

Pathways to climate neutrality: Europe's energy transition under the Green Deal

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ABSTRACT

The EU committed to reducing 55 % of its greenhouse gas emissions by 2030 and achieving climate neutrality by 2050 through its Green Deal and Fit for 55 policy package. This study employs the TIMES-Europe model to assess multiple pathways for the required energy transition and their cost implications, while explicitly accounting for the interplay between existing EU energy policies. We do so by analysing, from both a pan-European and a national perspective, the impact of the proposed 2040 climate target, the energy efficiency-first principle, and various collaboration frameworks such as fairness-based burden-sharing. Our projections show that under the most ambitious policy scenarios, renewable electricity could contribute up to 44 % of Europe's Primary Energy Consumption mix by 2050. Domestic fossil fuel shares decline from 51 % to 12 %. However, import dependency increases to 49 %, with a shift from crude oil to refined petroleum products, raising concerns over emissions leakage. Residual emissions of ~0.3 GtCO₂ persist under current policy trajectories, which highlights the need for more stringent measures to achieve net-zero emissions by 2050. Implementing the 2040 climate target and the EU Energy Efficiency Directive could reduce cumulative emissions by an additional 10.62 GtCO₂ but at a 100–116 % increase in policy costs. The application of equitable burden-sharing frameworks, however, induces no extra costs at the European level, which demonstrates that collaboration can facilitate cost-effective decarbonisation. Our findings emphasise the need for enhanced policies targeting hard-to-abate sectors and balancing equity with efficiency in Europe's energy transition.

List of Abbreviations

a	Attained (scenario codes)
BECCS	Bioenergy with Carbon Capture and Storage
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage
CO ₂	Carbon Dioxide
EED	Energy Efficiency Directive
EEA	European Environment Agency
e	Efficient (scenario codes)
EJ	Exajoule
EPBD	Energy Performance of Buildings Directive
ETS	Emissions Trading System
ETS 1	Emissions Trading System – Part 1
ETS 2	Emissions Trading System – Part 2
EU	European Union
EU ETS	European Union Emissions Trading System

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EVs	Electric Vehicles
F	Fair (scenario codes)
FEC	Final Energy Consumption
GDP	Gross Domestic Product
GHG	Greenhouse Gas
HDV	Heavy-Duty Vehicle
i	Implemented (scenario codes)
IPCC	Intergovernmental Panel on Climate Change
LCV	Light Commercial Vehicle
LRF	Linear Reduction Factor
LP	Linear Programming
Mtoe	Million Tonnes of Oil Equivalent
MtCO ₂	Million Tonnes of CO ₂
NETs	Negative Emission Technologies
OECD	Organisation for Economic Co-operation and Development
PC	Passenger Car

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PEC	Primary Energy Consumption
PJ	Petajoule
RED	Renewable Energy Directive
REF	Reference Scenario
S	Solo (scenario codes)
T	Together (scenario codes)
TIMES	The Integrated MARKAL-EFOM System

1. Introduction

Emerging climate evidence stresses the increasing severity of global warming [1]. Observations from across the globe confirm that 2024 marks a worrying milestone: global temperatures surpassed the critical threshold of a 1.5 °C increase above pre-industrial levels [2–8]. This alarming development unequivocally confirms the acceleration of the climate crisis and reflects the global community's possible collective failure to meet the Paris Agreement's most ambitious target [9]. With the 1.5 °C goal perhaps already out of reach, the urgency to strengthen global mitigation efforts is more pressing than ever, as the focus must now shift to prevent warming from exceeding 2 °C [9]. Europe is among the regions particularly vulnerable to climate change, with several countries facing heightened risks due to rising temperatures and varying levels of adaptive capacity [10]. The continent has already experienced an average temperature rise of 2.3 °C over land compared to pre-industrial levels [8], which exacerbates socio-economic challenges across the region [10–16]. These include rising healthcare costs due to heat-related illnesses and disease prevalence [17], declining agricultural yields due to increased droughts and extreme weather [18], and escalating infrastructure maintenance costs to mitigate damage from more frequent and intense weather events [10]. Despite these vulnerabilities, European governments have positioned themselves as global leaders in climate action. As one of the world's largest historical emitters [19–21], the region has taken on a central role in spearheading decarbonisation efforts through its transformative policy initiatives [22–26].

The European Green Deal, published in 2019, expresses the EU's commitment to lead the fight against the climate crisis by setting ambitious climate targets: reducing 55 % of the EU's emissions by 2030 and making Europe the first climate-neutral continent by 2050 [27]. This *climate law* has been operationalised through a plethora of policies known as the *Fit for 55* policy package, designed as tools to achieve Europe's climate ambitions [28]. These policies target all energy sectors across the supply side (e.g. upstream and power sectors) and demand side (e.g. industry, buildings, and mobility sectors). The EU Emissions Trading System (ETS) stands out as a significant initiative to progressively reduce annual emission allowances to meet the 2030 and 2050 Greenhouse Gas (GHG) abatement objectives [29]. Additionally, the European Energy Efficiency Directive (EED) outlines fundamental principles for achieving these goals [30], while the recently proposed 2040 CO₂ reduction goals signal the EU's more aggressive trajectory toward net zero [31]. As the milestone year of 2030 approaches, it is important to evaluate the efficacy of the European Green Deal and its policy packages.

A substantial literature exists on energy transition pathways [32–40]. At the European level, Hainsch et al. and Panarello & Gatto investigated European decarbonisation in the context of the EU Green Deal, with particular attention to social aspects and public perception [41,42]. At the national level, Scheepers et al. explored climate-neutral scenarios in the Netherlands, reporting up to 71 % electrification of primary energy consumption (PEC) in 2050 and emphasising the importance of hydrogen as an energy carrier [43]. Similarly, Weiss et al. used a power market model to assess the impact of international and national policies on Switzerland's energy transition, quantifying potential cost increases for the public [44]. Salim et al. highlighted the potential for up to 3000 PJ of energy savings to be realised in the

European residential sector by 2030 [45]. West et al. showcased the value of adding detail to material flows and industrial processes, which leads to different investment decisions for achieving net zero [46]. Mathisen et al. examined the implications of REPowerEU, a component of the EU's strategy to rapidly reduce dependence on Russian fossil fuels by saving energy, diversifying supplies, and accelerating the clean energy transition [47]. They showed that the Nordic countries could play a significant role in Europe's green transition by exporting more energy [48]. Long et al. evaluated the EU sustainability criteria under the Renewable Energy Directive (RED) [49] as applied to renewable heat and transport in Ireland. Their analysis found that while biomethane meets the sustainability criteria for the transport sector, it falls short in the context of heat supply [50]. Capros et al. explored pathways for the EU to achieve climate neutrality by 2050 or 2070, emphasising the critical role of disruptive energy carriers such as hydrogen [51]. While literature to date contributes valuable insights, significant research gaps remain, as most existing studies are constrained by their narrow focus, whether at the sub-national or national level [33,35,43], by a single-sector approach [32,33,37], or by the examination of individual policies in isolation [45,48,52]. A comprehensive approach is needed to study (i). the interactions between multiple energy policies, (ii). the synergies between national and Europe-wide targets, and (iii). the inclusion of all energy sectors, as these dimensions are deeply interconnected and must be analysed collectively to identify effective decarbonisation pathways under the current suite of energy policies.

In the present paper, we address these research gaps by creating projections with the TIMES-Europe energy system model, a new tool uniquely suited to quantitatively analyse European energy policies. One of the key features of TIMES-Europe is its ability to evaluate pan-European and country-level dynamics simultaneously. The present study leverages this capability to address several important research questions. First, it assesses viable pathways for decarbonising Europe's energy system while considering the interplay between policies, technologies, and investments. Second, it examines the cost implications of implementing the EU EED and evaluates the necessity of 2040 climate targets as a pivotal step toward achieving Europe's 2050 ambitions. Third, it explores the potential advantages of various collaborative frameworks among European countries: system-level collaboration (in which countries collectively share the burden of regional climate targets), fair collaboration (in which contributions are aligned with each country's historical responsibility), and partial collaboration (where the burden is distributed uniformly, regardless of countries' differing capabilities or responsibilities). Our research questions collectively aim to unravel the intricate dynamics that shape Europe's energy transition while providing actionable insights to support the achievement of climate objectives at both the EU and national levels.

This article is organised as follows: Section 2 details the modelling methodology and justifies the selection of the TIMES-Europe model alongside key assumptions regarding the current European energy policy landscape and scenario descriptions. Section 3 presents our findings, followed by a discussion of insights in Section 4. Section 5 provides the main conclusions and policy recommendations, while Section 6 offers an outlook, which highlights future research directions.

2. Methodology, context, and scenarios

2.1. The TIMES-Europe energy system model

We here provide a brief overview of the TIMES-Europe model, which highlights the aspects most relevant to the present study. A more detailed description of the model is available in Ref. [53], and specific details on the modelling of the residential sector can be found in Refs. [37,45]. TIMES-Europe is a European energy system model that provides country-level detail by representing each EU27 member state, together with the United Kingdom, Norway, Switzerland, and Iceland, as an individual region within the model. The model analyses energy

systems at both the pan-European and the national level simultaneously. The various countries in TIMES-Europe are linked through trade and infrastructure connections, allowing for an integrated analysis of cross-border energy flows and regional interactions. Spatial variation and national-level nuances are captured through country-specific data on renewable resource availability (e.g. wind, solar, hydro), existing energy infrastructure, technology stock, and sectoral energy demands. The model operates with a base year in 2015 and milestone years in five-year intervals up to 2060, reflecting key target years in European climate and energy policy. Each milestone year is represented through 12 time slices, combining day, night, and peak hours across the four seasons. This level of temporal detail provides a balanced representation of seasonal and daily variation while maintaining computational tractability for long-term energy system analysis. TIMES-Europe is a perfect foresight model, which assumes that all future costs, demands, and constraints are known at the time of decision-making. This characteristic allows for globally optimal planning across the time horizon, providing a robust benchmark for assessing long-term transition pathways [54–57]. The model is built using the TIMES model generator [58], a widely adopted framework used to construct global, regional, national, and sub-national energy system models. TIMES has been employed in

numerous studies [59–70], showcasing its versatility and robustness. TIMES-Europe uses a Linear Programming (LP) formulation to determine the least-cost configuration of Europe's energy system [58]. It is categorised under the energy system optimisation model family, which primarily focuses on studying possible evolutions of the energy system [71,72]. The model simultaneously makes decisions regarding equipment investments, operations, primary energy supply, and energy trade for each country. The output includes the optimal mix of technologies and fuels for each period, as well as the embedded emissions and the trade flows of energy commodities and carriers between countries.

Fig. 1 presents the TIMES-Europe schematic. The model's macroeconomic drivers, such as Gross Domestic Product (GDP) and population growth, serve as the basis for projecting future energy service demands. TIMES-Europe categorises these demands into five energy sectors: industry, transport, residential, services, and agriculture. Each sector is further subdivided into detailed demand accounts. For example, the transport sector includes road, rail, and aviation demands, while the residential sector includes space heating and water heating demands. These energy service demands are met by a range of end-use technologies, such as heat pumps, electric vehicles (EVs), and blast furnaces. To satisfy the energy requirements of these technologies, the model selects

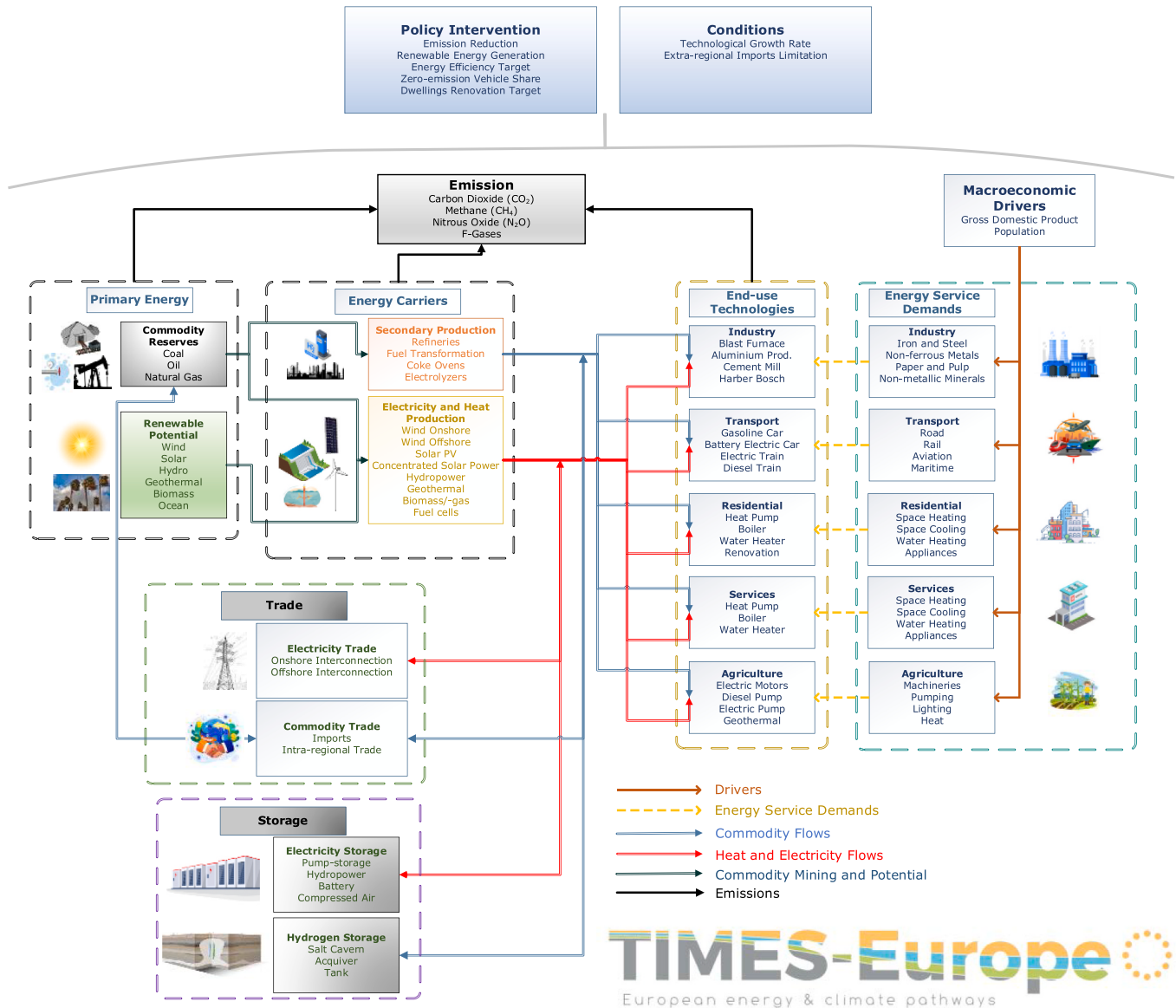


Fig. 1. TIMES-Europe model.

the most cost-effective energy carriers (e.g. secondary fuels, electricity, or heat). These carriers can be produced locally, which utilises a region's primary energy resources and renewable energy potential, or sourced through trade, imports, or storage. TIMES-Europe categorises the accounting of energy supply into the power & heat sector and the upstream sector. The power & heat sector addresses electricity and thermal energy generation from various sources, while the upstream sector focuses on the extraction, refining, and distribution of primary fuels such as natural gas, oil, and coal. TIMES-Europe directly accounts for CO₂ emissions in each sector. The model also incorporates constraints that reflect, for instance, policy interventions. For the present study, the constraints are specific to the current European energy policy and are explained in detail in the subsequent sub-sections.

2.2. European energy policy landscape

The European Green Deal embodies the overarching vision and primary objectives of Europe's energy transition [27]. This vision is supported and directed by a series of policy packages that further specify how these objectives can be met [28]. In Fig. 2, we present a schematic representation of the EU energy policy landscape, in which we categorise the different policy packages into three separate tiers, under the umbrella of the Green Deal.

