



Net0Pathways through impRoved IAMs across Sectors, diMensions, and scAles

Deliverable 2.4

Report on Policies for a just and efficient net zero transition in Europe and extension of the DPET online tool

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Executive Summary

The EU's strengthened climate targets require policy approaches that can deliver climate neutrality while also addressing affordability, industrial competitiveness, energy security, implementation capacity and the distribution of transition costs and benefits. These objectives are increasingly interconnected. Climate policies must reduce emissions rapidly, but they must also remain economically credible, socially acceptable and resilient to changing political and geopolitical conditions. This deliverable therefore combines two complementary strands of analysis. The first, led by the E3-Modelling team, uses forward-looking model scenarios to assess how alternative trajectories of EU climate ambition affect emissions, sectoral decarbonisation, the energy system, investment, prices and fossil-fuel dependence. The second, led by the University of Cambridge team, expands and updates empirical evidence on the environmental, innovation and distributional impacts of decarbonisation policy instruments. Together, the studies examine both the system-wide consequences of alternative climate-policy futures and the importance of policy design for achieving an effective and just transition.

The first study (Chapter 1) compares six established modelling frameworks across four core scenarios. Meet Aspirations represents a pathway in which announced EU climate objectives are pursued. Asymmetric Roll-Back delays and weakens those objectives. Late Reawakening follows the rollback pathway until 2035 before climate ambition is restored, while Staying Alive maintains support for selected low-regret technologies, including renewables, grids, storage and electric vehicles, despite a broader weakening of climate policy. An additional Asymmetric Roll-Back with High Costs scenario examines the consequences of delayed ambition under less favourable conditions, including weaker technology spillovers, higher clean-technology costs and increased financing costs. As this scenario is available for only part of the model ensemble, its results are presented separately in the Appendix. The scenarios are designed to assess whether delayed climate action simply postpones the same transition or instead changes its feasibility, cost, technological structure and sectoral composition.

The results show that deep decarbonisation is possible, but the EU's stated climate timeline remains highly demanding even under sustained ambition. Under Meet Aspirations, all models substantially reduce emissions, but none reaches the 2030 EU NDC level of 2,093 Mt CO₂eq. The ensemble approaches net-zero CO₂ around 2050, while net-zero GHG emissions are reached only after 2060 on average. Across the models, stronger ambition is consistently associated with declining fossil-fuel use, rapid renewable deployment, greater electrification and sustained investment in electricity generation, networks and storage. Carbon removal also becomes important for addressing residual emissions, although its scale and technological composition vary considerably. The analysis therefore does not identify a single technology pathway, but instead shows that climate neutrality requires a broad combination of clean energy deployment, reduced fossil fuel demand, infrastructure expansion and measures addressing residual emissions.

Delaying climate action has consequences beyond shifting the same transition into the future. Under Asymmetric Roll-Back, emissions remain above Meet Aspirations throughout the modelled horizon, with approximately 670 Mt CO₂/yr still emitted in 2050. Rollback also prolongs fossil-fuel dependence, slows electrification and defers clean-technology investment, with increasingly persistent effects in power, transport and bunkers by mid-

century. Late Reawakening can recover a substantial part of the lost progress, but requires faster emissions reductions, sharper policy signals and more concentrated investment after 2035, without guaranteeing full recovery across all sectors and models. Staying Alive preserves some technological and industrial momentum, but its emissions and energy-system outcomes remain closer to rollback than to Meet Aspirations. At the same time, stronger ambition does not produce a systematic increase in modelled electricity prices and reduces exposure to fossil-fuel imports, supporting both affordability and energy security.

The second study (Chapter 2) complements the forward-looking analysis by expanding and updating the empirical evidence base underlying the INNOPATHS Decarbonization Policy Evaluation Tool. The work aimed to broaden its policy coverage and provide a more granular understanding of how decarbonisation policies affect different societal groups, vulnerable communities and geographical areas. As the existing platform could not be directly or sustainably updated, the work focused on extending its underlying evidence base. UCAM conducted a systematic review of the innovation and environmental outcomes of 14 road-transport policy instruments, covering 468 peer-reviewed studies and more than 1,000 individual policy evaluations. It also updated the review of distributional outcomes with evidence published between 2019 and 2026, identifying 85 sources, 108 policy evaluations and 370 distinct outcomes. The findings show that the effectiveness of transport policies depends strongly on how instruments interact, while the negative or regressive effects of standalone decarbonisation policies can be substantially mitigated through complementary measures and targeted redistribution. The work provides an expanded evidence base for a future open and scalable DPET 2.0, whose development lies outside the scope of PRISMA.

