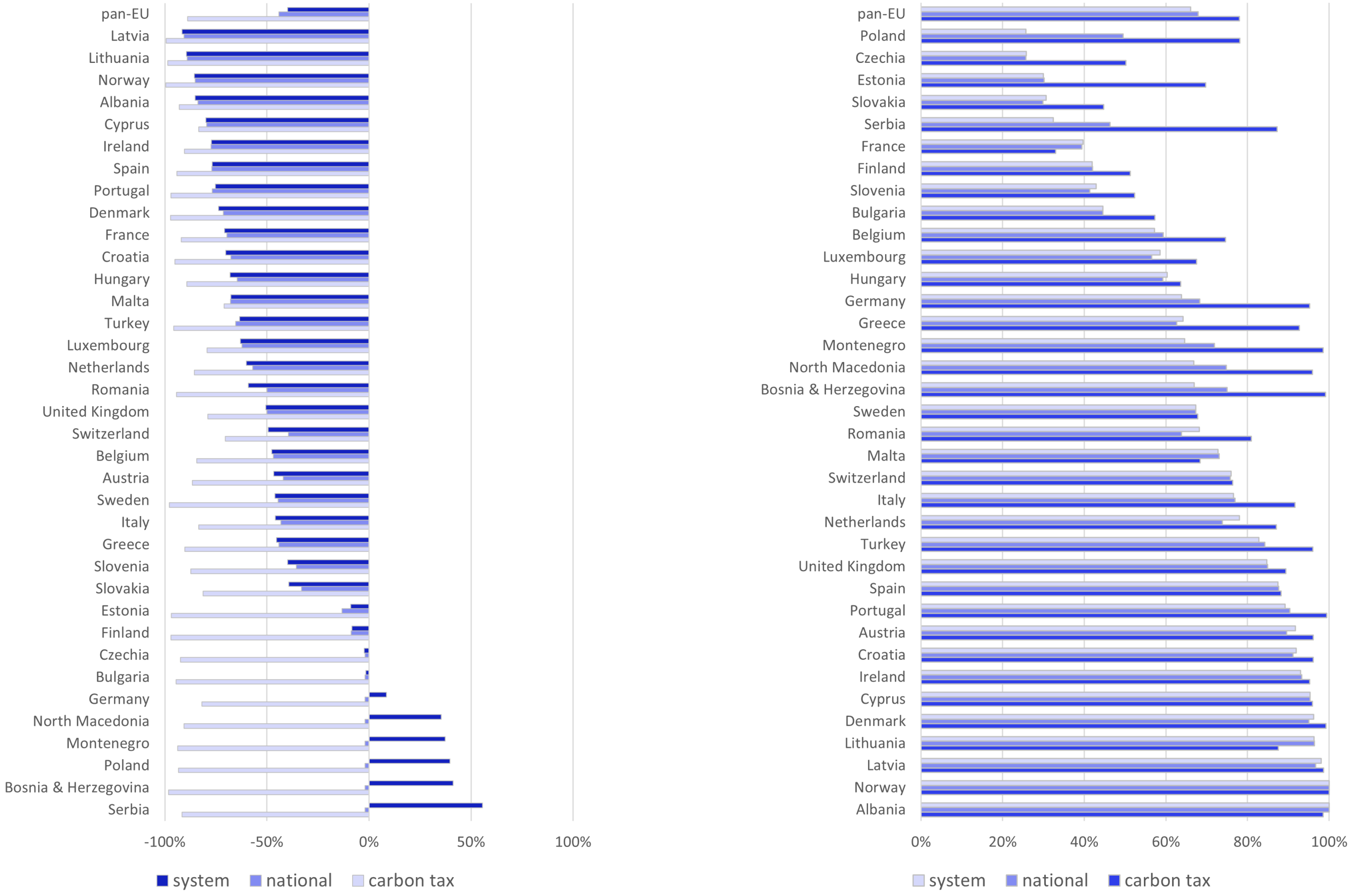
5.2. *National target mismatch*

Reducing emissions and increasing the share of renewable energy in our consumption are essential and interlinked policy targets, especially in the current years leading up to 2030 and the Fit-for-55 and REPowerEU targets. Figure 2 illustrates the performance of each country on these indicators. Figure 2a shows the alignment of each country to the national emission budget in each scenario, corresponding to the allocated budget. It is important to keep in mind here that comparison to the national allocation depends on how that allocation is made. The analysis in Section 5.5 is done to reflect on this. Figure 2b shows the renewable share of electricity production from each country.

Figure 2a shows that the total emissions from the pan-European energy system fall well below the allocated budget across all scenarios. The country-level implementation of the budget in the national scenario leads to slightly lower emissions than the system-level budget in the system scenario, undercutting by 8 %. The results also show that, given the allocation assumptions in the system scenario, some countries fall short of 2030 targets under the relaxed constraint, allowing for free emission allocation. In absolute numbers, Poland and Germany show the greatest target overshoot, but several non-EU West Balkan countries such as Serbia, Bosnia & Herzegovina, and Montenegro also show significant relative mismatches under these assumptions. The country-level budget implementation brings the national emissions in line with targets, but while the emissions difference from all countries with a mismatch amounts to 91.7 MtCO2, the difference in system-wide emissions only amounts to 79.7 MtCO2. This indicates an emission displacement effect amounting to 11.9 MtCO2 across borders taking place, or 13 % of emissions from the reduced emissions from countries with a mismatch. In the case of the West Balkan countries, this leads to increased emissions in almost all neighboring countries, most notably Romania, which increased its emissions by 22 % from a larger consumption of coal and electricity exports.

In the carbon tax scenario, the rate of decarbonization occurs much more rapidly. All countries emit well below their allocated budget, indicating great effectiveness at incentivizing decarbonization, something that is also highlighted by Peñasco et al. and Meckling et al. [23, 24]. A potential barrier to this path, however, is cost, as was also highlighted by Papadis et al. and Zhang et al. [21, 22]. This we will look into in a later section.

Figure 2b shows the renewable share in electricity production. It is estimated in EU working papers that an overall share of 69 % of renewables in electricity production is needed [33] to align with REPowerEU. The system and national scenarios barely fall short of this target (66 & 68 %), while the target is fully met in the carbon tax scenario (78 %). The general pattern is similar to what was highlighted based on emission performance. Underperforming countries under the assumptions, such as Poland, Germany, Serbia, Bosnia & Herzegovina, and Montenegro, all increase their renewable shares by 5–23 percentage points in the national scenario, leading to slightly reduced shares in neighboring countries such as the Netherlands, Romania, Greece, and Hungary. Additionally, some of the countries with low shares of renewables, such as Slovakia, Czechia, and France, have large shares of nuclear in their electricity mix, which is thus not affecting their emissions. Again,



(a) National alignment compares to each country's budget.

(b) National renewable share in electricity production.

Figure 2: Alignment of decarbonization- and renewable targets for modeled countries in 2030.

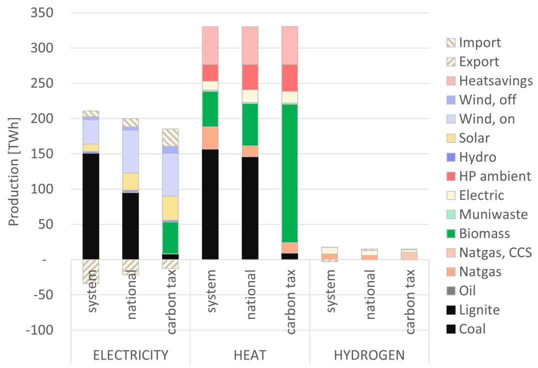
5.3. *National impacts*

To highlight the mechanisms discussed in the previous section inder scenario assumptions, we dive into a selection of countries. Figures 3a to 3c shows a highlight of the energy system mix of Poland, Serbia, and Romania in 2030. The profiles show the observed trend of increased decarbonization effectiveness across the three scenarios and the dynamics between the countries.