The first tier is the EU ETS, the only policy instrument that directly caps emissions across all economic sectors [29]. This makes it the policy most closely aligned with the ultimate goal of achieving net-zero emissions stipulated in the European Green Deal. In the latest amendment, the total emissions cap under the EU ETS is divided into two systems: ETS 1 and ETS 2 (Fig. 3). ETS 1 encompasses emissions from sectors such as electricity and heat, industry, upstream activities, aviation, and maritime transport, while ETS 2 focuses on emissions from buildings and road transport.

Fig. 4 illustrates the annual EU ETS cap, with detailed calculations of the annual emissions cap provided in Appendix 1. The EU ETS cap is represented in emission allowances, where one allowance grants the emission of one tonne of CO₂ equivalent. Under the policy design, allowances are primarily distributed via an auction process. Certain hard-to-abate energy sectors (e.g. some parts of industry and aviation) receive free allocations to mitigate carbon leakage, a phenomenon in which

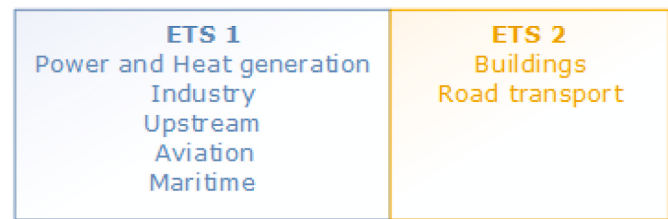


Fig. 3. The EU ETS sectoral scope.

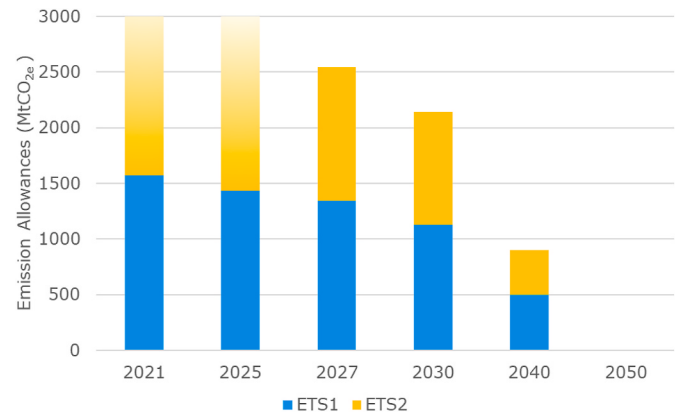


Fig. 4. The EU ETS 1 and 2 allowances.

production relocates to other countries due to the cost implications of climate policies, resulting in a displacement of emissions. In the present study, we excluded the principle of free allowances. The year 2027 marks the introduction of ETS 2, which extends carbon pricing to the buildings and transport sectors. This transition is visually highlighted in Fig. 4, in which fading yellow bars represent the absence of an emission cap for buildings and road transport before 2027.

The second tier comprises the main principles underlying EU climate policies, i.e. the enhancement of energy efficiency and the enforcement of an ambitious emission reduction trajectory towards climate neutrality. The EU EED [30] and the proposed 2040 climate target [31] are the policies we deem most significant in this respect. The EU EED aims to reduce overall energy consumption by 2030 down to a maximum of 992.5 Mtoe for PEC and 763 Mtoe for Final Energy Consumption (FEC). The proposed 2040 climate target, currently under debate by the European Commission, aims to solidify the EU's commitment to achieving net-zero emissions. Specifically, the European Commission has recommended a 90 % reduction in net GHG emissions by 2040 compared to 1990 levels.

The third layer includes the various sector-specific energy policies linked to the European Green Deal, which serve as essential tools for driving progress toward the overarching goal of net-zero emissions by 2050. For instance, we include in this block the RED [49], the ReFuelEU Aviation [73], and the Energy Performance of Buildings Directive (EPBD) [74]. Appendix 2 provides a comprehensive overview of these initiatives, summarising relevant EU-level energy and climate policies along with their sectoral applications.

For this study, in addition to the EU27, Norway and Iceland, we assume that the United Kingdom and Switzerland also fully participate in the EU energy policy framework. This assumption reflects their broadly aligned decarbonisation commitments, despite the fact that both countries pursue independent emission reduction strategies. Corresponding EU ETS allowances for the United Kingdom and Switzerland are therefore included in the present modelling constraints.



Fig. 2. Schematic representation of the European energy policy landscape.

2.3. Scenario overview

We designed a set of scenarios to examine how differing levels of climate ambition alongside varying types of collaboration may shape the development of the European energy system. Our scenarios are structured along two distinct axes (see Fig. 5). The vertical axis represents climate ambition, categorised into three levels: implemented (i), efficient (e), and attained (a). The horizontal axis defines the type of collaboration, divided into three categories: Solo (S), Fair (F), and Together (T).

The three levels of climate ambition on the y-axis of Fig. 5 were chosen to reflect the varying degrees of effort that Europe could pursue in achieving its climate goals. Each level corresponds to specific targets for emission reduction and energy system transformation. The 'i' scenarios represent scenarios in which climate ambitions are pursued at the pace currently projected by existing policies, specifically the ETS (top of the pyramid in Fig. 2) and the sectoral policies (bottom of the pyramid in Fig. 2). The 'e' scenarios correspond to a condition where, in addition to the current set of policies, Europe implements the energy efficiency-first principle. In the 'a' scenarios, we add the requirement that Europe also commits to achieving the proposed 2040 emission reduction target and reach net zero by 2050. Table 1 summarises the relationship between climate ambition and EU policies in our scenario framework.

The three types of collaboration between European countries, on the x-axis of Fig. 5, were chosen to explore the role of inter-country cooperation and burden sharing in reducing emissions. The 'S' scenarios represent a situation in which each country pursues its climate objectives independently. The 'F' scenarios introduce fairness as a central principle: countries contribute to emission reductions based on their historical responsibility (i.e. past emissions). The 'T' scenarios assume a fully coordinated effort, where countries share the burden of emission reductions across borders, optimising the European energy system as a whole.

These two dimensions, i.e. climate ambition and collaboration, combine to create nine distinct scenarios for Europe's energy transition. This scenario setup allows us to address both the environmental and social dimensions of climate action, encompassing not only the technical feasibility of emission reductions but also the economic and political realities that shape how countries may cooperate to meet shared goals. These scenarios capture the diverse ways in which Europe could navigate its energy transition, from individual national efforts to pan-European cooperation while accounting for the equity considerations that are central to any global climate agreement. A reference scenario 'REF' serves as a baseline for comparison, assuming a situation in which no effort is put into reducing emissions.

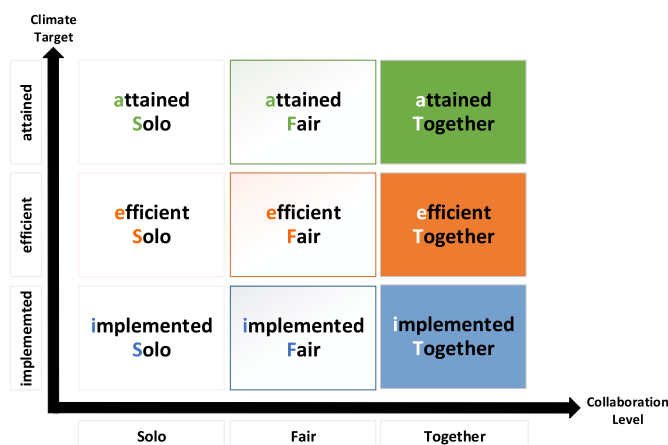


Fig. 5. Definition of scenarios.

2.4. Scenario parametrisation

To implement our scenario framework in TIMES-Europe, the policies that determine the three levels of climate ambitions are translated into model parameters (see Appendix 2 for details on how this is done). These define a series of constraints that are applied in the model depending on the specific scenario, as outlined in Table 1.

The collaboration level determines how these constraints are distributed across the various countries in Europe. In the 'S' scenarios, each country is allocated exactly the same amount of ETS allowances, has to attain the same energy efficiency goal, and is required to achieve the same emission reduction rate in 2040. The 'F' collaboration scenarios are based on an equal cumulative per capita rationale, along the lines described in Dekker et al. [75,76]. In this case, national targets are exogenously allocated based on historical responsibility, using cumulative emissions from 1850 to 2021. Each country is assigned a remaining carbon budget by comparing its historical emissions with what it would have been entitled to emit based on its population over time. Once this historical balance is accounted for, future emissions allocations converge toward an equal per capita distribution. This approach assumes that all individuals have an equal right to emit, thereby treating each person as equally responsible for carbon debt. However, in practice, emissions profiles vary significantly, e.g. across income groups. In the 'T' collaboration scenarios, the targets are applied at the European level. This means that the model can choose to e.g. allow certain countries to settle for emission reduction rates that are more modest than those prescribed by the EU-level target, as long as this is compensated by other countries achieving deeper CO₂ reductions, ensuring that the overall EU-level target is met. Sectoral policies are consistently implemented at the European level, irrespective of the collaboration scenario, as they serve as tools to drive collective progress toward overarching climate targets without imposing specific burdens on individual member states.

3. Results

Our results are organised into two parts covering: (i). A regional perspective, which includes our analysis of the EU27 countries and the UK, Switzerland, Iceland, and Norway taken together, and (ii). A country-level examination, in which we explore the differences between countries within this overall geographical scope.

3.1. European-level insights

Fig. 6 illustrates the annual PEC of the European energy system, measured in Exajoules (EJ), across our ten scenarios. Following the EU EED definition of PEC, electricity generation from nuclear and renewable electricity generation is also accounted as part of PEC [30]. The 'REF' and 'i' scenarios project an increase in PEC by 9–15 % between 2020 and 2050. In contrast, the 'e' and 'a' scenario projections show a 10–14 % reduction over the same period. Across all scenarios, there is a notable rise in the share of renewable electricity within PEC sources, which reflects an ongoing electrification process. By 2050, this transformation could result in renewable electricity constituting up to 44 % of the total PEC share under our most stringent climate control scenario 'aT'. Concurrently, the total amount of domestic fossil fuels in Europe exhibits a declining trend, with shares dropping from 48 % in 2020 to 4–23 % in 2050. The reliance on imported fossil- and bio-fuels is projected to undergo minor variation across scenarios, with total shares going from 41 % to 39–59 % between 2020 and 2050. However, a shift in the composition of imports is observed: in all scenarios, crude oil imports decline significantly (virtually to zero in all scenarios with emission reduction targets), while natural gas, biofuels, and refinery oil product imports increase sharply. The type of collaboration has only triggered some appreciable effect on the import mix. While in 'eS', 'eF', 'aS', and 'aF' the model favours natural gas imports over domestic

Table 1
EU policies along the climate target axis of our scenarios.

	Climate Target	Sectoral Policies	ETS	EED	2040 Climate Target
i	implemented	✓	✓		
e	efficient	✓	✓	✓	
a	attained	✓	✓	✓	✓

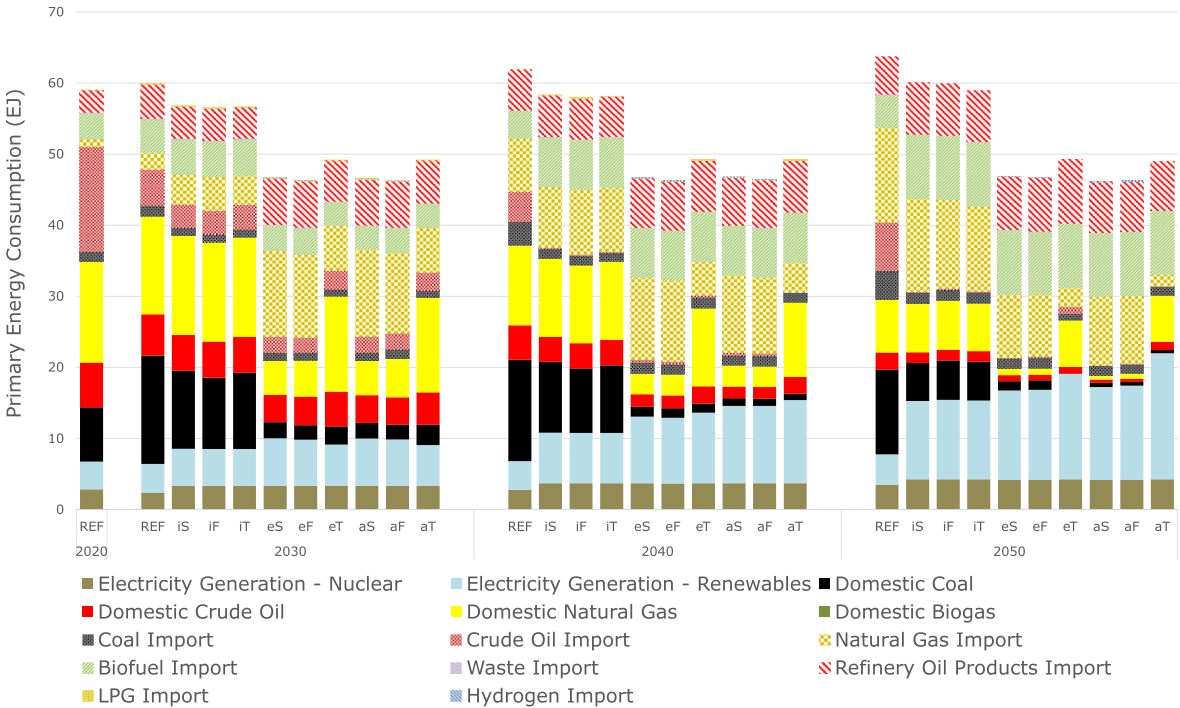


Fig. 6. Europe's annual primary energy consumption.

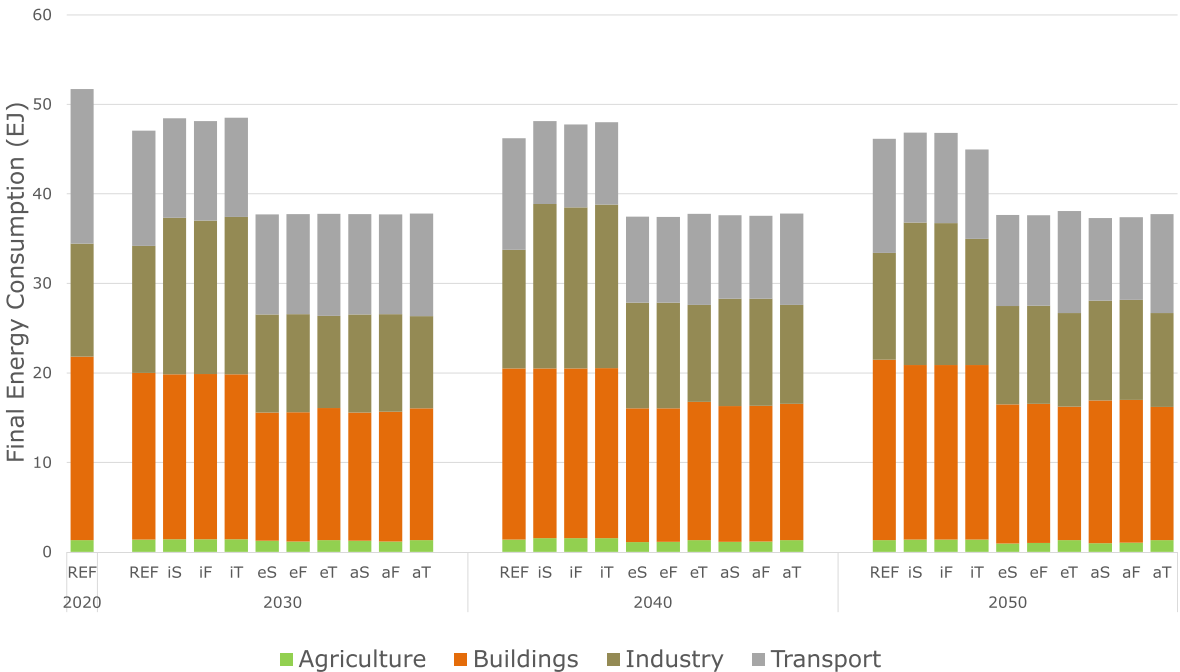


Fig. 7. Europe's annual final energy consumption.

extraction, the situation is reversed in 'eT' and 'aT'. This suggests that, in the presence of ambitious climate targets ('e' and 'a' scenarios), system-wide collaboration 'T' allows for a more cost-efficient use of domestic natural gas resources compared to other types of collaboration. The higher shares of domestic natural gas in 'eT' and 'aT' are accompanied by a slight increase in total PEC relative to the other 'e' and 'a' scenarios.

Fig. 7 shows the FEC, measured in EJ, from 2020 to 2050 across all scenario variants. The results are disaggregated by demand sectors, offering a detailed perspective on sectoral trends. A clear divergence emerges between the 'REF' and 'i' scenarios, where total FEC remains relatively high, with the 'e' and 'a' scenarios, where a sharp decline is observed as early as 2030, after which the FEC stabilises. Despite differences in total FEC, the relative shares of demand sectors remain largely consistent across years and scenarios. Variations due to collaboration frameworks are minimal, with only marginal differences observed in 'T' scenarios.

Fig. 8 presents the net CO₂ emissions across all scenarios alongside GDP growth projections taken from OECD [77]. Apart from the 'REF' scenario, the results unveil a decoupling of CO₂ emissions from projected GDP growth in scenarios incorporating climate targets (i.e. 'i', 'e', and 'a' scenarios). Notably, the ambition level of the climate targets plays a greater role in driving emission reductions than the degree of collaboration among countries. The 'i' and 'e' scenarios follow relatively similar emission reduction pathways. By contrast, the 'a' scenarios, which implement the proposed 2040 climate target, demonstrate a significantly steeper decline in annual emissions. By 2040, net emissions in these scenarios are halved compared to those in the 'i' and 'e' scenarios. Moreover, by 2050, the 'a' scenarios achieve net-zero emissions, whereas the other scenarios retain approximately 0.3 GtCO₂ of residual emissions.

Fig. 9 further elaborates on the net CO₂ emissions presented in Fig. 8, providing a sectoral breakdown. The bars are colour-coded to represent different sectors, while the net emissions are indicated by blue diamond markers. The 'REF' scenario is projected to have a slight increase in the annual CO₂ emission level, approximately up to 3.9 GtCO₂ at the end of the modelling horizon. In contrast, all scenarios implementing climate targets result in a significant reduction in annual emissions. In 2040, the 'a' scenarios are projected to emit only half as much annually as compared to the 'i' and 'e' scenarios. Some scenarios exhibiting an earlier deployment of negative emission technologies, particularly all 'a' scenarios and the 'eT' scenario. Within the 'T' collaboration framework, slightly higher levels of negative emissions are observed, which offset the comparatively elevated emissions from the industrial sector. The industrial and transport sectors may face slower decarbonisation due to higher costs and significant technological barriers in comparison to, e.g. the buildings sector. The 'a' scenarios respond to these challenges

through earlier deployment of negative emission technologies than those observed in the 'i' and 'e' scenarios. Furthermore, under 'T' collaboration, which promotes coordinated regional strategies, earlier and greater deployment of negative emission technologies is also projected, relative to the 'S' and 'F' scenarios.

Fig. 10 illustrates the avoided CO₂ emissions from 2020 to 2050 across scenarios with implemented climate targets. These values are calculated by subtracting the cumulative net emissions of each scenario from those of the 'REF' scenario over the same period. We observe that the primary determinant of avoided emissions is the ambition level of the climate targets rather than the type of collaboration. Scenarios with more stringent climate policies achieve significantly higher emission reductions. In the 'e' scenarios, avoided CO₂ emissions are 3.3 % higher than in the 'i' scenarios. This effect is even more pronounced in the 'a' scenarios, where avoided emissions increase by up to 15.9 % compared to the 'i' scenarios.

Fig. 11 illustrates cumulative policy costs through the end of the modelling horizon, which represent the additional system costs incurred in each scenario relative to the 'REF' scenario. These costs reflect the extra investment required beyond the baseline technological expenditures assumed under the 'REF' scenario. The 'i' scenarios show a steady increase in cumulative policy costs across all collaboration types. In contrast, the 'e' and 'a' scenarios exhibit varying cost trajectories depending on the collaboration framework. Under more stringent climate targets ('e' and 'a'), a higher degree of collaboration helps mitigate cost increases over time. By 2050, compared to the 'i' scenarios, cumulative policy costs rise by up to 98 % in the 'eS' scenario, while 'eF' scenario results in a 94 % increase. The 'eT' scenario leads to an 83 % increase, which reflects cost-mitigation effects associated with system-wide collaboration. In the 'a' scenarios, cumulative policy costs escalate further, rising between 100 % under 'T' scenarios and 116 % under 'S' collaboration. However, the additional policy cost burden associated with implementing the 2040 climate target remains relatively minor if the EU EED is already in place.

3.2. Country-level insights

We here present our country-level projection results. Each figure comprises a set of maps that differentiate the scenarios, with the maps arranged according to the scenario description axes of Fig. 5.

Fig. 12 presents CO₂ emissions per capita across Europe in 2050, measured in tCO₂ per capita. A breakdown of emissions by sector is provided in Appendix 3. In general, scenarios with higher climate ambition lead to lower emissions per capita (see Fig. 9). The 'REF' scenario shows emissions remain high across Europe, particularly in Central and some Northern European countries, e.g. Germany, the Netherlands, Poland, Denmark, Norway, and Finland, with values

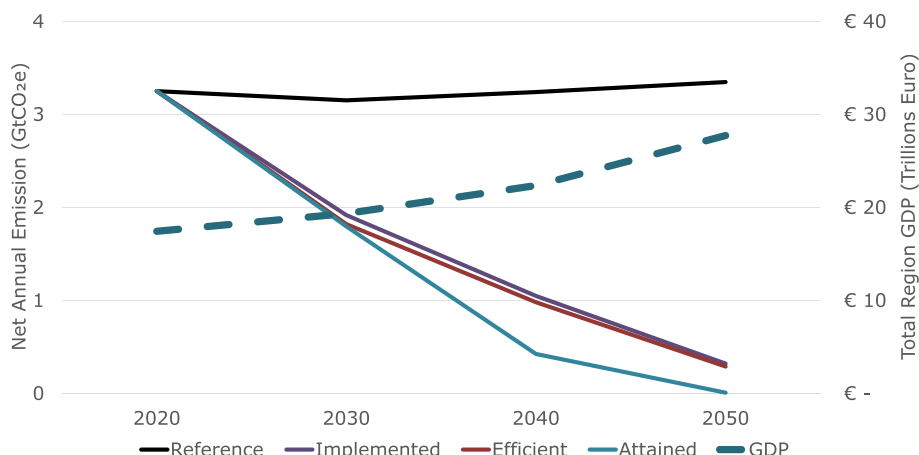


Fig. 8. Europe's net CO₂ emissions and GDP trajectory.

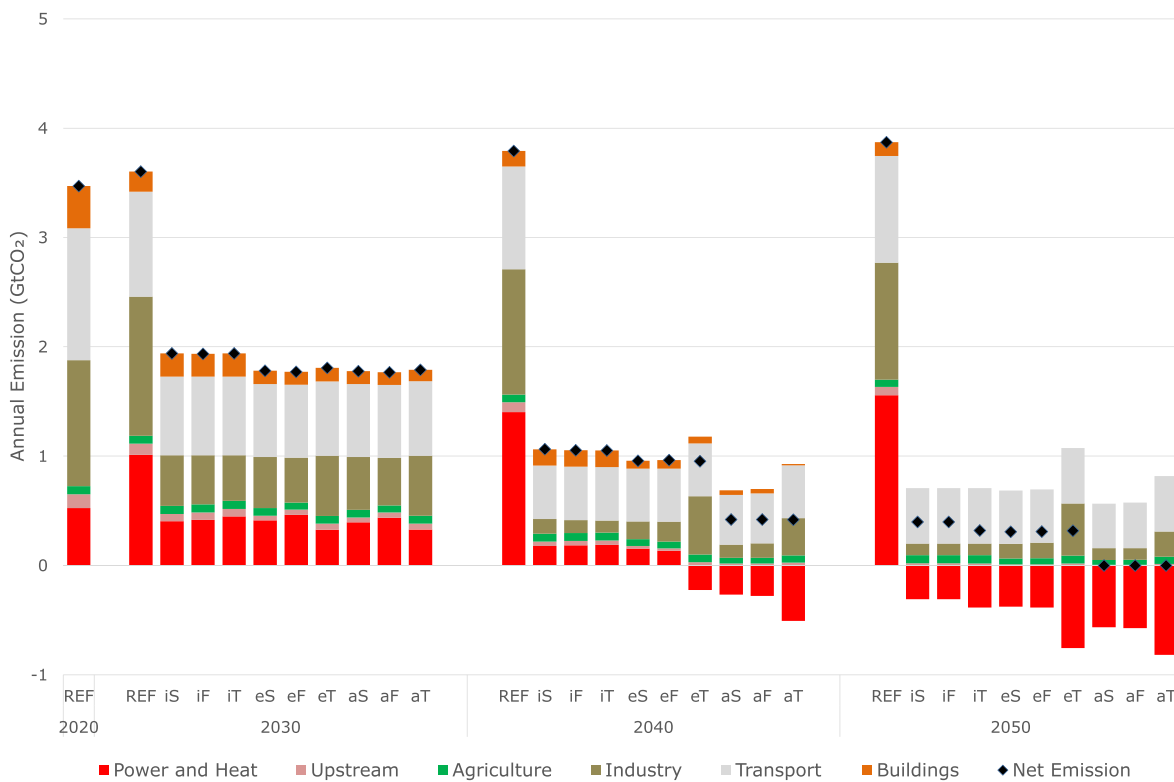


Fig. 9. Europe's annual sectoral CO₂ emissions.

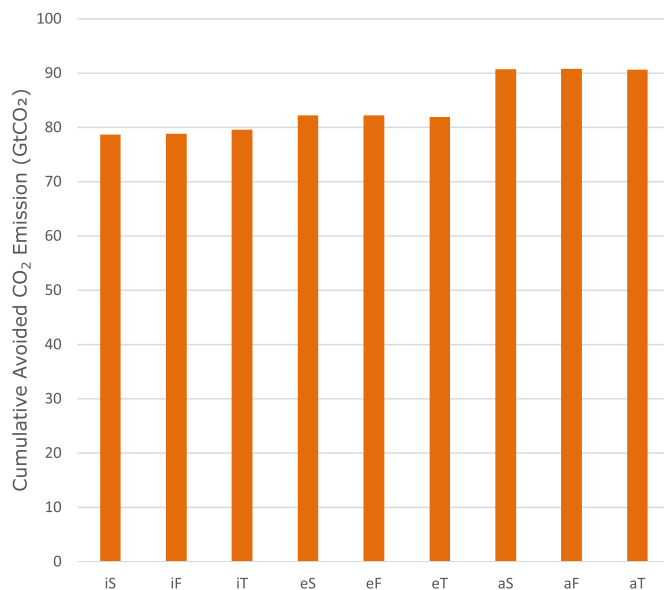


Fig. 10. Avoided CO₂ emissions between 2020 and 2050 at the European level.

approaching or exceeding 7.5 tCO₂ per capita. On the other hand, most of the Southern and Eastern European countries, e.g. Spain, Italy, Romania, and Greece, show comparatively lower emissions, typically below 5 tCO₂ per capita. Across all decarbonisation scenarios, emissions are substantially reduced relative to the 'REF' case. However, the degree and spatial distribution of these reductions vary significantly. In the 'iS', 'iF', 'eS', and 'eF' scenarios, modest residual emissions remain in countries such as Finland, Iceland, Ireland, the Netherlands, Portugal, Spain, Greece, and Estonia, though differences across regions are relatively limited. The 'iT' and 'eT' scenarios exhibit more uneven regional patterns. In these cases, countries such as Norway, Finland, France,

Spain, Portugal, the Netherlands, Belgium, the United Kingdom, and Denmark still emit between 2 and 4 tCO₂ per capita. These emissions are offset by strong negative emissions projected in countries like Germany, Poland, Switzerland, Slovakia, Italy, and Czechia, where emissions per capita fall below zero, in some cases reaching as low as -7.5 tCO₂ per capita. In the most ambitious scenarios ('aS', 'aF', and 'aT'), emissions are minimised across all regions. Under 'aS' and 'aF', all countries achieve net-zero emissions by 2050. In the 'aT' scenario, regional disparities emerge despite net-zero being reached at the continental level (as shown in Fig. 9). A similar pattern to the 'iT' and 'eT' scenarios is observed, with some countries exhibiting residual emissions while others compensate through deep net removals.

Fig. 13 presents the cumulative policy costs per capita across all scenarios over the modelling horizon, expressed in thousand euros. These costs correspond to the European-level data in Fig. 11 but are disaggregated at the country level. Under the 'iS' and 'iF' scenarios, cumulative policy costs are relatively evenly distributed across Europe. Most countries remain below 20 k€/capita, with slightly higher costs in Norway, Sweden, Finland, and Latvia. In the 'eS' and 'eF' scenarios, costs rise more noticeably compared to their 'i' scenario counterparts. Higher values are seen in the Nordics and Baltics, particularly Sweden, Finland, and Estonia, as well as in parts of Southern and Western Europe, including Spain, Portugal, France, the Netherlands, Belgium, Denmark, and Ireland. In contrast, Central and Eastern European countries such as Poland, Hungary, and Romania show cost levels similar to those in the 'i' scenarios. Notably, Norway's policy costs decline as climate ambition increases in the 'S' and 'F' scenarios. The 'a' scenarios result in the highest overall costs. In both 'aS' and 'aF', the burden is more pronounced in Northern Europe (i.e. Scandinavia and the Baltics) and Western Europe (i.e. France, the Netherlands, Spain, Portugal, and Ireland), with several countries exceeding 40 k€/capita. Across all 'T' scenarios, policy costs are more evenly distributed. Although costs generally rise with higher climate ambition, the increase is less pronounced compared to the corresponding 'S' and 'F' scenarios.

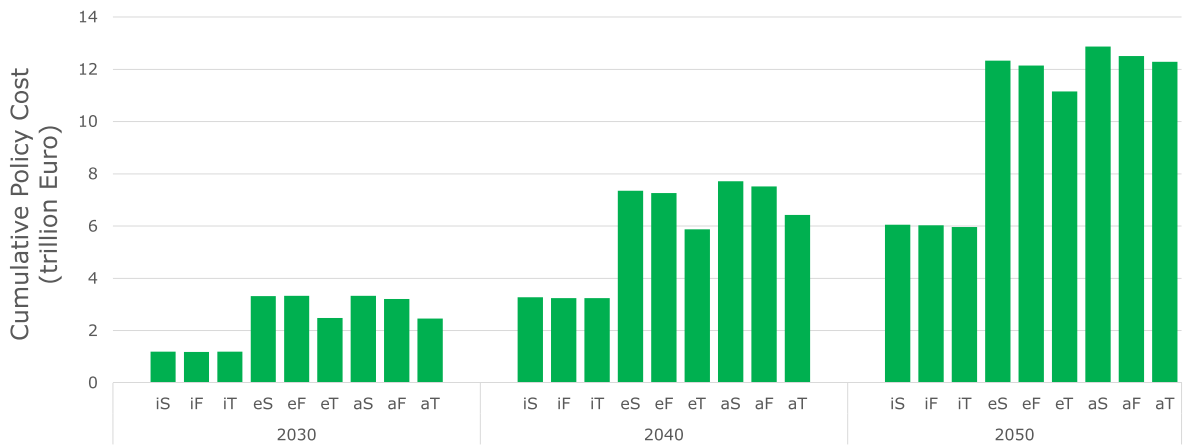


Fig. 11. Europe's cumulative policy cost.