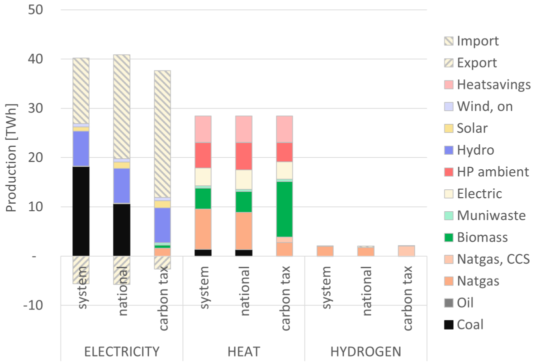
For Poland (Figure 3a), this is seen through a near doubling of electricity production from solar and wind compared to the system scenario and increased biomass usage in the carbon tax scenario. At the same time, less electricity with high carbon intensity is exported, and electricity imports increase.

In Serbia (Figure 3b), a significant decrease in consumption of coal is observed while greatly ramping up imports, utilizing the interconnection potential to surrounding countries. We also see new natural gas, both with and without CCS in the carbon tax scenario, as well as decreased electrification.

(a) Poland



(b) Serbia



(c) Romania

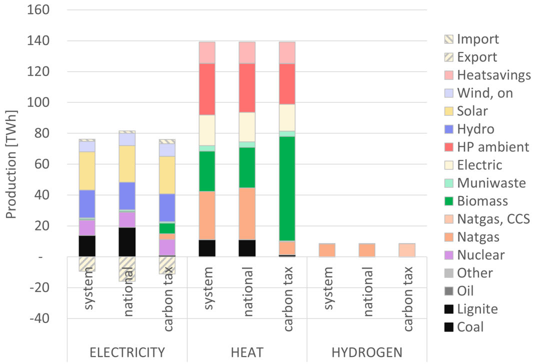


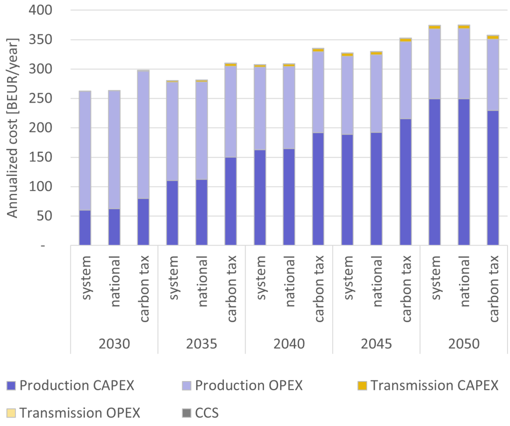
Figure 3: The production profiles of Poland, Serbia, & Romania in 2030 show the increasing effectiveness of the three scenarios to decarbonize.

In Romania (Figure 3c), we observe the emission displacement dynamic, where in the national scenario, coal consumption increases by 37 % and exports increase by 68 %. In heat and hydrogen production, we see smaller differences between the system and national scenarios, while in the carbon tax scenario, biomass and blue hydrogen substitute fossil production.

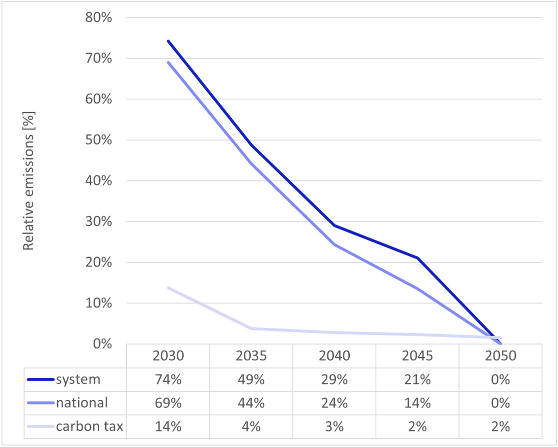
5.4. *Cost of implementation*

Significant investments in renewable technologies are needed to decarbonize the pan-European energy system. The aggregate system costs across the scenarios (shown in Figure 4a), show a transition from a cost structure dominated by operational expenditures (including fuel costs) to capital expenditures from the increased electrification and VRE penetration. We observe only a minor difference between the system and national scenarios, while the carbon tax scenario leads to increased costs in the early years but lower in 2050.

The low cost increase of the country-level budget implementation in the national scenario over the system case speaks positively of this mechanism to reduce cross-border effects. In the carbon tax scenario, the intermediary years reveal higher costs from capacity investments and the use of more expensive fuels until the very last year. From 2040 on, there is an observed switch where VRE sources overtake, leading to capital expenditures overtaking operational expenditures. While effective at reaching rapid decarbonization, the carbon tax shows a 13 % cost increase in 2030, not including the price paid for the carbon tax. This leaves room for considering distributional effects and how to utilize the carbon tax income, as significant GDP differences exist among the pan-EU countries.



(a) Aggregate annualized system cost.



	2030	2035	2040	2045	2050
system	74%	49%	29%	21%	0%
national	69%	44%	24%	14%	0%
carbon tax	14%	4%	3%	2%	2%

(b) Relative emission reduction.

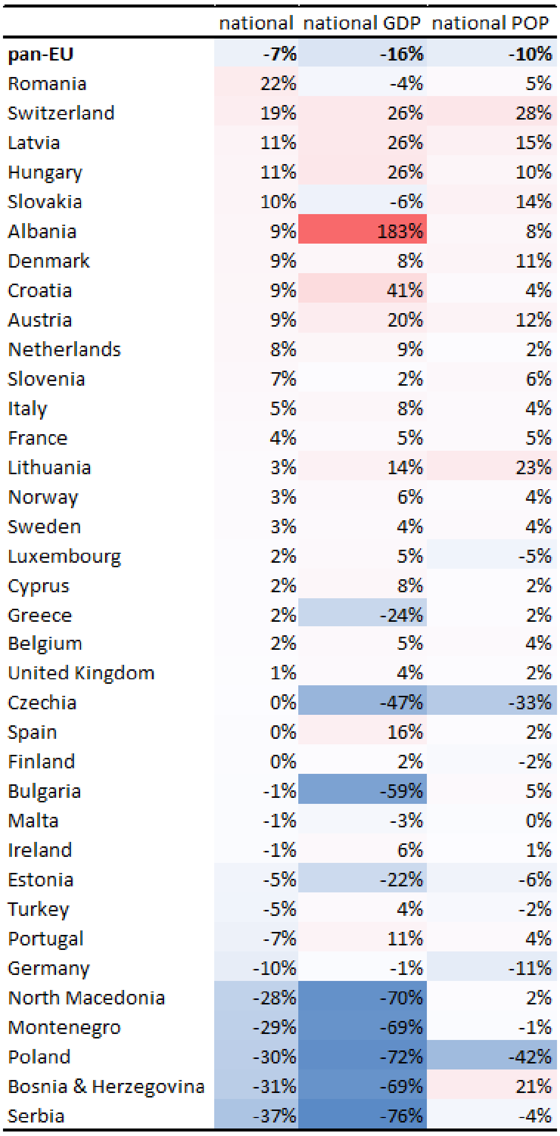
Figure 4: Cost and decarbonization across the years for all scenarios.

The system-wide relative emissions (as compared to system scenario, 2025) shown in Figure 4b also show how the change in emissions follows the investments, how the system and national scenarios follow closely, and how the carbon tax provides an aggressive early incentivization. The carbon tax effectiveness mostly flatlines after 2035, leaving room for some remaining emissions despite the still-increasing tax.

5.5. *Sensitivity*

Two essential parameters of this study of particular uncertainty are 1) the distribution of the carbon budget and 2) the level of the carbon price.

Firstly, emulating scenarios in Hainsch et al. and Pedersen et al. [18, 19], we distribute the national carbon budgets solely

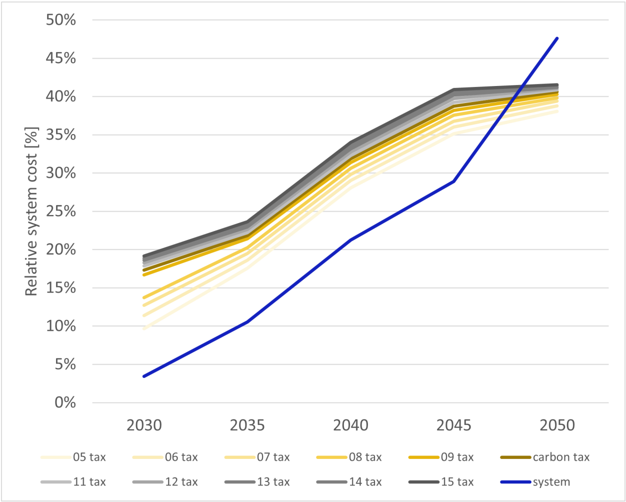


	national	national GDP	national POP
pan-EU	**-7%**	**-16%**	**-10%**
Romania	22%	-4%	5%
Switzerland	19%	26%	28%
Latvia	11%	26%	15%
Hungary	11%	26%	10%
Slovakia	10%	-6%	14%
Albania	9%	183%	8%
Denmark	9%	8%	11%
Croatia	9%	41%	4%
Austria	9%	20%	12%
Netherlands	8%	9%	2%
Slovenia	7%	2%	6%
Italy	5%	8%	4%
France	4%	5%	5%
Lithuania	3%	14%	23%
Norway	3%	6%	4%
Sweden	3%	4%	4%
Luxembourg	2%	5%	-5%
Cyprus	2%	8%	2%
Greece	2%	-24%	2%
Belgium	2%	5%	4%
United Kingdom	1%	4%	2%
Czechia	0%	-47%	-33%
Spain	0%	16%	2%
Finland	0%	2%	-2%
Bulgaria	-1%	-59%	5%
Malta	-1%	-3%	0%
Ireland	-1%	6%	1%
Estonia	-5%	-22%	-6%
Turkey	-5%	4%	-2%
Portugal	-7%	11%	4%
Germany	-10%	-1%	-11%
North Macedonia	-28%	-70%	2%
Montenegro	-29%	-69%	-1%
Poland	-30%	-72%	-42%
Bosnia & Herzegovina	-31%	-69%	21%
Serbia	-37%	-76%	-4%

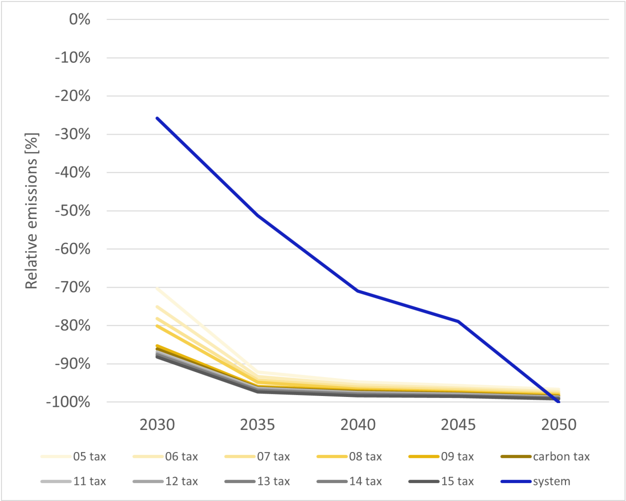
Figure 5: National relative emission difference to system scenario across different carbon budget distributions in 2030.

by GDP (national GDP) and population (national POP), instead of the existing ESR distribution. In Figure 5 we see the percentage difference in emissions from each country compared to the system scenario in 2030, according to the different distributions. Table C.12 shows the national budget allocation in 2021 and 2030 for each country and the population and GDP used. The choice of budget allocation impacts the overall emission reduction, showing between -7 to -16 % as compared to the system scenario, but all lead to an overall emission reduction. The choice of budget impacts the emission displacement significantly. In the case of a GDP-based allowance distribution, there is an even stronger restriction on many Balkan countries and Poland. This is indicated by the increased emissions from neighboring countries such as Croatia and Albania. Distributing based on population is more relaxed for the Balkan countries, showing smaller differences from the system scenario.

Secondly, to investigate the robustness of the carbon tax, we vary the carbon tax by +/- 50 % in 10 % increments as compared to the level presented in Table 2. Figure 6 shows the relative difference in system costs and emissions compared to the system scenario level in 2025.



(a) Change in system cost as compared to the system scenario 2025.



(b) Change in emissions as compared to the system scenario 2025.

Figure 6: Carbon tax sensitivity. The Carbon tax is altered by a factor varying from 0.5 to 1.5.

The total system costs (Figure 6a) exclude the carbon tax itself. The results reveal the same trend as discussed in Section 5.4, where system costs are higher initially from the increased new investments and end in a more affordable state in 2050. This indicates robustness in the effect of using a carbon tax, and while the difference between tax levels is significant in the early years, they converge and reduce spread in 2050.

This is also seen through system-level emissions (Figure 6b). The difference in initial investments causes a spread in emission levels, but already in 2035, the different scenarios converge at a more than 90 % relative emission reduction.

6. Conclusion and Policy Implications

Achieving the policy targets in the European Green Deal, Fit-for-55, and RepowerEU, for a decarbonized Europe is a feasible achievement in the pan-European energy system. Through investment in renewable technologies like solar and wind, together with interconnections between countries fostering trade, it is possible to achieve a decarbonized energy system in 2050 and also to achieve 2030 targets. The electricity sector can enable sustainable heat and hydrogen production, which, together with added biomass consumption, can aid in decarbonizing the hard-to-abate industry and heat-saving renovations to decrease the needed capacity investments. At the aggregate system level, there is only a minimal difference in the geographical allocation of the carbon budget, both for production, emissions, and system costs.

In the current policy horizon towards 2030, the choice of carbon budget implementation methods can impact individual countries' ability to meet targets. While the overall system can meet the allocated budget, some countries, including Germany, Poland, and several non-EU West Balkan countries, reveal a mismatch with decarbonization targets. These mismatches are generally caused by large shares of coal and lignite in energy production. Implementing emission restrictions at the national level results in more investments in renewable production and higher trade in the energy profiles of these countries, while phasing out coal and lignite faster. Still, enforcing decarbonization at the national level can result in increased fossil use and exports from neighboring countries, reducing new investments in cleaner technologies. The choice of budget distribution has a significant impact on the observed effect of the achieved decarbonization. We observe that the same effect of emission displacement can be seen, but that the burden shifts as well as the aggregate GHG emission savings. These results are in line with findings from Pedersen et al. [19].