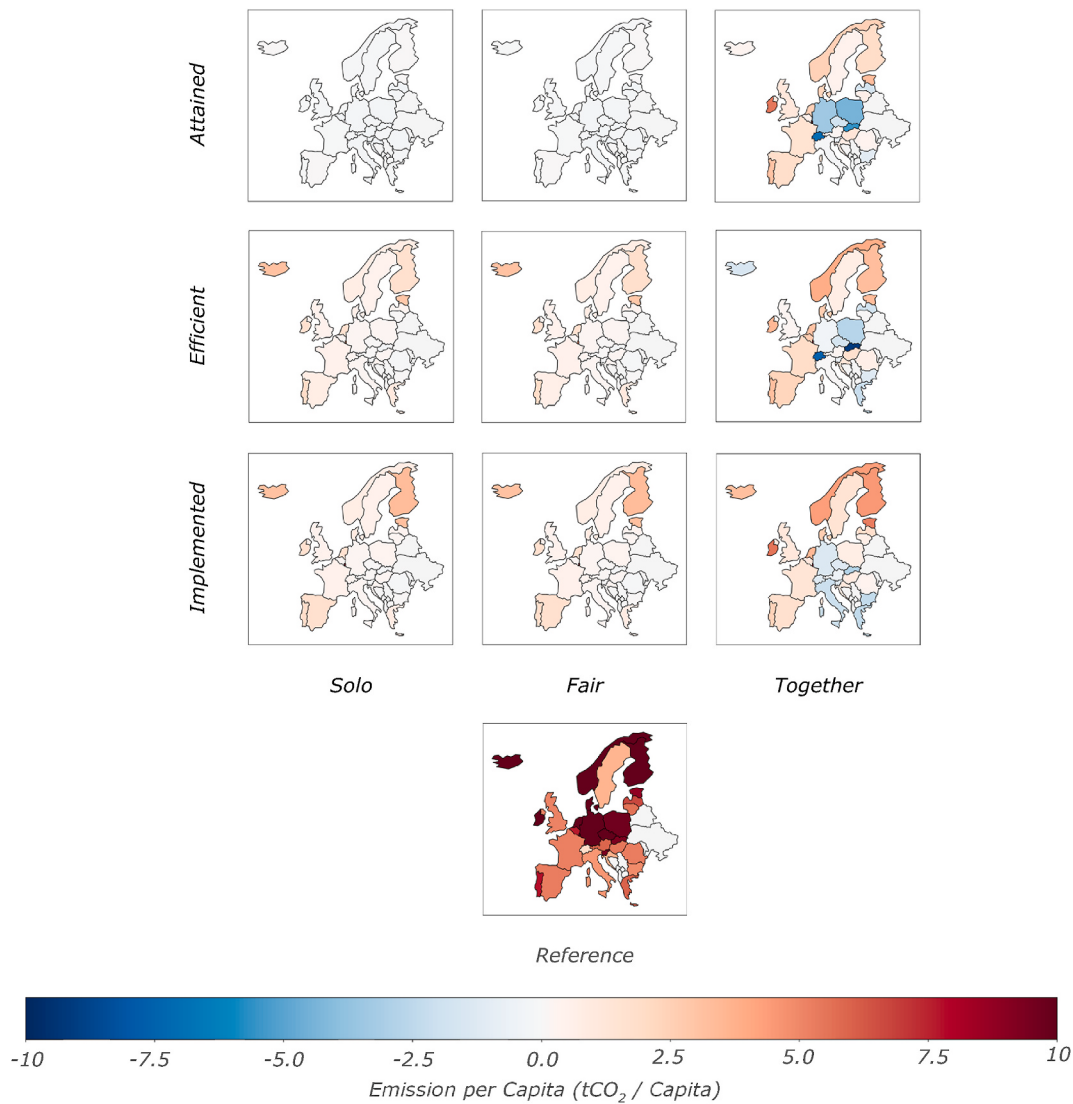


Fig. 12. CO₂ emissions per capita in 2050 across Europe (tCO₂/capita).

4. Discussion

The PEC reduction projected in 'e' and 'a' scenarios is mostly driven by the implementation of the EED PEC savings target, i.e. a 25 %

reduction in PEC relative to 2005 levels by 2030. Projection from various collaboration types suggests that sharing the burden regionally and setting collective targets (i.e. 'T' scenarios) can make domestic energy production more cost-effective than relying on imports (observed in

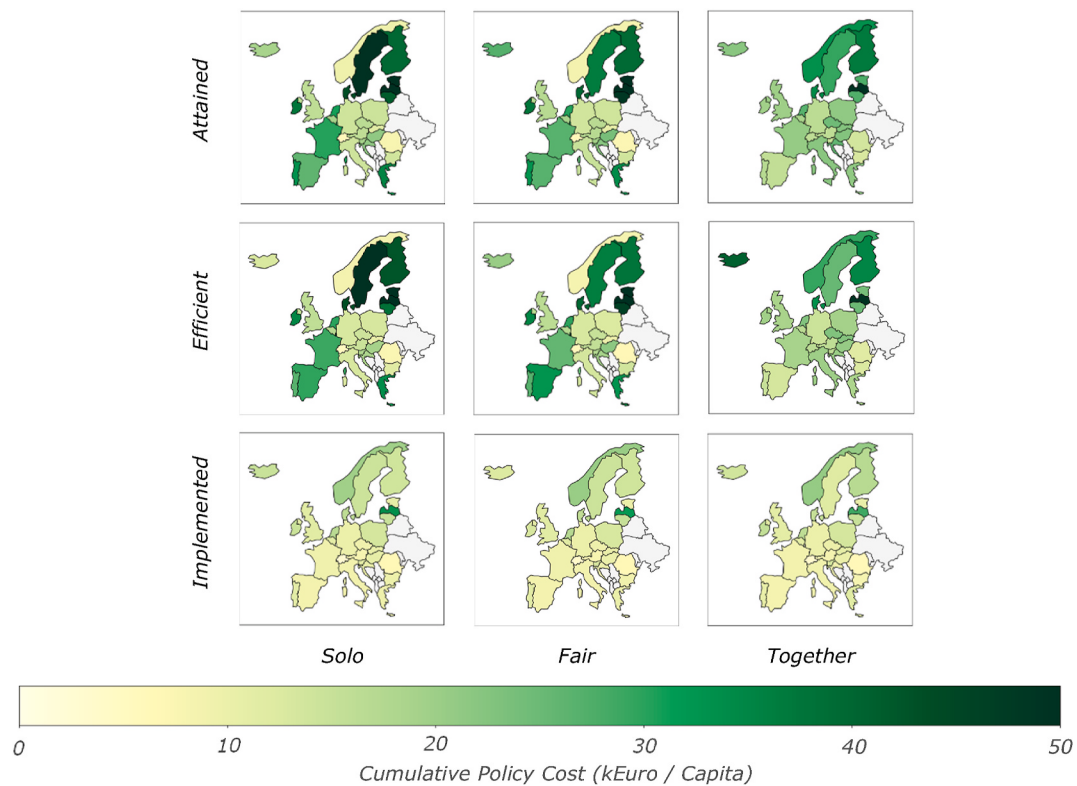


Fig. 13. Cumulative policy cost per country (kEuro/capita).

'S' and 'F' scenarios). Conversely, the energy imports from outside Europe projected by 'S' and 'F' scenarios highlight potential challenges to Europe's energy security; This is a particularly pressing issue amid rising geopolitical concerns. Furthermore, climate action scenarios indicate a shift in the composition of energy imports, with crude oil imports declining while refinery oil product imports rising. This shift raises concerns about emission displacement, as emissions from fuel production could be displaced outside Europe. The projected growth of the share of renewable electricity in PEC is influenced by two key factors: (i). The decreased levelisedcost of renewable energy technologies, as seen even in the 'REF' scenario and (ii). The implementation of the EU RED mandates that at least 42.5 % of electricity supply comes from renewables by 2030. Furthermore, we projected that under the individual target setup, i.e. the 'S' and 'F' scenarios, PEC savings may overshoot the EED target, a trend not seen in the system-wide burden-sharing

framework. This suggests that when countries prioritise self-sufficiency over collective optimisation, they may implement more aggressive domestic energy-saving measures than necessary, potentially leading to higher costs.

Fig. 14 quantifies the contributions of energy savings toward achieving the 2030 energy efficiency target, which illustrates changes in PEC and FEC between 2020 and 2030. PEC changes, represented by blue bars, are derived from Fig. 6, while FEC savings, shown as green bars, are taken from Fig. 7. FEC savings are most prominently realised in the building sector (see Fig. 7), while other demand sectors show minimal energy savings across all scenarios. In the building sector, these savings are achieved through retrofitting efforts (i.e. mostly driven by the EU EPBD policy on dwelling retrofitting targets) and the adoption of highly efficient end-use technologies, such as heat pumps. For a detailed analysis of energy savings in the building sector, we refer readers to our

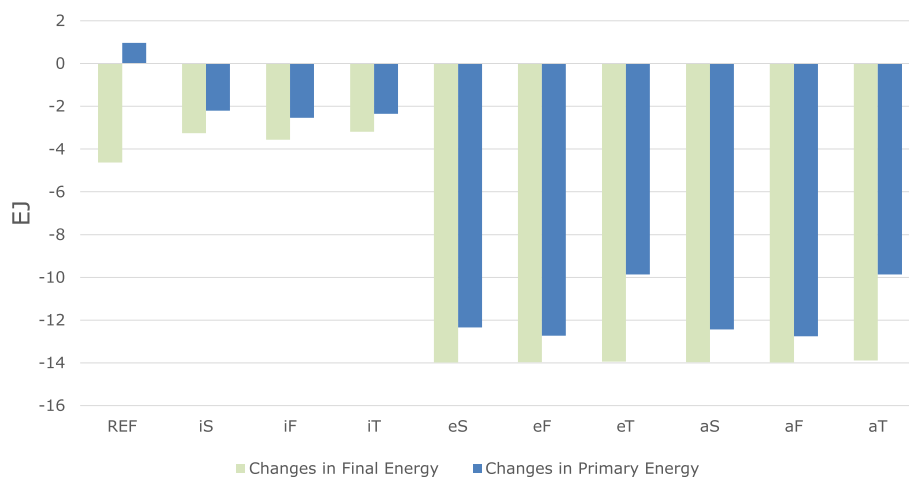


Fig. 14. Changes in energy transformation and import, FEC, and PEC between 2020 and 2030.

previous studies [37,45].

Not all reductions in FEC translate directly into PEC savings, as energy transformation processes introduce additional energy requirements. The gap between primary and FEC reflects the overall efficiency of the energy system, with larger discrepancies indicating increasing inefficiencies in energy conversion. In the 'REF' and 'i' scenarios, FEC savings are estimated at approximately 4 EJ and 3 EJ, respectively. However, their impact on PEC differs: while the 'i' scenarios achieve a reduction of around 2 EJ in PEC demand, the 'REF' scenario sees an increase of approximately 1 EJ. This suggests that without climate control measures, declines in FEC, primarily driven by population decline in some countries and demand-side efficiency improvements, do not necessarily lead to proportional PEC savings. Instead, the 'REF' scenario experiences a rise in PEC, indicating an increasingly inefficient energy transformation process. The difference of approximately 1 EJ between final and PEC savings in the 'i' scenarios is due to the cumulative effect of energy losses in the various energy conversion processes in the system.

The implementation of the EED target in the 'e' and 'a' scenarios may lead to substantial FEC savings, reaching approximately 14 EJ across all scenario variants. In the 'eS', 'eF', 'aS', and 'aF' scenarios, around 12–13 EJ of PEC savings are observed, implying conversion losses of about 1–2 EJ, roughly consistent with those observed in the 'i' scenarios. However, in the 'eT' and 'aT' scenarios, PEC savings are lower, at roughly 10 EJ, suggesting increasing losses in energy conversion up to about 4 EJ. Notably, the 'S' and 'F' collaboration frameworks overshoot the necessary PEC savings targets compared to the system-wide optimisation in the 'T' scenario (see Fig. 6 for the extent of this overshooting). This occurs because these collaboration frameworks provide fewer opportunities for cross-border coordination, leading to an excessive focus on domestic PEC reductions rather than optimising energy use across regions. Consequently, while they achieve higher PEC savings, these collaboration frameworks lead to higher energy system costs (see Fig. 11). This highlights the trade-offs between national energy independence and system-wide optimisation.

Avoided CO₂ emissions between 2020 and 2050 are primarily driven by the level of climate ambition rather than the collaboration framework. While the 'e' scenarios achieve slightly higher emission reductions than the 'i' scenarios, the 'a' scenarios deliver the most substantial cuts, largely due to the inclusion of the proposed 2040 climate target. The additional policy cost associated with meeting the 2040 target in the 'a' scenarios is relatively insignificant when compared to the 'e' scenarios. This suggests that the proposed 2040 climate target is a cost-effective strategy for achieving the EU's long-term climate objectives.

The examination of country-level per capita emissions and policy costs (Figs. 12 and 13, respectively) reveals only marginal differences between the 'S' and 'F' collaboration frameworks. This similarity arises from their comparable burden-sharing structures, which indicates that the fairness-based allocation used in our study closely mirrors a scenario in which all European countries undertake equal decarbonisation efforts. This is because the carbon budget allocation described in Dekker et al. [65] shows only minor differences within Europe between the equal responsibility principle (i.e. the basis of the 'F' scenarios) and grandfathering (i.e. the driver of the 'S' scenarios).

Emission intensity varies significantly across regions under the 'T' scenarios framework. Some countries, particularly in Western and Northern Europe, will retain residual emissions in 2050. To balance these emissions and achieve climate neutrality at the European level, other regions, mainly in Central Europe, are projected to yield negative emissions through the deployment of Negative Emission Technologies (NETs). Given a certain EU-level emission reduction target, the model typically decides whether a country retains residual emissions or achieves negative emissions, primarily based on two factors: (i). The availability of negative emission technology potential, e.g. CCS storage and biomass potential for bioenergy with carbon capture and storage (BECCS), and (ii). The share of hard-to-abate sectors in each country.

Nevertheless, the projected high deployment of BECCS in countries such as Germany, Poland, Switzerland, and Austria seems unlikely given the current low levels of CCS deployment in general, the national policy trends in such countries, economic viability, and public acceptance [78–80].

Under the 'T' strategy, Europe achieves its climate objectives at the lowest possible costs (within the set of scenarios considered here), as attested by the fact that 'T' bars in Fig. 11 are consistently lower than their 'S' and 'F' counterparts. This collaborative approach also supports a more balanced distribution of policy costs across countries by enabling coordinated action. Conversely, the 'S' and 'F' frameworks lead to greater regional cost disparities, with Western and Northern European countries shouldering the highest burdens. The policy cost disparity across Europe, as shown in Fig. 13, indicates that South-West Europe, Scandinavia, and the Baltic countries are projected to face significantly higher per capita policy costs under the 'S' and 'F' collaboration frameworks when meeting the EED target ('e' and 'a' climate ambition). This is driven by several factors, one of which is that the most cost-effective way to achieve energy savings is through demand-side management, e.g. retrofitting buildings to reduce space heating demand. This is particularly beneficial in regions with high space heating needs, e.g. Northern Europe, and in areas with older, poorly insulated building stock, e.g. Eastern Europe (see Refs. [37,45] for a detailed analysis of the European residential sector).