The use of a carbon tax has been shown to be a very effective way of achieving fast decarbonization with much lower emission levels as well as high renewable shares. It comes at a greater cost to replace production capacity with renewable alternatives, which could be a burden to countries with more infrastructure in need of replacement. Still, even lower levels of carbon taxes show great effectiveness at incentivizing decarbonization. Even a 50 % reduction in the carbon tax showed similar emission levels and system costs in the long term, though not reaching a fully decarbonized energy system due to the high marginal costs of the last bits of CO2 abatement.

We show that while the use of a national carbon budget over a system carbon budget leads to similar outcomes at the aggregate system level, it is important to ensure national alignment with emission targets and can be done without incurring significantly higher costs. Still, emission displacement can occur, showing the importance of ensuring access to new renewable investments and facilitating cross-border energy trade. Agreeing upon a carbon tax would accelerate energy system decarbonization, but at a higher initial price, making considerations of distributional effects important, such as the allocation of investments from the carbon tax income. This method leads to a cheaper, final energy system but fails to achieve full decarbonization at the considered levels of the tax.

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Credit Author Statement

Competing interests

The authors declare no competing interests

Additional information

Supplementary information: Supplementary material document is provided along with the main article.

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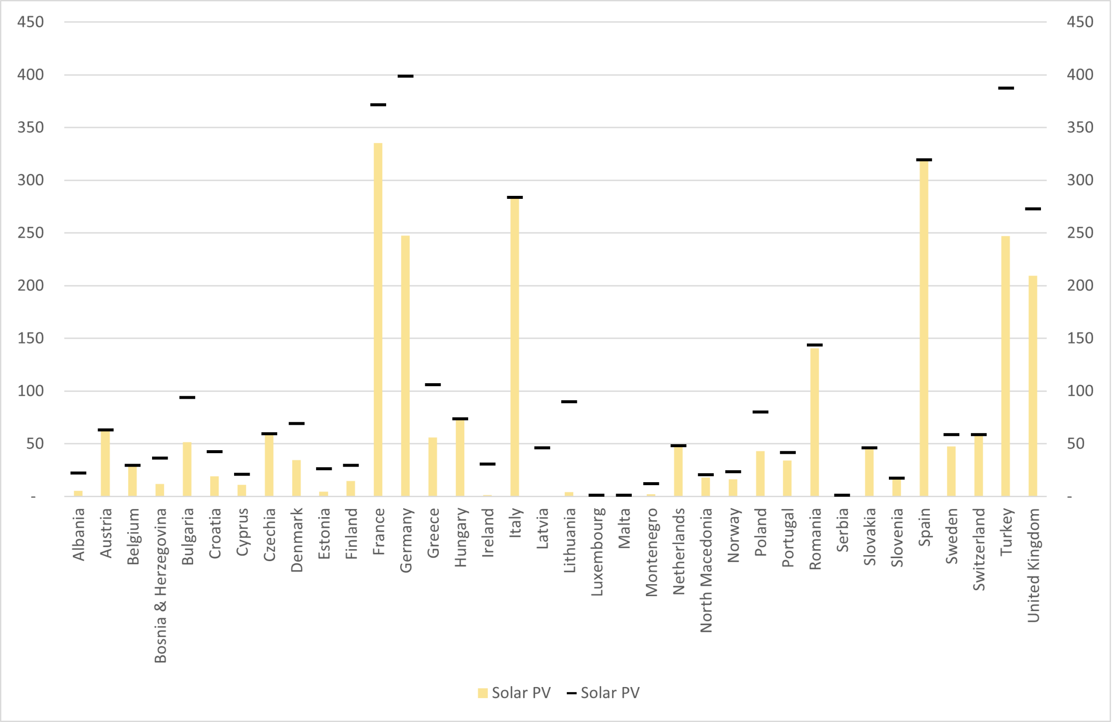
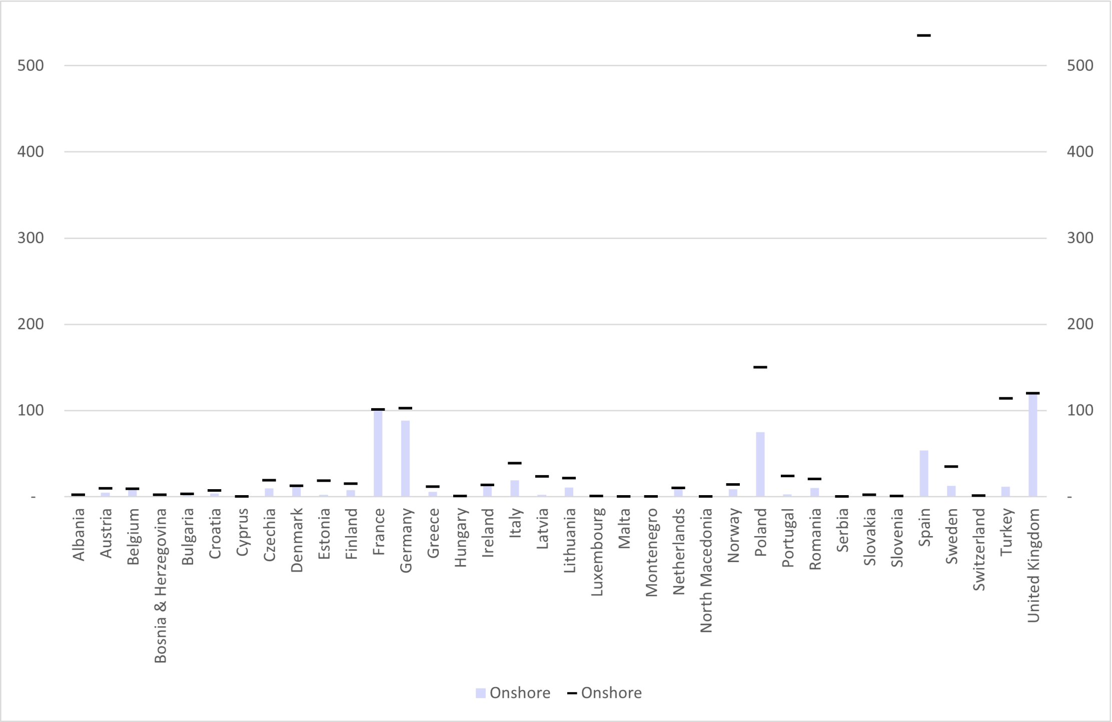
Appendix A. Extended results

(a) Solar PV



(b) Onshore wind



(c) Offshore wind

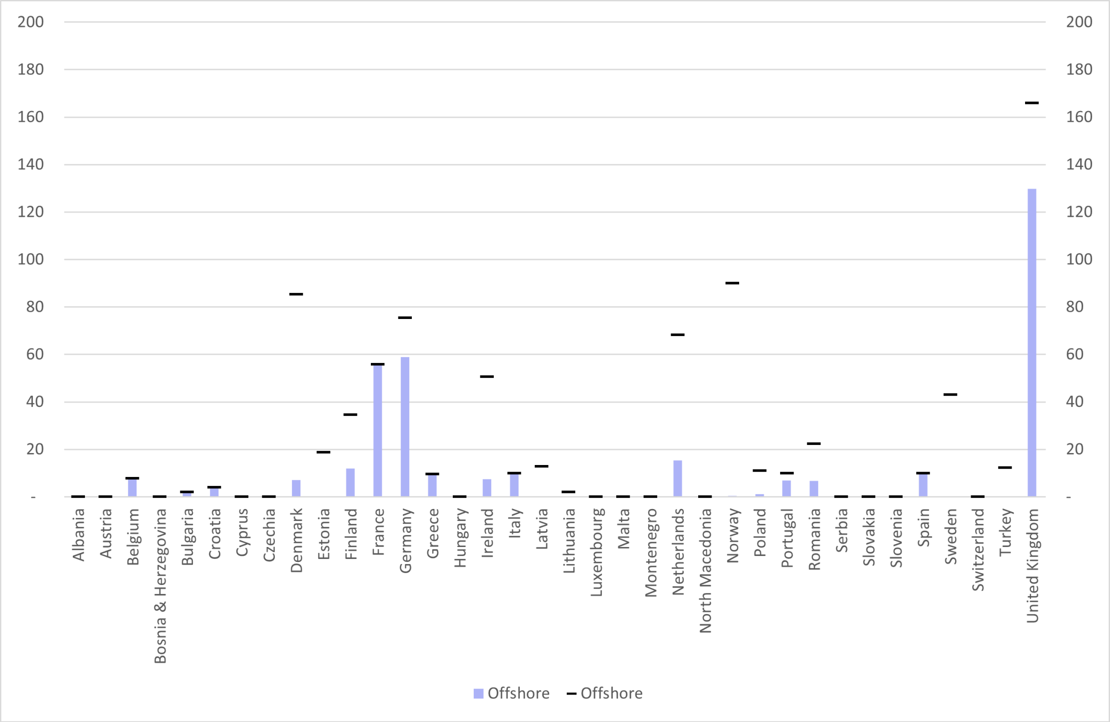


Figure A.7: Renewable potential utilization

Appendix B. Model input

The Balmorel model contains a large amount of data on the European energy system describing power, district heating, hydrogen, and more. This section describes the data and assumptions part of the methodology, laying the model foundation for the study.

Appendix B.1. Electric vehicles

In 2015, non-ETS transportation (excluding aviation and shipping) made up 35% of ESR CO2 emissions, a total of 888 MtCO2. From this sector, commercial transportation of goods and passenger cars make up 90% of the total final energy consumption. To address this source of emissions, this study considers the gradual shift from internal combustion engine (ICE) vehicles to electric vehicles (EV), shifting the burden of emission reduction towards the ETS sector and allowing for higher penetration of cheap, variable renewable energy (VRE) in the energy mix.

The method for projecting future demand for EVs stems from the energy consumption and stock of passenger cars in 2015, combined with driving efficiency [34, 35, 36, 37]. The following formula describes the calculation:

$$E_{EV} = E_{ICE} \cdot \frac{\eta_{EV}}{\eta_{ICE}} \tag{B.1}$$

$$\eta_{ICE} = \frac{E_{ICE}}{dd \cdot n_{car}} \tag{B.2}$$

Where E_{EV} is the projected electricity demand from EVs, E_{ICE} is the current demand from ICEs, η_{EV} is the driving efficiency of EVs, 0.2 kWh/km, and η_{ICE} is the driving efficiency of ICEs. The driving efficiency of ICEs is calculated from the passenger car demand in 2015, the average yearly driving distance in the EU, and the stock of passenger cars assumed to remain constant. The calculated demand is implemented with a linear ramping starting in 2030 and ending in 2050. In 2050, the resulting electricity demand from EVs is 656 TWh. In some cases under lack of data, GDP ratio is used as a proxy.

Table B.5: National demands for e-mobility in TWh, 2050

Country	E-mobility	Country	E-mobility	Country	E-mobility
AL	1.3	ES	75.1	MT	0.8
AT	16.4	FI	12.1	NL	28.4
BA	2.4	FR	130.1	NO	8.8
BE	19.3	HR	4.8	PL	65.9
BG	10.7	HU	15.0	PT	15.3
CH	15.9	IE	7.5	RO	20.7
CY	1.6	IT	110.3	RS	9.3
CZ	18.8	LT	3.9	SE	20.9
DE	156.1	LU	1.8	SI	4.8
DK	8.4	LV	2.3	SK	7.2
EE	2.4	ME	0.5	TR	25.1
EL	16.4	MK	1.2	UK	103.3

Trains, busses, and heavy goods transportation are assumed decarbonized in a similar way through electrification of trains and busses, and use of hydrogen as a fuel for heavy transport.

Table B.6: Exogenous electricity demand

	Conventional[35]	E-mobility		
(GWh)		2030	2040	2050
Albania	5 674	294	633	1 010
Austria	68 715	5 285	11 200	20 043
Belgium	83 100	4 849	10 171	18 660
Bosnia and Herzegovina	11 494	841	1 790	2 882
Bulgaria	30 313	2 262	4 850	7 977
Croatia	15 715	1 500	3 146	5 219
Cyprus	4 404	578	1 303	2 027
Czech Republic	62 338	3 656	7 953	16 010
Denmark	32 883	2 792	6 113	10 731
Estonia	7 664	516	1 110	2 171
Finland	81 986	313	1 279	2 244
France	447 795	34 582	73 831	138 564
Germany	530 374	39 847	84 361	157 875
Greece	55 034	3 661	7 749	12 298
Hungary	38 262	2 468	5 621	11 581
Ireland	26 493	3 175	7 610	12 853
Italy	322 762	26 513	55 657	97 487
Latvia	6 482	655	1 479	2 551
Lithuania	10 626	1 145	2 537	4 151
Luxembourg	6 366	1 356	2 926	4 811
Malta	2 117	124	250	376
Montenegro	2 671	129	279	441
Netherlands	110 464	8 026	17 267	31 442
North Macedonia	6 308	283	615	977
Norway	121 309	3 197	7 294	12 689
Poland	143 763	9 192	21 375	40 953
Portugal	48 739	4 658	9 777	17 246
Romania	47 142	3 743	7 958	15 175
Serbia	28 869	2 255	4 820	8 052
Slovakia	25 966	1 277	3 015	5 495
Slovenia	13 120	1 566	3 593	6 439
Spain	250 705	19 300	41 265	75 828
Sweden	130 614	6 226	15 117	31 274
Switzerland	46 920	5 002	10 566	19 058
Turkey	231 204	8 026	17 847	27 708
United Kingdom	311 138	27 222	58 571	105 122

Table B.7: Exogenous heat demand

	District heating[38]	Individual[38]	Industry[39]			
(GWh)			2020	2030	2040	2050
Albania	-	3 510	2 056	2 042	2 012	1 970
Austria	20 550	71 990	79 500	73 184	52 663	46 996
Belgium	1 150	99 794	84 900	75 489	57 497	54 196
Bosnia and Herzegovina	-	8 168	3 490	3 414	3 214	2 813
Bulgaria	5 174	20 786	22 400	21 779	20 271	17 624
Croatia	1 815	24 105	10 300	10 075	9 486	8 301
Cyprus	-	3 200	1 500	1 500	1 500	1 500
Czech Republic	17 990	75 160	66 000	64 719	58 838	52 768
Denmark	31 622	23 939	18 300	17 958	17 283	16 941
Estonia	4 603	6 849	4 600	4 573	4 501	4 456
Finland	-	43 811	88 900	85 840	80 856	79 208
France	24 932	412 886	207 400	192 227	161 146	144 235
Germany	115 600	687 701	500 400	459 253	357 572	306 091
Greece	577	41 313	24 200	24 038	23 676	23 182
Hungary	7 714	74 466	21 200	20 299	16 096	11 078
Ireland	-	34 460	16 800	16 359	15 504	15 081
Italy	15 803	405 627	236 400	225 265	193 159	175 787
Latvia	5 982	7 632	8 100	8 064	7 992	7 965
Lithuania	7 651	8 313	8 900	8 711	7 934	6 485
Luxembourg	1 059	7 561	5 800	5 566	5 125	4 936
Malta	-	1 040	-	-	-	-
Montenegro	-	1 127	660	656	646	632
Netherlands	5 737	112 320	127 500	118 520	106 233	82 319
North Macedonia	-	2 658	1 557	1 547	1 523	1 492
Norway	4 279	26 834	27 000	26 658	25 983	25 641
Poland	61 045	145 929	127 600	121 969	109 694	93 167
Portugal	303	21 357	41 300	40 535	39 086	38 402
Romania	11 755	73 355	60 000	53 756	45 607	37 609
Serbia	-	16 289	13 323	11 937	10 127	8 351
Slovakia	7 292	24 278	39 400	38 478	30 492	21 144
Slovenia	1 482	11 028	8 600	8 294	7 709	7 430
Spain	-	148 010	177 900	168 069	146 641	138 229
Sweden	52 085	34 255	84 500	80 543	73 709	71 858
Switzerland	3 805	72 255	22 700	22 358	21 683	21 341
Turkey	-	157 472	92 243	91 626	90 246	88 363
United Kingdom	8 668	506 487	191 400	184 896	171 088	160 901