In Norway, policy costs are projected to decrease under the 'eS', 'eF', 'aS', and 'aF' scenarios compared to the 'iS' and 'iF' cases. This decline in costs with increasing climate ambition may appear counterintuitive. It is primarily driven by a reduction in electricity exports and the associated infrastructure requirements, such as interconnectors and generation capacity, assuming domestic demand remains relatively constant across scenarios. The projected drop in exports under scenarios with EED targets is mainly due to more limited capacity expansion. Under the 'S' and 'F' collaboration frameworks, countries are projected to rely more on domestic energy production, as net electricity trade is counted as PEC. This accounting method reduces the demand for electricity imports and, in turn, lowers the need for Norwegian exports and related infrastructure investment. In contrast, under the 'T' framework, Norway is projected to contribute a larger share of the system-wide effort, primarily through increased utilisation of its energy resources to support the broader European energy transition. This outcome is linked to the PEC savings target being applied at the European level, where the PEC associated with renewable electricity generation is counted only in the country where it is generated.

5. Conclusion and policy messages

This study examines how varying levels of climate ambition and cross-border collaboration influence Europe's ability to reach net-zero emissions by 2050, as stipulated under the European Green Deal. Assessment of current energy policies through our set of scenarios signals the inadequacy of existing energy policies in directly limiting CO₂ emissions, with the EU ETS being the only mechanism in Europe that imposes a strict emissions cap. This outcome emphasises the limitations of the existing EU ETS coverage, which does not fully address hard-to-abate sectors, i.e. international aviation and maritime, as well as agriculture. To achieve net zero, Europe requires supplementary policies, e.g. stricter emissions caps, targeted incentives for advanced technologies specific to last-mile decarbonisation efforts, and increased support for renewables & energy efficiency measures. Without such enhancements, Europe risks falling short of its 2050 climate neutrality goal. Ambitious climate goals, e.g. the recently published EED and the proposed enforcement of a 2040 emission abatement target, further drive significant CO₂ reductions. However, it is also important to consider the cost burden and fairness for each national government within Europe.

The 'S' and 'F' collaborations result in more evenly distributed emissions, reflecting their emphasis on either uniform burden-sharing or

fair-based allocations. However, these approaches are less cost-effective overall compared to the “T” collaboration framework. System-wide cooperation demonstrates the potential for minimising total policy costs by optimising resource use and emission reductions across Europe. However, this framework requires strong political will and coordination, as it creates disparities in Europe-wide cost burdens that may require compensation mechanisms designed at the EU level. Although this approach reduces Europe’s reliance on external energy sources, it does not always translate into a more cost-effective or coordinated energy transition at the European level. Ultimately, the collaboration framework determines how equitably and efficiently Europe can achieve its climate goals. While equity-focused frameworks like the fairness approach may align better with social and political priorities, the system-wide collaboration offers a pathway to decarbonisation at the lowest aggregate cost, albeit with greater regional disparities that must be addressed through policy design at the European level. To reconcile the tension between cost-efficiency and fairness, a hybrid policy mechanism that integrates redistributive funding (e.g. the EU Modernisation fund [81]) into system-wide burden-sharing could help align equity and efficiency in practice.

A significant dependency on imports of refinery oil products from outside Europe may arise to meet the growing energy demand in Europe. This shift is particularly more pronounced in scenarios with aggressive reduction of PEC. This dynamic highlights a critical challenge in meeting the EU EED targets: while domestic PEC savings contribute to emission reductions, they do not eliminate Europe’s dependence on external energy sources. Although the EU has introduced mechanisms to address carbon leakage, such as the Carbon Border Adjustment Mechanism (CBAM) [69], this policy currently places a price only on embedded carbon in imported goods while excluding emissions from imported refinery oil products. Given this gap, we recommend extending the CBAM framework to include refinery imports, ensuring that carbon-intensive fuels are subject to equivalent pricing regardless of their origin. This interdependence between PEC, energy savings, and import reliance underscores a tripartite challenge for Europe: achieving decarbonisation goals, ensuring energy security, and minimising the outsourcing of emissions to its vicinity regions.

Our model projections underscore the strategic role of Norway in a decarbonised European energy system across different scenarios. Norway’s low-cost power system emerges as a valuable asset in supporting regional adequacy and system integration. However, these projections should be interpreted with caution. They are subject to significant uncertainty, particularly concerning domestic support for energy infrastructure development in Norway, and due to model simplifications regarding short-term operational dynamics and interconnection constraints. In addition, the accounting method for net electricity trade plays a key role in shaping these outcomes. We recommend a reassessment of how PEC is accounted for at the national level, particularly concerning electricity trade. For example, a distinction should be made between electricity traded within the EU and from outside the Union. Ideally, electricity generated within the EU would be accounted for only in the country of origin, while electricity imported from outside the EU should be counted in the country where it is consumed.

6. Outlook

This study communicates key systemic trade-offs between fairness, cost-efficiency, and energy independence in Europe’s decarbonisation strategy. Furthermore, we show how different collaboration frameworks shape the distribution of emissions, costs, and technological deployment across member states. Nevertheless, there remain several avenues for future research that could complement and expand upon our findings.

First, our analysis underscores the need for dedicated studies targeting the industrial and transport sectors, which are among the hardest to decarbonise. These sectors face unique barriers, e.g. high process temperatures, reliance on liquid fuels, and slower adoption of

electrification technologies. An exploration of innovative solutions tailored to these sectors is crucial, e.g. direct electrification, advanced biofuels, green hydrogen, or along with the strategic deployment of NETs. Further work is needed to explore these dynamics in greater depth using more detailed land use, biomass, and infrastructure assessments.

Second, expanding the geographical scope of analysis to include Europe’s neighbouring regions, e.g. North Africa, the Middle East, and the Eurasian region, is vital to address the growing reliance on energy imports observed across all scenarios in this study. Europe’s energy transition is deeply intertwined with global energy systems and supply chains. Understanding these interdependencies is crucial for ensuring both energy security and global equity in resource utilisation.

Third, the present study’s fairness scenario framework is based on historical emissions as the primary determinant of burden-sharing. Analysing this scenario enables us to introduce, to some extent, the national perspectives in the context of high-level EU climate policies. At the same time, this study does not explicitly represent national policies, e.g. Germany’s Climate Action Law (*Klimaschutzgesetz*) [82] and Spain’s Climate Change and Energy Transition Law [83]. While this simplifies the complex real-world policy landscape, it allows for a clearer analysis of the effect of EU-level climate policy alone on the energy transitions at the national level. It also enables us to assess the role of European-level collaboration and system-wide trade-offs. We acknowledge that in many countries, national instruments may exert a stronger influence than the European-level policies. Future work could explore more detailed bottom-up representations of national policy frameworks and examine their interactions with EU-wide mechanisms. This analysis could be strengthened by linking models that operate at different geographical scales, from global frameworks to European scale models to national and local level models that capture place-specific constraints. Methodological coupling, for example, between energy system optimisation models, agent-based models, and simulation approaches, would enable bottom-up detail to inform top-down strategies and vice versa, thereby reducing blind spots of policy recommendations.

Sensitivity analyses should be conducted to address the uncertainties identified in this study. For instance, the role of the Norwegian power system varies considerably across scenarios, yet the model does not capture regional or cultural dimensions. Potential impacts on Indigenous communities, such as the Sámi people described in Refs. [84,85], who may be directly affected by future infrastructure developments, are not represented. Further research employing market-based models with higher temporal resolution could offer more detailed insights into the availability and flexibility of the Norwegian power system in supporting the broader European grid. Such models could also account for factors like grid congestion, which can significantly influence electricity prices. Another important area for sensitivity analysis is the deployment of NETs. At the time of writing, many aspects of these technologies remain uncertain. Exploring a range of NETs deployment scenarios would help to assess their potential implications for system development and policy outcomes.

Lastly, there are some policies not fully captured by the current modelling approach that merit further research. For instance, policies such as the CBAM [86] could significantly impact global trade and emission displacement from Europe to the rest of the world, yet their implications on the energy transition require further consideration. Similarly, integrating detailed market behaviours, such as the decision-making processes of energy producers and consumers, and socio-economic factors, such as migration within Europe, or shifts in labour markets, could provide a more nuanced understanding of the transition. Additionally, incorporating potential breakthroughs in decarbonisation technologies, such as solid-state batteries or advanced small modular nuclear reactors, could refine future pathways and reveal new opportunities for innovation-driven mitigation strategies. These directions for future research would not only address gaps in the current study but also provide a more holistic and forward-looking framework to support Europe’s ambitious climate goals.

Author contributions

Steven S. Salim: Conceptualisation, Methodology, Data Curation, Formal Analysis, Visualisation, Writing - Original Draft. Stefan L. Luxembourg: Conceptualisation, Data Curation, Methodology. Koen Smekens: Conceptualisation, Methodology. Francesco Dalla Longa: Conceptualisation, Methodology, Formal Analysis, Visualisation, Writing - Review & Editing, Supervision. Bob van der Zwaan: Conceptualisation, Writing - Review & Editing, Supervision.

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.

Appendix 1. EU Emissions Trading System [29]

In section 2, we outlined the EU ETS as one of the most essential policies among EU climate policies. This appendix provides an interpretation of the EU ETS policy and how we incorporate the climate targets into the TIMES-Europe model as constraints. While our approach is stylistic and comprises minor deviations from the official policy documents, it aligns with the overarching goals of the EU ETS. The calculation of emission allowances considers historical emissions, reduction targets, and the Linear Reduction Factor (LRF).

The LRF, which determines the annual decrease in the total number of allowances, is applied in several phases as follows.

- Phase I (2005–2007): No LRF was applied during this pilot phase, with a fixed cap of approximately 2299 MtCO₂ per year for participating countries.
- Phase II (2008–2012): An implicit annual reduction aligned with Kyoto Protocol targets was applied, though no formal LRF was defined.
- Phase III (2013–2020): An LRF of 1.74 % was introduced.
- Phase IV (2021–2030): The LRF increased to 2.2 % and was further adjusted to 4.2 % under the Fit for 55 packages. For ETS2 sectors, a separate LRF of 5.1 % applies starting in 2026.

The EU ETS Phases I and II were based on verified emissions from 2005, which serve as the baseline for reduction targets. For the EU27, UK, Iceland, and Norway, this data is published by the European Environment Agency (EEA) transparency database [87]. For Switzerland, the data can be sourced from the UNFCCC national inventory submission [88]. The aggregated 2005 emissions baseline for Europe is shown in Table 2.

Table 2
Europe's total CO₂ emissions 2005 [87].

Country	2005 Emissions (MtCO ₂)
Austria	32
Belgium	58
Bulgaria	38
Croatia	5
Cyprus	5
Czech Republic	97
Denmark	37
Estonia	17
Finland	45
France	150
Germany	493
Greece	71
Hungary	30
Ireland	19
Italy	216
Latvia	4
Lithuania	13
Luxembourg	3
Malta	2
Netherlands	86
Poland	238
Portugal	37
Romania	74
Slovakia	30
Slovenia	9
Spain	172
Sweden	22
EU27 Total	1883
UK	201
Switzerland (CH)	5

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Table 2 (continued)

Country	2005 Emissions (MtCO ₂)
Iceland (IS)	2
Norway (NO)	14

The critical phases for our modelling are Phase III and Phase IV of ETS. From here, the EU implement a hard cap on emissions that reduces annually. The annual reduction in emissions R is calculated using equation (1):

$$R = C_0 \times LRF \quad (1)$$

Where.

R = Annual reduction in emissions (in MtCO₂).

C_0 = Cap at the start of the period (in MtCO₂).

LRF = Linear Reduction Factor

Example of calculation:

For Phase III (2013–2020), with an initial cap C_0 of 2084 MtCO₂ [87,88] and an LRF of 1.74 %, for the first year of ETS:

$$R = 2,084 \times 1.74\% = 38.3 \text{ MtCO}_2$$

Hence, approximately 38.3 MtCO₂ was removed from the annual allowances for the year 2013.

In this study, we focus solely on CO₂ emissions, whereas the EU ETS officially also includes N₂O and PFCs. For modelling purposes, emission allowances are implemented starting in 2020 and are presented in Table 3. While the official EU ETS only extends to 2030, in this study, we assume the trajectory continues linearly until 2050 following the Phase IV LRF.

Table 3
ETS allowances cap

Year	ETS 1 (MtCO ₂)	ETS 2 (MtCO ₂)	Total Allowances (MtCO ₂)
2020	1561	–	1561
2025	1433	–	1433
2027	1347	1200	2547
2030	1128	1015	2143

The EU ETS sectoral coverage as represented in the TIMES-Europe model is detailed in Table 4. For modelling purposes, all ETS 1 sectors are capped starting in 2020, while ETS 2 sectors begin in 2027. This slightly deviates from the official starting years for aviation (2021) and maritime (2024).

Table 4
The EU ETS sectoral coverage.

	TIMES-Europe Sector	Inclusion
ETS 1	Power & Heat generation	All processes
	Industry	All processes
	Aviation	Intra-Europe flights only
	Maritime	All emissions for all intra EU voyages; 50 % emission of extra EU voyages
ETS 2	Buildings	All processes
	Road transport	All processes

Appendix 2. Parametrisation of EU Energy Policies

The model parameters presented in Table 5 are derived from a broad range of EU policies. These policies, which we classify as sectoral policies (positioned at the bottom of the policy pyramid). They serve as background parameters in our modelling framework. However, certain EU policies, e.g. FuelEU Maritime [89] and CBAM [86], are not incorporated in this study, though they may influence future emission trajectories. As outlined in Section 2, these policies are interpreted as modelling constraints that apply at the European level, independent of the collaboration framework. This allows the TIMES-Europe model to endogenously optimise the most cost-efficient allocation of investments to meet these constraints.

Table 5
Background parameter synthesised from EU policies

Policy	Model Parameter	Reference
Renewable Energy Directive (RED I & II)	Renewable electricity shares Europe-wide target: ≥ 42.5 % by 2030	[49]
Part of RED: Offshore energy strategy	Offshore wind capacity: 60 GW (2030), 300 GW (2050)	
	Ocean energy capacity: 300 GW by 2050	
Part of RED: Hydrogen strategy	Electrolyser capacity: 6 GW (2024), 40 GW (2030)	

(continued on next page)

Table 5 (continued)

Policy	Model Parameter	Reference
Alternative Fuels & Transport Decarbonisation	Green hydrogen production: 120 PJ (2024), 1200 PJ (2030) Sustainable aviation fuel: ≥ 2 % (2025), 70 % (2050) All new vehicles will have zero emissions by 2035 Emission reductions: 55 % by 2030 for passenger cars (PC) and light commercial vehicles (LCV), and 90 % by 2040 for heavy-duty vehicles (HDV).	[73,90]
Energy Performance of Buildings Directive (EPBD)	Retrofitting rate: 3 % dwelling stock per year Europe-wide All new buildings must be zero-emission	[74]
Carbon Management & Net-Zero Industry	CO ₂ injection capacity: 50 MtCO ₂ /year (2030), 280 MtCO ₂ /year (2050)	[91,92]

Table 6 presents the foreground parameters, which drive the key distinctions between scenarios in this study. Unlike background parameters, foreground parameters are optimised differently depending on the collaboration framework.

- Solo (S) Collaboration: Each country faces equal reduction rates and final allowances.
- Fair (F) Collaboration: Emission reductions and allowances are allocated per country based on an equal cumulative per capita principle.
- Together (T) Collaboration: Emission reductions and allowances are optimised at the European level as a whole.

For instance, the EU EED requires a 25 % reduction in PEC by 2030 (relative to 2005 levels), setting a PEC cap of 49.1 EJ in 2030 (EU-wide). Under.

- Solo (S) Collaboration: Each country must achieve a 25 % reduction in PEC.
- Fair (F) Collaboration: The required reduction is divided equitably per country, based on fair-share principles as described in Dekker et al.
- Together (T) Collaboration: Europe as a whole must achieve a 25 % reduction, allowing some countries to underperform if others overcompensate.

Table 6

Foreground parameter synthesised from EU Policies

Policy	Model Parameter	Reference
Energy Efficiency Directive (EED)	PEC cap: 49.1 EJ by 2030 Europe-wide FEC cap: 38.1 EJ by 2030 Europe-wide	[30]
2040 Climate Target	CO ₂ emissions cap: ~ 0.42 GtCO ₂ e by 2040 (reflecting a 90 % reduction from 1990 levels)	[31]

Table 7 summarises the scenario-specific parameters applied across all scenarios. The REF serves as a baseline, assuming background parameters (Table 5) evolve at historical growth rates observed between 2015 and 2020 (post-Paris Agreement trends). For example, the building retrofitting rate under 'REF' follows the 1 % annual dwelling stock renovation rate observed in 2015–2020. Additionally, as noted earlier, the EU EED is only implemented in the 'e' and 'a' scenarios, while the 2040 climate target is exclusive to 'a' scenarios.

Table 7

Scenario parameterisation

	Scenario	Burden Sharing Type	Sectoral Policies	ETS	EED: 2030 PEC and FEC Cap	2040 Emission Reduction Target
REF	Reference	–	Growth rate trend derived from 2015 to 2020	–	–	–
iS	Implemented – Solo	Equal reduction rate and final allowances per country.	Optimise at the European level.	Emission cap with identical LRF per country.	–	–
iF	Implemented – Fair	Reduction rate and final allowances per country based on an equal cumulative per capita principle.	Optimise at the European level.	Emission cap with fair LRF burden.	–	–
iT	Implemented - System	Reduction rate and final allowances at the European level as a whole.	Optimise at the European level.	Emission cap with LRF at the European level.	–	–
eS	Efficient – Solo	Equal reduction rate and final allowances per country.	Optimise at the European level.	Emission cap with identical LRF per country.	Reduce 25 % PEC and 34 % FEC relative to the 2005 levels.	–
eF	Efficient – Fair	Reduction rate and final allowances per country based on an equal cumulative per capita principle.	Optimise at the European level.	Emission cap with fair LRF burden.	Reduce 25 % PEC and 34 % FEC relative to the 2005 levels.	–
eT	Efficient – System	Reduction rate and final allowances at the European level as a whole.	Optimise at the European level.	Emission cap with LRF at the European level.	Reduce 25 % PEC and 34 % FEC relative to the 2005 levels.	–
aS	Ambitious – Solo	Equal reduction rate and final allowances per country.	Optimise at the European level.	Emission cap with identical LRF per country.	Reduce 25 % PEC and 34 % FEC relative to the 2005 levels.	90 % reduction in net emissions compared to 1990 levels by 2040.
aF	Ambitious - Fair	Reduction rate and final allowances per country based on an equal cumulative per capita principle.	Optimise at the European level.	Emission cap with fair LRF burden.	Reduce 25 % PEC and 34 % FEC relative to the 2005 levels.	90 % reduction in net emissions compared to 1990 levels by 2040.

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Table 7 (continued)

Scenario		Burden Sharing Type	Sectoral Policies	ETS	EED: 2030 PEC and FEC Cap	2040 Emission Reduction Target
aT	Ambitious - System	Reduction rate and final allowances at the European level as a whole.	Optimise at the European level.	Emission cap with LRF at the European level.	Reduce 25 % PEC and 34 % FEC relative to the 2005 levels.	90 % reduction in net emissions compared to 1990 levels by 2040.

Appendix 3. Sectoral emissions intensity across Europe

Fig. 15, 16, 17, 18, 19 and 20 present the sectoral emissions intensity as a breakdown of Fig. 12. In the power and heat sector (Fig. 15), emissions shift into negative territory across Europe relative to the ‘REF’ scenario, especially in central countries like Germany, Switzerland, Poland, Czechia, and Slovakia under the ‘T’ scenarios. The agricultural sector (Fig. 16) shows minimal change across scenarios, reflecting limited decarbonisation options in the model. Industrial emissions (Fig. 17), consistent with Fig. 9, are higher in ‘T’ scenarios, particularly in Central Europe. The transport sector (Fig. 18) follows similar trends across scenarios, suggesting cost-driven rather than policy-driven decarbonisation by 2050. In contrast, the upstream and buildings sectors show marked differences between ‘REF’ and climate policy scenarios, highlighting the critical role of policy in driving their transition.

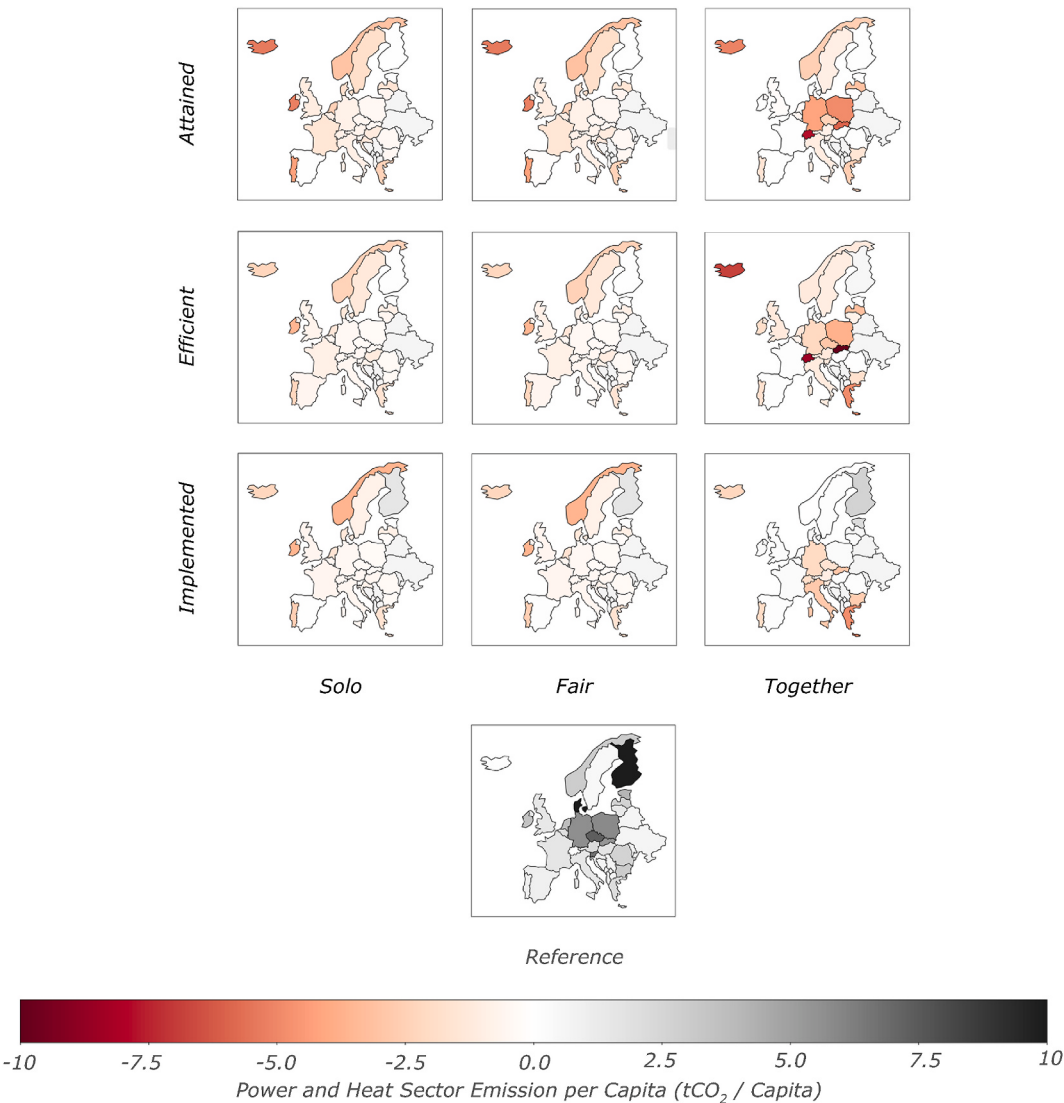


Fig. 15. 2050 Power &Heat Sector CO₂ emissions per capita across Europe (tCO₂ / capita).

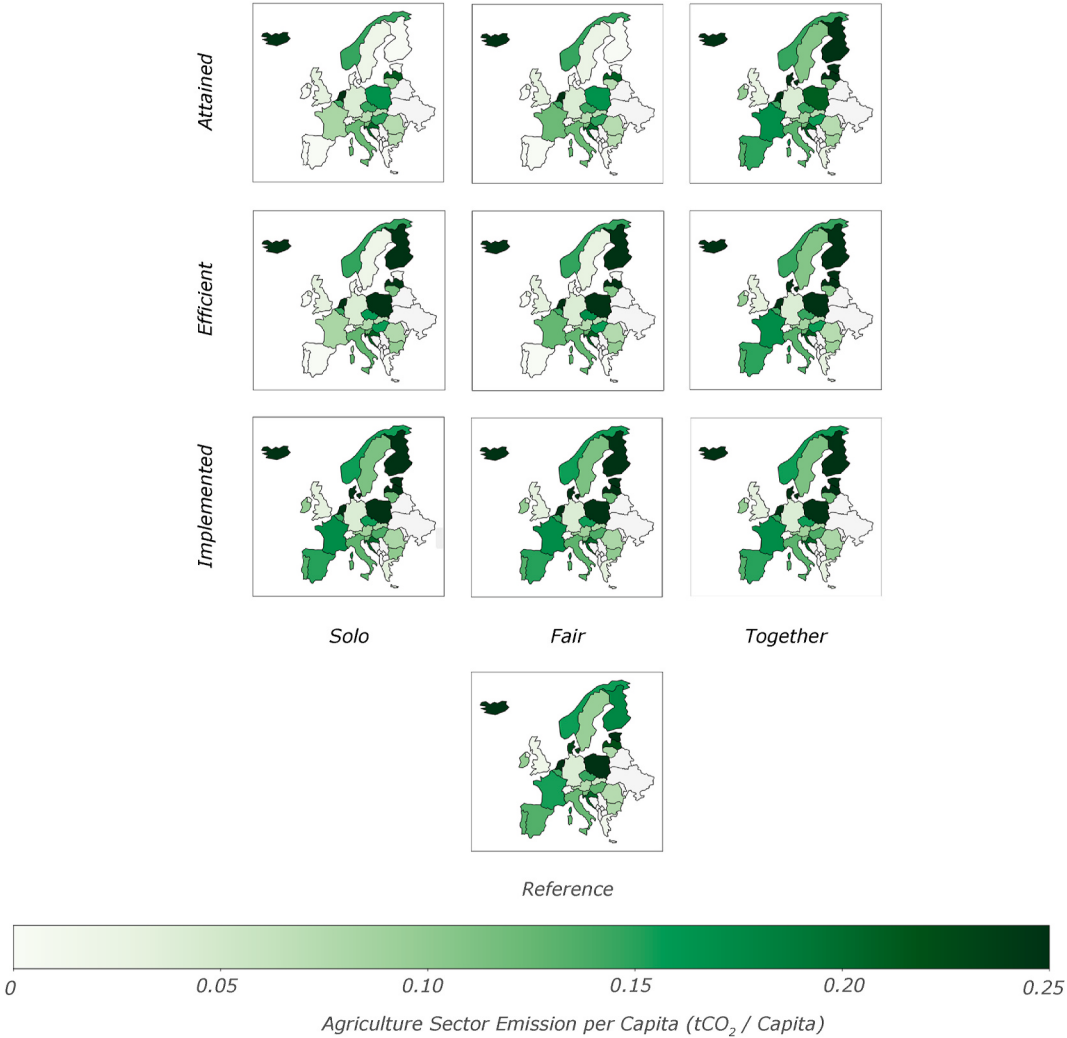


Fig. 16. 2050 Agriculture Sector CO₂ emissions per capita across Europe (tCO₂ / capita).

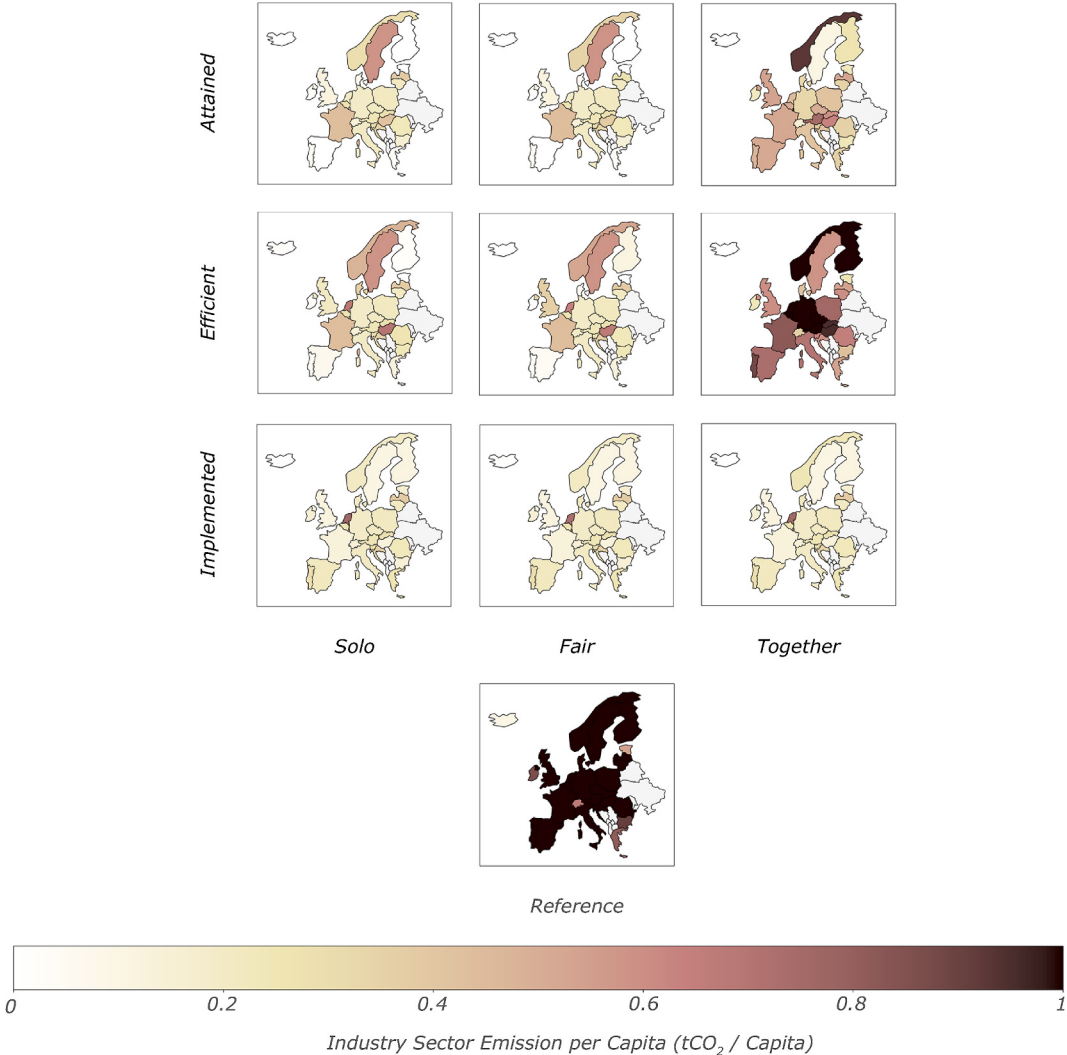


Fig. 17. 2050 Industry Sector CO₂ emissions per capita across Europe (tCO₂ / capita).