Table B.8: Exogenous hydrogen demand

	Industry[40]				Transport[40]			
(GWh)	2020	2030	2040	2050	2020	2030	2040	2050
Albania	93	765	2 170	3 079	-	31	206	392
Austria	426	7 510	24 390	29 010	0	300	2 100	5 600
Belgium	1 303	17 860	49 940	63 310	0	301	2 100	4 200
Bosnia and Herzegovina	137	640	1 928	3 290	-	73	512	951
Bulgaria	446	3 070	9 440	16 940	-	300	1 800	2 900
Croatia	405	1 890	5 690	9 710	-	100	700	1 300
Cyprus	-	-	-	-	-	100	700	1 300
Czech Republic	327	3 430	11 770	18 750	28	727	3 400	5 700
Denmark	82	2 580	7 350	10 180	2	314	2 300	4 700
Estonia	-	30	110	160	0	100	400	700
Finland	522	5 230	13 210	16 910	14	514	2 900	5 800
France	1 454	30 920	87 090	116 280	1	3 307	21 300	41 500
Germany	5 555	60 970	182 550	245 110	776	3 621	19 800	41 500
Greece	1 094	9 000	25 540	36 240	-	300	2 000	3 800
Hungary	666	2 930	9 980	17 230	-	400	2 700	6 100
Ireland	26	1 360	3 900	5 330	-	200	2 300	11 200
Italy	1 681	30 340	90 220	121 940	0	2 200	13 800	23 400
Latvia	0	40	120	150	0	102	700	1 500
Lithuania	657	2 530	8 030	15 800	-	200	1 300	2 200
Luxembourg	1	260	750	960	-	100	500	1 900
Malta	-	-	-	-	-	1	7	13
Montenegro	30	245	697	989	-	15	97	184
Netherlands	4 194	25 030	70 080	102 420	109	1 575	4 700	10 800
North Macedonia	70	579	1 643	2 332	-	34	229	436
Norway	690	2 400	3 055	11 000	0	1 000	4 000	8 000
Poland	2 545	11 950	35 200	61 070	-	2 500	15 500	26 600
Portugal	333	6 110	17 320	23 930	-	300	2 000	4 100
Romania	727	7 870	19 640	34 420	-	400	2 300	4 200
Serbia	161	1 748	4 361	7 643	-	286	1 714	2 762
Slovakia	538	2 290	9 890	17 450	-	400	2 400	4 100
Slovenia	6	340	999	1 300	-	400	2 400	4 100
Spain	1 798	27 650	79 740	107 580	0	1 900	11 900	23 700
Sweden	535	7 860	20 650	26 460	0	1 900	11 900	23 700
Switzerland	66	3 083	6 458	9 834	1	507	2 000	5 000
Turkey	4 171	34 305	97 351	138 136	-	1 260	8 402	15 964
United Kingdom	1 659	24 820	73 080	100 880	74	2 459	16 300	36 700

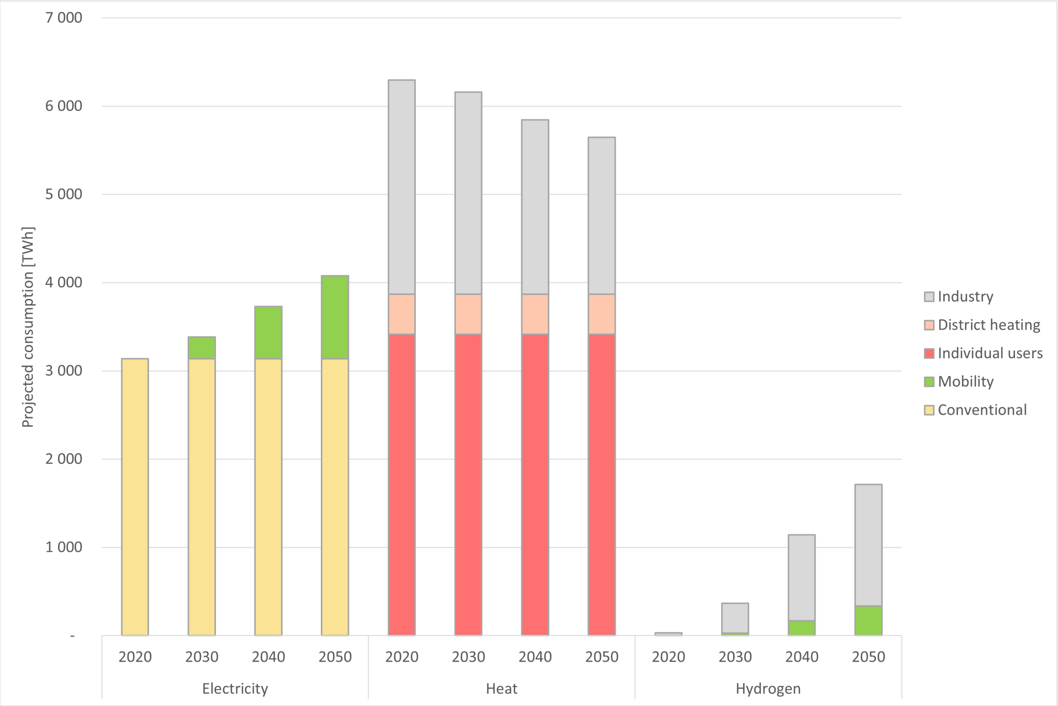


Figure B.8: Yearly aggregated final energy consumption by commodity.

Table B.9: Fuel prices

(EUR/GJ)	2020	2025	2030	2035	2040	2045	2050
Natural gas	6.90	7.61	8.32	8.72	9.11	9.51	9.98
Coal	2.96	3.13	3.30	3.32	3.35	3.38	3.41
Lignite	0.75	0.88	1.01	1.00	0.99	0.98	0.96
Fuel oil	5.43	8.76	12.10	11.96	11.82	11.68	11.54
Heavy fuel oil	12.60	12.60	12.60	12.60	12.60	12.60	12.60
Light oil	9.93	13.27	16.61	16.47	16.33	16.19	16.05
Municipal waste	-3.26	-3.26	-3.26	-3.26	-3.26	-3.26	-3.26
Straw	5.17	6.16	7.16	8.06	8.96	9.23	9.51
Wood	6.24	7.29	8.35	9.28	10.21	10.49	10.77
Recycled wood	2.59	2.59	2.59	2.59	2.59	2.59	2.59
Woodwaste	0.65	0.65	0.65	0.65	0.65	0.65	0.65
Woodchips	6.20	6.20	6.20	6.20	6.20	6.20	6.20
Woodpellets	8.65	9.65	10.65	11.55	12.44	12.72	12.99
Biooil	9.93	13.27	16.61	16.47	16.33	16.19	16.05
Biogas	12.72	12.72	12.72	12.72	12.72	12.72	12.72
Nuclear	0.76	0.76	0.76	0.76	0.76	0.76	0.76
Other gas	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Waste heat	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Shale	1.70	1.89	1.97	1.99	2.02	2.04	2.07
Peat	1.39	1.63	1.87	1.84	1.82	1.80	1.77
Retort gas	0.69	0.75	0.82	0.91	1.01	1.11	1.23
LNG	7.64	10.36	11.27	11.93	12.58	13.24	13.89
Carbon price [EUR/tCO2]	22.16	73.68	106.67	131.43	156.20	173.34	190.48