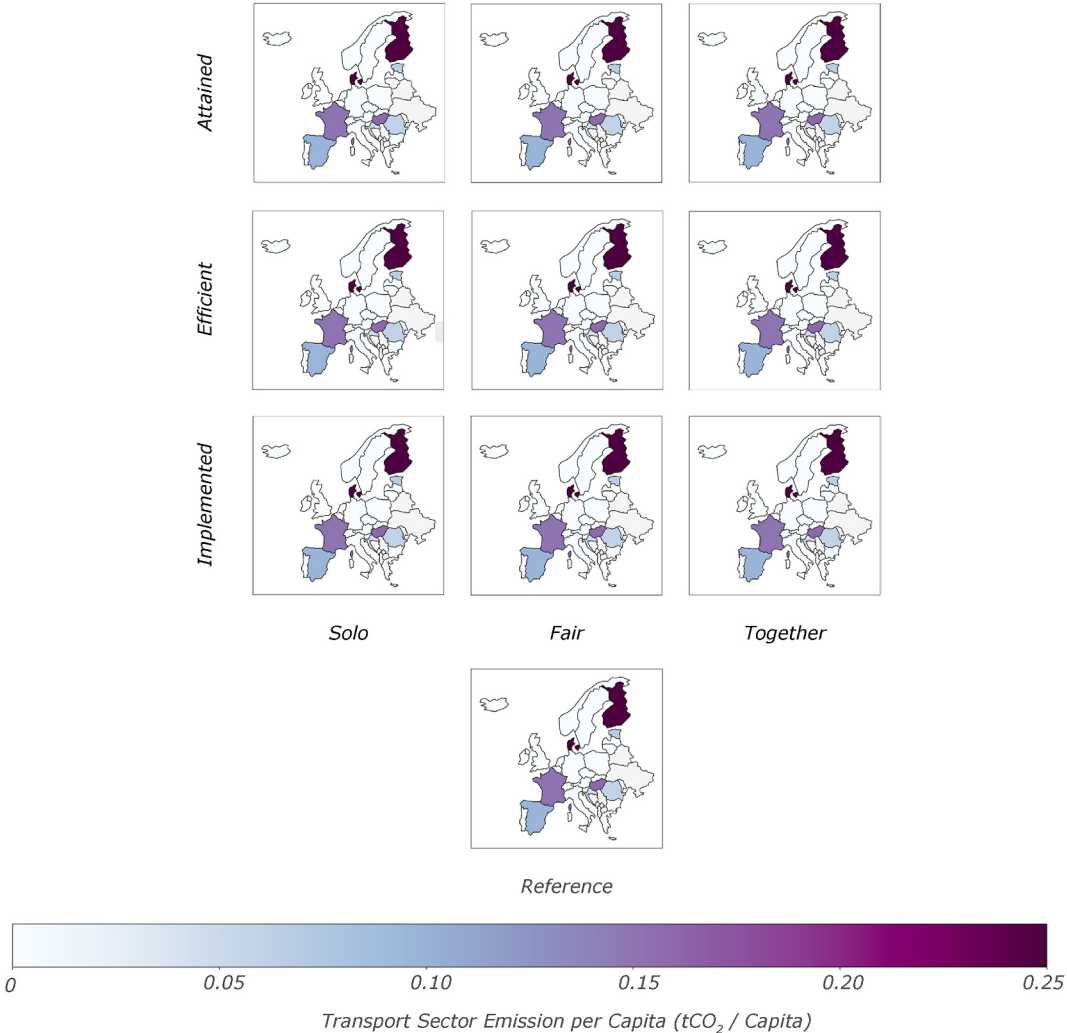


Fig. 18. 2050 Transport Sector CO₂ emissions per capita across Europe (tCO₂ / capita).

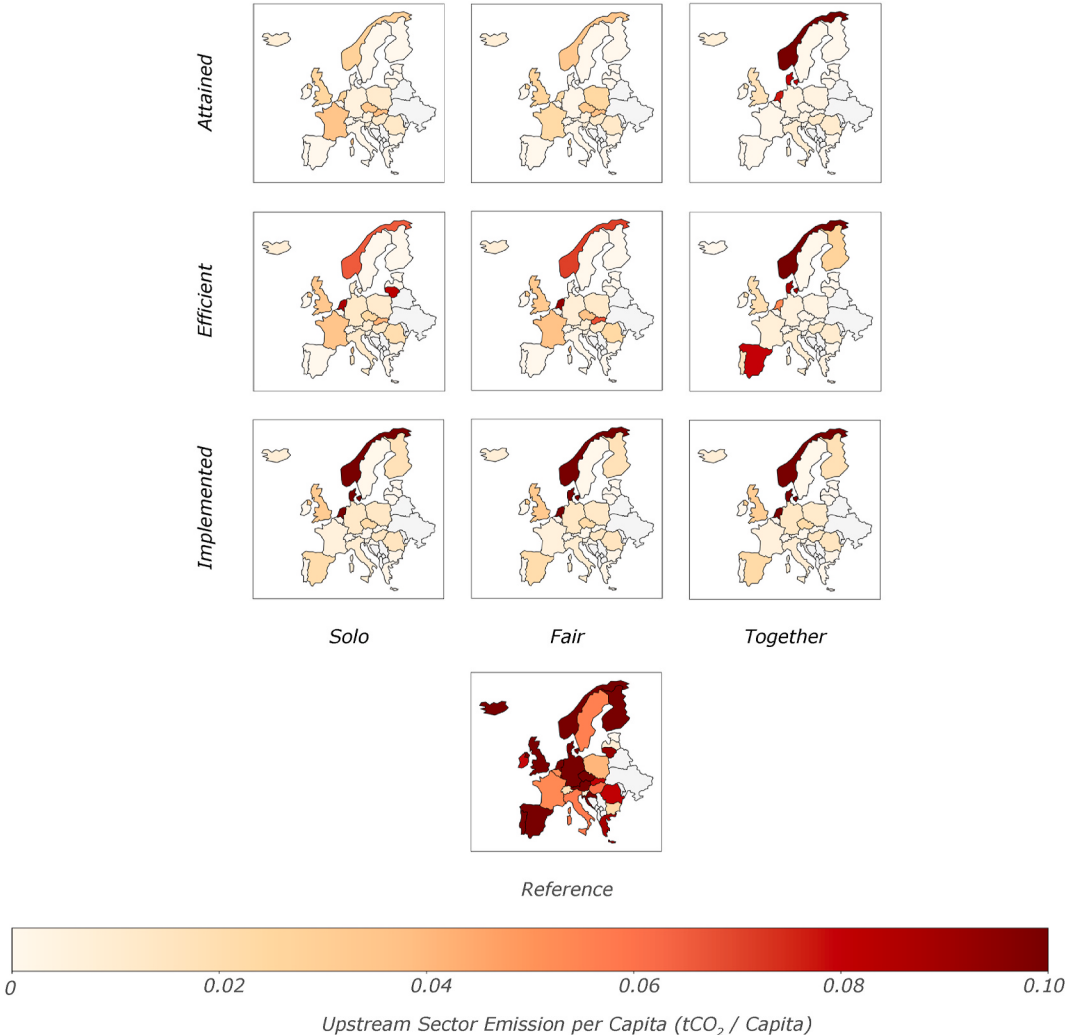


Fig. 19. 2050 Upstream Sector CO₂ emissions per capita across Europe (tCO₂ / capita).

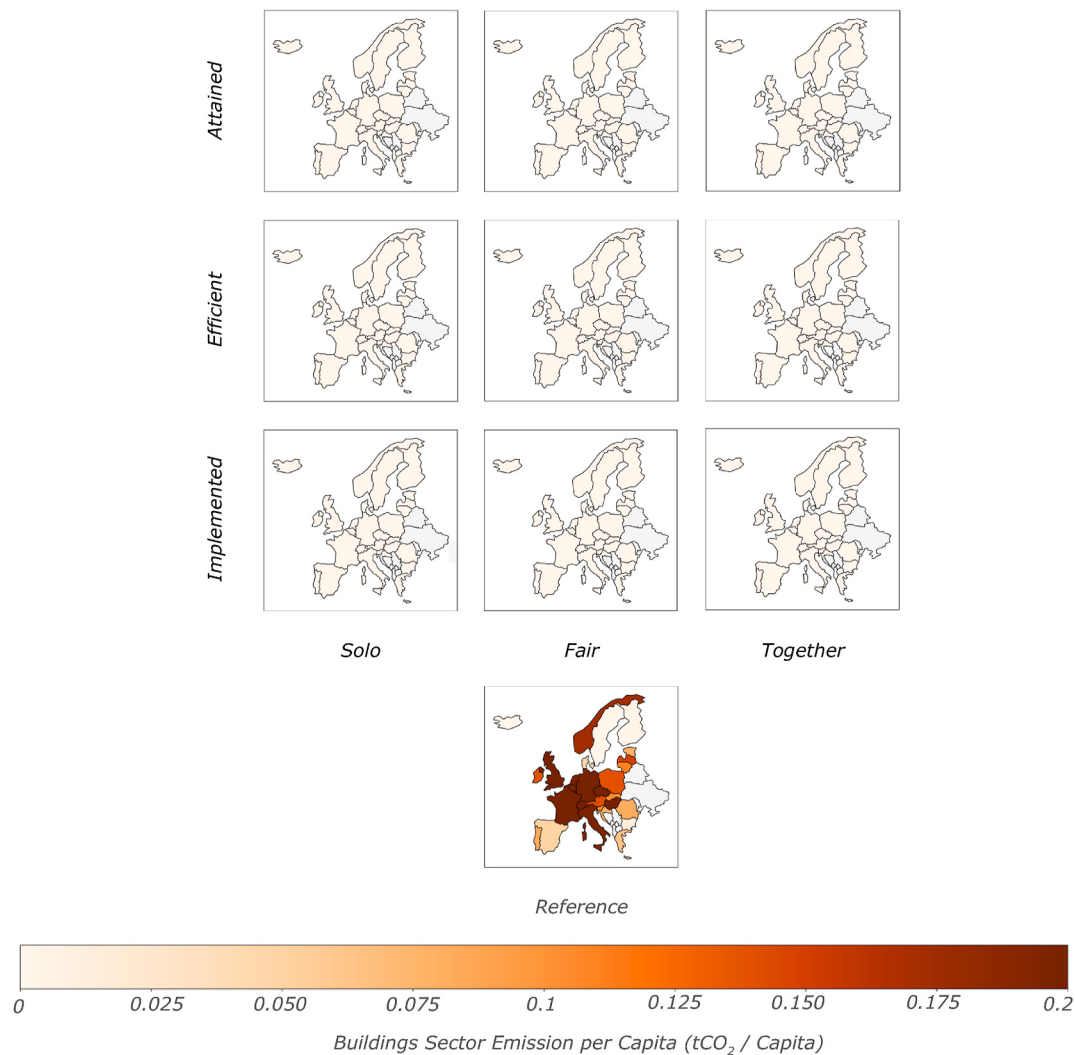


Fig. 20. 2050 Buildings Sector CO₂ emissions per capita across Europe (tCO₂ / capita).

Data availability

Data will be made available on request.

References

- [1] IPCC. Climate change 2023: synthesis report. Contribution of working groups I, II and III to the sixth assessment report of the intergovernmental Panel on climate change. Geneva: IPCC; 2023.
- [2] H. Hersbach et al. ERA5 monthly averaged data on single levels from 1940 to present.
- [3] Kosaka Y, et al. The JRA-3Q reanalysis. Journal of the Meteorological Society of Japan Ser II 2024;102(1):49–109. <https://doi.org/10.2151/jmsj.2024-004>.
- [4] Loughhead JN. Can we develop better international research collaboration on decarbonization? Technology Review for Carbon Neutrality 2024. <https://doi.org/10.26599/TRCN.2025.9550002>.
- [5] Morice CP, et al. An updated assessment of near-surface temperature change from 1850: the HadCRUT5 data set. J Geophys Res Atmos 2021;02/16 2021;126(3). <https://doi.org/10.1029/2019JD032361>. e2019JD032361.
- [6] Huang B, Yin X, Menne MJ, Vose R, Zhang H-M. Improvements to the land surface air temperature reconstruction in NOAA GlobalTemp: an artificial neural network approach. Artificial Intelligence for the Earth Systems 2022;1(4):e220032. <https://doi.org/10.1175/AIES-D-22-0032.1> (in English).
- [7] Rohde RA, Hausfather Z. The Berkeley Earth land/ocean temperature record. Earth Syst Sci Data 2020;12(4):3469–79. <https://doi.org/10.5194/essd-12-3469-2020>.
- [8] Copernicus. Global climate Highlights 2024 [Online]. Available: <https://climate.copernicus.eu/global-climate-highlights-2024>; 2024.
- [9] COP 21 Session. The paris agreement [Online]. Available: <https://unfccc.int/documents/184656>; 2018.
- [10] EEA. European climate risk assessment, 1. European Environment Agency Publishing Office; 2024. p. 486. <https://doi.org/10.2800/8671471>.
- [11] IPCC. Climate change 2022: impacts, adaptation and vulnerability. Cambridge, UK and New York, NY, USA: IPCC; 2022 [Online]. Available: <https://www.ipcc.ch/report/ar6/wg2/>.
- [12] Friedlingstein P, et al. Global carbon budget 2023. Earth Syst Sci Data 2023;15(12):5301–69. <https://doi.org/10.5194/essd-15-5301-2023>.
- [13] Jacob D, et al. Climate impacts in Europe under +1.5°C global warming. Earths Future 2018;02/01 2018;6(2):264–85. <https://doi.org/10.1002/2017EF000710>.
- [14] Harrison PA, et al. Cross-sectoral impacts of climate change and socio-economic change for multiple, european land- and water-based sectors. Clim Change 2015;02/01 2015;128(3):279–92. <https://doi.org/10.1007/s10584-014-1239-4>.
- [15] Forzleri G, et al. Escalating impacts of climate extremes on critical infrastructures in Europe. Glob Environ Change 2018;01/01/2018;48:97–107. <https://doi.org/10.1016/j.gloenvcha.2017.11.007>.
- [16] Moore FC, Lobell D. The fingerprint of climate trends on European crop yields, 112. Proceedings of the National Academy of Sciences; 2014. p. 2670–5.
- [17] Campagnolo L, et al. The cost of climate change on households and families in the EU. The European Economic and Social Committee (EESC); 2023. <https://doi.org/10.2864/229292>.
- [18] Ciscar J-C, et al. Physical and economic consequences of climate change in Europe. Proc Natl Acad Sci 2011;108(7):2678–83. <https://doi.org/10.1073/pnas.1011612108>.
- [19] Jones MW, et al. National contributions to climate change due to historical emissions of carbon dioxide, methane, and nitrous oxide since 1850. Sci Data 2023;03/29 2023;10(1):155. <https://doi.org/10.1038/s41597-023-02041-1>.