Appendix C. Carbon budget

Appendix C.1. Baseline carbon budget

To ensure decarbonization in line with the Fit-for-55 policy targets, emissions are restricted by a carbon budget. This budget is enforced through the ETS and ESR tools, which set budgets that are EU-wide and nation-specific respectively. The EU ETS covers CO2 emissions from electricity and heat production, energy-intensive industry sectors (such as steel works and oil refineries), aviation within the European Economic Area, and maritime transportation. This study only considers emissions from the energy and intensive industry sectors under the “stationary installations” label. In 2021 the number of allowances corresponds to 1 571 MtCO2, after which the number decreases yearly towards 2030 by 43 MtCO2 as defined by commission decision (EU) 2020/1722, document 32020D1722 [6]. Table C.10 shows the defined ETS budget considered until 2030, followed by a linear reduction towards zero in 2050.

Table C.10: Carbon budget in MtCO2 from the number of allowances under the EU, UK, and Swiss ETS

ETS	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
EU	1 571.6	1 528.6	1 485.6	1 442.6	1 399.6	1 356.6	1 313.6	1 270.6	1 227.6	1 184.6
UK	155.6	151.4	147.2	142.9	138.7	134.5	130.2	126.0	121.7	117.5
Swiss	4.7	4.6	4.5	4.3	4.2	4.1	3.9	3.8	3.7	3.6

An additional 1̃.5 % is removed from the UK ETS to account for aviation, and 11 % from all budgets to account for non-process-heat related industrial emissions.

The ESR system covers emissions from waste, non-ETS transportation and industry, buildings, and agriculture. Only the building sector is considered by Balmorel through the heat consumption of households and commercial buildings not connected to district heating and is by extension the only part that is included in the carbon budget considered endogenously. Historically, this number has been 25% of total non-ETS emissions [31]. The total ESR budget amounts to 2,226 MtCO2 in 2021, decreasing to 1,795 MtCO2 in 2030 followed by a linear decrease towards zero emissions in 2050. The budget defined until 2030 is shown in Table C.11 (25% of this budget is included) and defined by commission decision (EU) 2020/2126, document 32020D2126 [7].

Table C.11: Carbon budget in MtCO2 from the emission allocation under the ESR

(MtCO2)	2005	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Germany	484.7	427.3	413.2	399.1	385.1	371.0	356.9	342.8	328.7	314.7	300.6
France	401.1	335.7	326.5	317.3	308.1	298.8	289.6	280.4	271.2	262.0	252.7
Italy	343.1	273.5	268.8	264.0	259.3	254.6	249.8	245.1	240.3	235.6	230.9
Spain	242.0	201.0	198.7	196.3	194.0	191.7	189.4	187.0	184.7	182.4	180.1
Poland	192.5	215.0	204.4	201.2	198.0	194.9	191.7	188.5	185.3	182.2	179.0
The Netherlands	128.1	98.5	96.7	94.8	93.0	91.2	89.3	87.5	85.7	83.8	82.0
Belgium	81.6	71.1	69.1	67.1	65.1	63.1	61.1	59.1	57.1	55.1	53.0
Romania	78.2	87.9	76.9	76.9	76.9	76.8	76.8	76.8	76.7	76.7	76.7
Czechia	65.0	66.0	60.9	60.3	59.7	59.0	58.4	57.8	57.1	56.5	55.9
Greece	63.0	46.2	47.0	47.7	48.5	49.2	49.9	50.7	51.4	52.2	52.9
Austria	57.0	48.8	47.4	46.0	44.7	43.3	41.9	40.6	39.2	37.8	36.5
Portugal	48.6	42.5	40.8	40.8	40.7	40.7	40.6	40.6	40.5	40.5	40.4
Hungary	47.8	49.9	43.3	43.5	43.6	43.8	43.9	44.1	44.2	44.3	44.5
Ireland	47.7	43.5	42.4	41.2	40.1	39.0	37.9	36.7	35.6	34.5	33.4
Sweden	43.2	31.3	30.7	30.1	29.5	28.9	28.3	27.7	27.1	26.5	25.9
Denmark	40.4	32.1	31.3	30.5	29.6	28.8	28.0	27.1	26.3	25.5	24.6
Finland	34.4	28.8	28.0	27.1	26.2	25.4	24.5	23.6	22.7	21.9	21.0
Slovakia	23.1	23.4	21.2	21.1	21.0	20.9	20.8	20.7	20.6	20.5	20.4
Bulgaria	22.3	27.1	25.2	24.8	24.5	24.1	23.7	23.4	23.0	22.7	22.3
Croatia	18.1	17.7	16.5	16.6	16.6	16.6	16.7	16.7	16.7	16.8	16.8
Lithuania	13.1	16.1	13.7	13.5	13.3	13.0	12.8	12.6	12.3	12.1	11.9
Slovenia	11.8	11.4	11.1	11.0	10.9	10.8	10.6	10.5	10.4	10.3	10.2
Luxembourg	10.1	8.4	8.1	7.9	7.6	7.4	7.1	6.8	6.6	6.3	6.1
Latvia	8.6	10.6	8.9	8.8	8.7	8.6	8.5	8.4	8.3	8.2	8.1
Estonia	6.2	6.2	6.0	5.9	5.8	5.8	5.7	5.6	5.5	5.5	5.4
Cyprus	4.3	4.1	4.0	3.9	3.8	3.7	3.6	3.5	3.4	3.3	3.2
Malta	1.0	2.1	1.2	1.2	1.1	1.1	1.0	1.0	0.9	0.9	0.8

While the allowed emissions under the ESR system are set at national levels, this study combines the ETS and ESR budgets under a system-wide cap, resulting in the budget shown in Table 1.

Table C.12: National emission budget under ESR, GDP, and population distribution for 2021 and 2030.