- [20] Janssens-Maenhout G, et al. EDGAR v4.3.2 global atlas of the three major greenhouse gas emissions for the period 1970–2012. *Earth Syst Sci Data* 2019;11(3):959–1002. <https://doi.org/10.5194/essd-11-959-2019>.
- [21] Hoelsy RM, et al. Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the community emissions data system (CEDS). *Geosci Model Dev* (GMD) 2018;11(1):369–408. <https://doi.org/10.5194/gmd-11-369-2018>.
- [22] Delreux T, Ohler F. Climate policy in European union politics. Oxford University Press; 2019-03-26 2019. <https://doi.org/10.1093/acrefore/9780190228637.013.1097> (in English).
- [23] Vogler J. The European contribution to global environmental governance. *Int Aff* 2005;81(4):835–50. <https://doi.org/10.1111/j.1468-2346.2005.00487.x>.
- [24] Tkachuk O. The European union in its pursuit of being a global leader in climate neutrality. *Global Policy* 2024;12/01 2024;15(S8):69–74. <https://doi.org/10.1111/1758-5899.13480>.
- [25] Parker CF, Karlsson C, Hjerpe M. Assessing the European Union's global climate change leadership: from Copenhagen to the Paris agreement. *J Eur Integrat* 2017;02/23 2017;39(2):239–52. <https://doi.org/10.1080/07036337.2016.1275608>.
- [26] Oberthür S, Groen L. The European union and the Paris agreement: leader, mediator, or bystander? *WIREs Climate Change* 2017/01/01 2017;8(1):e445. <https://doi.org/10.1002/wcc.445>.
- [27] EU. European green deal. Off J Eur Union 2019 [Online]. Available: <https://www.consilium.europa.eu/en/policies/green-deal/>.
- [28] EU. Fit for 55. Off J Eur Union 2021 [Online]. Available: <https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/>.
- [29] EU. Establishing a scheme for greenhouse gas emission allowance trading within the community. Off J Eur Union 2003 [Online]. Available: <http://data.europa.eu/eli/dir/2003/87/2024-03-01>.
- [30] EU. Energy efficiency directive. Off J Eur Union 2023 [Online]. Available: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023L1791>.
- [31] EU. Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just, and prosperous society. Off J Eur Union 2024 [Online]. Available: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2024:63:FIN>.
- [32] Neumann F, Zeyen E, Victoria M, Brown T. The potential role of a hydrogen network in Europe. *Joule* 2023/08/16/2023;7(8):1793–817. <https://doi.org/10.1016/j.joule.2023.06.016>.
- [33] Brunsch D, Radek J, Ostmeier L, Weber C. Midterm perspectives on natural gas after the European gas crisis: reviewing German energy transition studies. *Renew Sustain Energy Rev* 2025/03/01/2025;210:115223. <https://doi.org/10.1016/j.rser.2024.115223>.
- [34] Gardumi F, et al. Carrying out a multi-model integrated assessment of European energy transition pathways: challenges and benefits. *Energy* 2022/11/01/2022; 258:124329. <https://doi.org/10.1016/j.energy.2022.124329>.
- [35] Oliveira FF, Sousa DM, Kotovica N. Going beyond European emission targets: pathways for an urban energy transition in the city of Riga. *Energy* 2022/05/01/2022;246:123352. <https://doi.org/10.1016/j.energy.2022.123352>.
- [36] Sarmiento L, et al. Comparing net zero pathways across the Atlantic A model inter-comparison exercise between the energy Modeling forum 37 and the European climate and energy Modeling forum. *Energy and Climate Change* 2024/12/01/2024;5:100144. <https://doi.org/10.1016/j.egycc.2024.100144>.
- [37] S. S. Salim, S. L. Luxembourg, F. Dalla Longa, and B. van der Zwaan, "From retrofitting to renewables: navigating energy transition pathways for European residential space heating," *Energies*, vol. 17, no. 10, doi: 10.3390/en17102363.
- [38] Capros P, et al. Outlook of the EU energy system up to 2050: the case of scenarios prepared for European Commission's "clean energy for all Europeans" package using the PRIMES model. *Energy Strategy Rev* 2018/11/01/2018;22:255–63. <https://doi.org/10.1016/j.esr.2018.06.009>.
- [39] Montenegro RC, Fahl U. Carbon leakage and competitiveness: socio-economic impacts of greenhouse gas emissions decrease on the European area until 2050. In: 2017 14th international conference on the European energy market (EEM); 6–9 June 2017 2017. p. 1–5. <https://doi.org/10.1109/EEM.2017.7981970>.
- [40] Li X, Liu Y, Zhang J, Yang L. Unilateral climate policy design should account for the effectiveness of different anti-leakage policies. *Commun Earth Environ* 2025/04/10 2025;6(1):280. <https://doi.org/10.1038/s43247-025-02258-5>.
- [41] Hainsch K, et al. Energy transition scenarios: what policies, societal attitudes, and technology developments will realize the EU green deal? *Energy* 2022/01/15/2022;239:122067. <https://doi.org/10.1016/j.energy.2021.122067>.
- [42] Panarello D, Gatto A. Decarbonising Europe – EU citizens' perception of renewable energy transition amidst the European green deal. *Energy Policy* 2023/01/01/2023;172:113272. <https://doi.org/10.1016/j.enpol.2022.113272>.
- [43] Scheepers M, et al. Towards a climate-neutral energy system in the Netherlands. *Renew Sustain Energy Rev* 2022;158:112097. <https://doi.org/10.1016/j.rser.2022.112097>. 2022/04/01/.
- [44] Weiss O, Pareschi G, Georges G, Boulouchos K. The Swiss energy transition: policies to address the energy trilemma. *Energy Policy* 2021/01/01/2021;148: 111926. <https://doi.org/10.1016/j.enpol.2020.111926>.
- [45] Salim SS, Luxembourg SL, Dalla Longa F, van der Zwaan B. Decarbonisation scenarios for the European residential sector. *Build Environ* 2025/02/01/2025; 269:112408. <https://doi.org/10.1016/j.buildenv.2024.112408>.
- [46] West K, van Harmelen T, Koning V, Kramer GJ, Faaij A. Detailed modelling of basic industry and material flows in a national energy system optimization model. *Resour Conserv Recycl* 2024/07/01/2024;206:107617. <https://doi.org/10.1016/j.resconrec.2024.107617>.
- [47] EU. REPowerEU plan. Off J Eur Union 2022 [Online]. Available: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2022:230:FIN>.
- [48] Mathisen S, et al. The REPowerEU policy's impact on the Nordic power system. *Energy Strategy Rev* 2024;54:101454. <https://doi.org/10.1016/j.esr.2024.101454>. 2024/07/01/.
- [49] EU. Renewable energy directive. Off J Eur Union 2023 (in English), <http://data.europa.eu/eli/dir/2023/2413/oj>.
- [50] Long A, Bose A, O'Shea R, Monaghan R, Murphy JD. Implications of European union recast renewable energy directive sustainability criteria for renewable heat and transport: case study of willow biomethane in Ireland. *Renew Sustain Energy Rev* 2021/10/01/2021;150:111461. <https://doi.org/10.1016/j.rser.2021.111461>.
- [51] Capros P, et al. Energy-system modelling of the EU strategy towards climate-neutrality. *Energy Policy* 2019/11/01/2019;134:110960. <https://doi.org/10.1016/j.enpol.2019.110960>.
- [52] Dechezleprêtre A, Nachtigall D, Venmans F. The joint impact of the European union emissions trading system on carbon emissions and economic performance. *OECD Economics Department Working Papers* 2018.
- [53] Luxembourg SL, Salim SS, Smekens K, Longa FD, van der Zwaan B. TIMES-Europe: an integrated energy system model for analyzing Europe's energy and climate challenges. *Environ Model Assess* 2024;1–19. <https://doi.org/10.1007/s10666-024-09976-8>.
- [54] Haliassos M. On perfect foresight models of a stochastic world. *Econ J* 1994;104(424):477–91. <https://doi.org/10.2307/2234626>.
- [55] Keppo I, Strubegger M. Short term decisions for long term problems – the effect of foresight on model based energy systems analysis. *Energy* 2010/05/01/2010;35(5):2033–42. <https://doi.org/10.1016/j.energy.2010.01.019>.
- [56] Lambert J, Hanel A, Fendt S, Spliethoff H. Evaluation of sector-coupled energy systems using different foresight Horizons. *Renew Sustain Energy Rev* 2023/09/01/2023;184:113562. <https://doi.org/10.1016/j.rser.2023.113562>.
- [57] J. Thomsen, N. S. Hussein, A. Dolderer, and C. Kost, "Effect of the foresight horizon on computation time and results using a regional energy systems optimization model," *Energies*, vol. 14, no. 2, doi: 10.3390/en14020495.
- [58] Loulou R, Remme U, Kanudia A, Lehtilä A, Goldstein G. Documentation for the TIMES model. 2016.
- [59] van der Zwaan B, Lamboo S, Dalla Longa F. Timmermans' dream: an electricity and hydrogen partnership between Europe and North Africa. *Energy Policy* 2021/12/01/2021;159:112613. <https://doi.org/10.1016/j.enpol.2021.112613>.
- [60] Fattahi A, Dalla Longa F, van der Zwaan B. Opportunities of hydrogen and ammonia trade between Europe and MENA. *Int J Hydrogen Energy* 2024/09/19/2024;83:967–74. <https://doi.org/10.1016/j.ijhydene.2024.08.021>.
- [61] Mc Guire J, Balyk O, Petrović SN, Moran P, Ó Gallachóir B, Daly H. Advancing cost-optimal residential decarbonisation pathways: an examination of heat pumps and thermal efficiency. *Energy Build* 2024/08/15/2024;317:114383. <https://doi.org/10.1016/j.enbuild.2024.114383>.
- [62] Seljom P, Rosenberg E, Haaskjold K. The effect and value of end-use flexibility in the low-carbon transition of the energy system. *Energy* 2024/04/01/2024;292: 130455. <https://doi.org/10.1016/j.energy.2024.130455>.
- [63] Pavičević M, et al. The potential of sector coupling in future European energy systems: soft linking between the Dispa-SET and JRC-EU-TIMES models. *Appl Energy* 2020/06/01/2020;267:115100. <https://doi.org/10.1016/j.apenergy.2020.115100>.
- [64] Calvillo CF, Katris A, Alabi O, Stewart J, Zhou L, Turner K. Technology pathways, efficiency gains and price implications of decarbonising residential heat in the UK. *Energy Strategy Rev* 2023/07/01/2023;48:101113. <https://doi.org/10.1016/j.esr.2023.101113>.
- [65] Fusco Nerini F, Keppo I, Strachan N. Myopic decision making in energy system decarbonisation pathways. A UK case study. *Energy Strategy Rev* 2017/09/01/2017;17:19–26. <https://doi.org/10.1016/j.esr.2017.06.001>.
- [66] Kato E, Kurosawa A. Evaluation of Japanese energy system toward 2050 with TIMES-Japan – deep decarbonization pathways. *Energy Proc* 2019/02/01/2019; 158:4141–6. <https://doi.org/10.1016/j.egypro.2019.01.818>.
- [67] Forsberg J, Lindman Å, Krook-Riekkola A. Tailoring climate mitigation strategies for passenger transportation by capturing contextual heterogeneity in TIMES-Sweden. *Transport Res Transport Environ* 2024;133:104310. <https://doi.org/10.1016/j.trd.2024.104310>. 2024/08/01/.
- [68] Kattelmann F, Marmullaku D, Blesl M, Hufendiek K. Opportunities for the German gas grid by using synthetic fuels from an energy system perspective. *Energy Policy* 2023/10/01/2023;181:113681. <https://doi.org/10.1016/j.enpol.2023.113681>.
- [69] Teotónio C, Fortes P, Roebeling P, Rodríguez M, Robaina-Alves M. Assessing the impacts of climate change on hydropower generation and the power sector in Portugal: a partial equilibrium approach. *Renew Sustain Energy Rev* 2017/07/01/2017;74:788–99. <https://doi.org/10.1016/j.rser.2017.03.002>.
- [70] Luh S, Kannan R, McKenna R, Schmidt TJ, Kober T. Quantifying the impact of travel time duration and valuation on modal shift in Swiss passenger transportation. *Appl Energy* 2024/02/15/2024;356:122412. <https://doi.org/10.1016/j.apenergy.2023.122412>.
- [71] Pfenninger S, Hawkes A, Keirstead J. Energy systems modeling for twenty-first century energy challenges. *Renew Sustain Energy Rev* 2014/05/01/2014;33: 74–86. <https://doi.org/10.1016/j.rser.2014.02.003>.
- [72] Gargiulo M, Gallachóir BÓ. Long-term energy models: principles, characteristics, focus, and limitations. *WIREs Energy and Environment* 2013/03/01 2013;2(2): 158–77. <https://doi.org/10.1002/wene.62>.
- [73] EU. ReFuelEU aviation. Off J Eur Union 2023 [Online]. Available: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023R2405>.
- [74] EU. Energy Performance of buildings directive. Off J Eur Union 2022;2023 [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L:202401275&pk_keyword=Energy&pk_content=Directive.

- [75] Dekker MM, et al. Navigating the black box of fair national emissions targets. *Nat Clim Change* 2025/06/16 2025. <https://doi.org/10.1038/s41558-025-02361-7>.
- [76] Dekker MM. The carbon budget explorer [Online]. Available: <https://www.carbonbudgetexplorer.eu>; 2023.
- [77] OECD. Real GDP long-term forecast. OECD Economics Department; 2023 [Online]. Available: <https://www.oecd.org/en/data/indicators/real-gdp-long-term-forecast.html>.
- [78] Tanzer SE, Blok K, Ramírez A. Decarbonising industry via BECCS: promising sectors, challenges, and techno-economic limits of negative emissions. *Current Sustainable/Renewable Energy Reports* 2021/12/01 2021;8(4):253–62. <https://doi.org/10.1007/s40518-021-00195-3>.
- [79] Rosa L, Sanchez DL, Mazzotti M. Assessment of carbon dioxide removal potential via BECCS in a carbon-neutral Europe. *Energy Environ Sci* 2021;14(5):3086–97. <https://doi.org/10.1039/D1EE00642H>. 10.1039/D1EE00642H.
- [80] Turner PA, et al. The global overlap of bioenergy and carbon sequestration potential. *Clim Change* 2018/05/01 2018;148(1):1–10. <https://doi.org/10.1007/s10584-018-2189-z>.
- [81] EU. Modernisation Fund supporting investments to modernise the energy systems and to improve energy efficiency of certain member states. Off J Eur Union 2020 [Online]. Available: <https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32020R1001>.
- [82] BMWK. Federal climate action act (*Bundes-Klimaschutzgesetz – KSG*) [Online]. Available: <https://www.gesetze-im-internet.de/ksg/BJNR251310019.html>; 2019.
- [83] BOE. de cambio climático y transición energética [Online]. Available: <https://www.boe.es/eli/es/l/2021/05/20/7>; 2021.
- [84] Kimura H. Differentiating Indigenous Peoples from local communities under climate regimes in just energy transition: implications for the Inuit and Sami Peoples. *Polar Science* 2025/06/01/2025;44:101123. <https://doi.org/10.1016/j.polar.2024.101123>.
- [85] Osakada Y. Pitfalls of the green transition: towards a genuine understanding of the right to free, prior and informed consent of the Indigenous peoples. *Polar Science* 2025/06/01/2025;44:101119. <https://doi.org/10.1016/j.polar.2024.101119>.
- [86] EU. Establishing a carbon border adjustment mechanism. Off J Eur Union 2023 [Online]. Available: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023R0956>.
- [87] EEA. European Union Emissions Trading System (EU ETS) data from EUTL. European Environment Agency Publishing Office; 2024 [Online]. Available: <https://www.eea.europa.eu/en/datahub/datahubitem-view/98f04097-26de-4fca-86c4-63834818c0c0>.
- [88] UNFCCC. National inventory submissions 2005. UNFCCC transparency and reporting. 2005 [Online]. Available: <https://unfccc.int/process/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories/submissions-of-annual-greenhouse-gas-inventories-for-2017/submissions-of-annual-ghg-inventories-2005>.
- [89] EU. The use of renewable and low-carbon fuels in maritime transport. Off J Eur Union 2023 [Online]. Available: <https://eur-lex.europa.eu/eli/reg/2023/1805/oj/eng>.
- [90] EU. Strengthening the CO₂ emission performance standards for new heavy-duty vehicles and integrating reporting obligations. Off J Eur Union 2024 [Online]. Available: <https://eur-lex.europa.eu/eli/reg/2024/1610/oj/eng>.
- [91] EU. Establishing a framework of measures for strengthening europe's net-zero technology manufacturing ecosystem. Off J Eur Union 2024 [Online]. Available: <https://eur-lex.europa.eu/eli/reg/2024/1735/oj/eng>.
- [92] EU. Establishing a union certification framework for carbon removals. Off J Eur Union 2024 [Online]. Available: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A672%3AFIN&qid=1669907104132>.