	ESR		GDP			POP		
(MtCO2)	2021	2030	(MEUR, 2022)	2021	2030	(population)	2021	2030
Albania	3.42	3.73	17 940	2.04	1.61	2 832 439	10.69	8.42
Austria	42.47	30.30	446 933	50.77	39.99	8 958 961	33.80	26.62
Belgium	61.96	44.07	549 456	62.42	49.16	11 686 140	44.09	34.72
Bosnia	5.21	4.73	23 317	2.65	2.09	3 210 848	12.11	9.54
Bulgaria	23.62	18.55	84 561	9.61	7.57	6 687 717	25.23	19.87
Croatia	15.38	13.96	66 939	7.60	5.99	4 008 617	15.12	11.91
Cyprus	3.55	2.69	27 006	3.07	2.42	1 264 346	4.77	3.76
Czechia	57.47	46.41	276 606	31.42	24.75	10 495 295	39.59	31.18
Denmark	27.98	20.46	376 087	42.73	33.65	5 910 913	22.30	17.56
Estonia	5.42	4.48	36 181	4.11	3.24	1 322 766	4.99	3.93
Finland	25.12	17.45	266 679	30.30	23.86	5 545 475	20.92	16.48
France	292.40	209.97	2 639 092	299.82	236.12	64 756 584	244.29	192.39
Germany	372.16	249.70	3 869 900	439.64	346.24	83 294 633	314.22	247.46
Greece	40.26	43.95	208 030	23.63	18.61	10 341 277	39.01	30.72
Hungary	43.47	36.95	170 247	19.34	15.23	10 156 239	38.31	30.17
Ireland	37.87	27.73	502 584	57.10	44.97	5 056 935	19.08	15.02
Italy	238.21	191.79	1 909 154	216.89	170.81	58 870 763	222.09	174.90
Latvia	9.28	6.71	39 063	4.44	3.49	1 830 212	6.90	5.44
Lithuania	14.03	9.87	66 791	7.59	5.98	2 718 352	10.25	8.08
Luxembourg	7.32	5.04	78 130	8.88	6.99	654 768	2.47	1.95
Malta	1.80	0.69	16 923	1.92	1.51	535 065	2.02	1.59
Montenegro	1.10	1.20	5 797	0.66	0.52	626 485	2.36	1.86
Netherlands	85.80	68.12	941 186	106.92	84.21	17 618 299	66.46	52.34
North Macedonia	2.59	2.83	12 898	1.47	1.15	2 085 679	7.87	6.20
Norway	25.66	18.91	551 409	62.64	49.33	5 474 360	20.65	16.26
Poland	187.26	148.71	656 906	74.63	58.77	41 026 068	154.77	121.89
Portugal	37.04	33.58	239 242	27.18	21.40	10 247 605	38.66	30.45
Romania	76.54	63.70	285 885	32.48	25.58	19 892 812	75.04	59.10
Serbia	17.72	13.92	60 368	6.86	5.40	7 149 077	26.97	21.24
Slovakia	20.39	16.91	109 652	12.46	9.81	5 795 199	21.86	17.22
Slovenia	9.93	8.45	58 989	6.70	5.28	2 119 675	8.00	6.30
Spain	175.06	149.58	1 327 108	150.77	118.73	47 519 628	179.27	141.18
Sweden	27.29	21.55	560 959	63.73	50.19	10 612 086	40.03	31.53
Switzerland	15.98	11.98	767 616	87.21	68.68	8 796 669	33.18	26.13
Turkey	153.47	167.54	862 011	97.93	77.12	86 040 771	324.58	255.62
United Kingdom	223.28	164.04	2 904 089	329.92	259.83	67 736 802	255.53	201.24

Appendix C.2. Heat saving

An important aspect of decarbonization is not only the transition of where we source our energy but also the decrease in the quantity of the energy we use. One way of achieving that goal is to improve energy efficiency, and there by reduce the amount of energy needed for the same purpose. A major source of potential energy efficiency improvements is renovations, leading to heat savings in buildings.

In this study, heat saving is implemented as generating technologies that can provide heat to district heating and individual users. Danish data shown in Figure C.9 forms the basis of how these technologies are modeled.

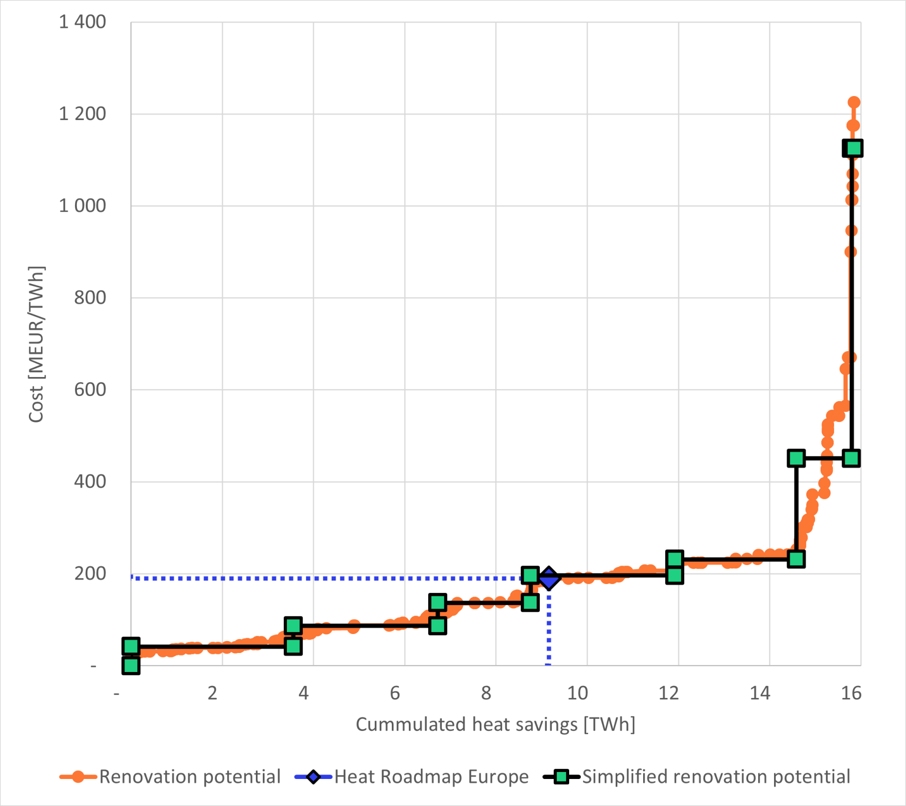


Figure C.9: Danish data on heat saving potential from renovation by potential and cost, simplification of data, and heat saving potential considered by Heat Roadmap Europe

The data consists of 360 steps of heat-saving measures each with a potential for yearly heat savings and associated cost per energy saving. This data is translated to other countries by means of scaling the cost based on construction costs and potentials based on data from the Heat Roadmap Europe study on saving potentials in residential and public buildings (see Table C.13).

Table C.13: National construction cost index in % from [41] with Denmark as a basis and heat saving potentials [42]

Country	CCI [%]	Potential [TWh]	Country	CCI [%]	Potential [TWh]	Country	CCI [%]	Potential [TWh]
AL	38.4	0.9	ES	48.5	39.8	MT	54.7	-
AT	69.2	22.1	FI	78.4	15.8	NL	56.4	30.8
BA	38.8	13.4	FR	71.4	146.2	NO	110.6	15.8
BE	61.4	34.4	HR	37.8	16.8	PL	45.1	84.4
BG	33.5	47.3	HU	36.6	21.1	PT	34.6	3.2
CH	94.5	22.1	IE	54.5	9.4	RO	31.9	17.4
CY	41.5	0.5	IT	64.4	88.3	RS	26.1	7.9
CZ	42.0	21.4	LT	40.4	18.1	SE	92.3	16.1
DE	66.5	361.4	LU	67.6	8.2	SI	55.0	13.0
DK	**100.0**	**15.8**	LV	39.8	8.2	SK	35.5	42.2
EE	40.8	5.0	ME	44.7	0.2	TR	46.8	26.7
EL	43.7	3.2	MK	33.1	0.6	UK	68.8	142.7

The steps for each country are aggregated into seven steps each with a cost (as in Figure C.9), which are turned to generation technologies using the following formulas:

$$Capacity = \frac{Potential}{52\ w \cdot 168\ h} \tag{C.1}$$

$$Investment\ cost = \frac{Potential \cdot Cost}{Capacity} \tag{C.2}$$

Equation (C.1) determines calculates the maximum capacity for each technology in MW, and Equation (C.2) determines the investment cost in EUR/MW. The result is seven different generating technologies with increasing investment costs representing the seven steps of heat-saving measures.