Overall, the deliverable shows that the timing, continuity and design of climate policy are all central to the EU transition. Early and sustained ambition produces a smoother, more manageable and more resilient pathway, while delayed action transfers a larger and more difficult adjustment burden to the period after 2035. At the same time, the empirical evidence confirms that policy outcomes depend not only on the level of ambition but also on how instruments are combined and how their costs and benefits are distributed. Credible targets and stable investment signals must therefore be accompanied by complementary and redistributive measures to ensure that the transition is technically feasible, economically credible and socially just.



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1 The bumpy road to EU's net zero: Assessing the impacts of rolling back climate ambition

1.1 Introduction

The European Union has long positioned itself as a global leader in climate policy. In 2005, it launched the world's first international emissions trading system and has since pursued some of the most ambitious climate commitments among major economies. Over time, this framework has been strengthened through a binding 2030 target, an indicative 2035 contribution under the EU's updated nationally determined contribution (NDC), and a binding 2040 target, all directed towards achieving climate neutrality by 2050. The climate-neutrality objective is legally enshrined in the European Climate Law (European Commission, 2021).

More recently, however, the political and economic conditions supporting this progression in climate ambition have become increasingly contested. Climate policy debates at both EU and Member State level are now shaped by several interrelated pressures. A central concern is the cost of the transition and its implications for the competitiveness of European industry. Mario Draghi's report on European competitiveness identified persistently high energy prices as a structural disadvantage for EU firms compared with their international competitors (Draghi, 2024). This has raised related concerns that the costs associated with the EU Emissions Trading System may contribute to carbon leakage, redirect industrial investment, or encourage some energy-intensive production to relocate outside the EU.

Energy security and resilience have also become more prominent. The energy crisis following Russia's invasion of Ukraine in 2022 exposed the EU's vulnerability to imported fossil fuels and led to the adoption of the REPowerEU plan, which aims to reduce dependence on Russian energy while accelerating energy efficiency, renewable-energy deployment, and supply diversification (European Commission, 2022). Continuing geopolitical tensions involving major energy exporters, including Russia and Iran, have reinforced concerns about exposure to external supply disruptions and volatile international energy markets.

At the same time, political opposition to specific climate policies has intensified in several Member States. This has been expressed through distributional protests, such as the Yellow Vests movement in France, local opposition to renewable-energy infrastructure, particularly onshore wind projects, and resistance to measures affecting combustion-engine vehicles, fossil fuel heating technologies, and established automotive manufacturing activities. These developments illustrate the political difficulty of implementing climate measures when their costs and distributional effects are perceived as immediate, while their benefits are more dispersed or long term.

These pressures have also begun to reshape EU policy instruments. One example is the Net-Zero Industry Act, which was adopted to support the expansion of clean-technology manufacturing within the EU and strengthen the resilience of European supply chains. The Act responds partly to concerns about the EU's dependence on imports of key clean technologies and components, including solar photovoltaic equipment and batteries, particularly from China (European Commission, 2024). Competitiveness, affordability, industrial capacity, and energy security have consequently become central considerations across EU climate policy debates.

The evolution of the EU's 2040 climate target further illustrates this recalibration. In 2023, the European Scientific Advisory Board on Climate Change recommended a net domestic greenhouse-gas emissions reduction of between 90% and 95% by 2040 relative to 1990 levels (European Scientific Advisory Board on Climate Change, 2023). The European Commission subsequently proposed a headline target of 90%. The final amendment to the European Climate Law retained the 90% target but permitted high-quality international carbon credits equivalent to up to 5% of the EU's 1990 net emissions to contribute towards its achievement from 2036 onwards. Consequently, at least an 85% reduction must be achieved through action within the EU (Council of the European Union, 2026).

A similar shift towards greater flexibility is visible in the proposed revision of the EU Emissions Trading System. In July 2026, the European Commission published a proposal to revise the system for the period after 2030. Among other changes, the proposal would reduce the Linear Reduction Factor, which determines the annual rate at which the overall emissions cap declines. Under the existing framework, the Linear Reduction Factor is 4.3% between 2024 and 2027 and 4.4% from 2028. The Commission proposes reducing it to 3.7% for 2031–2035 and to 1.7% for 2036–2040. This would moderate the rate at which allowances are removed from the market and allow the emissions cap to decline more gradually during the 2030s, potentially extending the availability of allowances into the 2040s (European Commission, 2026b).

At the same time, challenges are apparent in the national implementation of previously adopted EU legislation. In July 2026, the European Commission opened infringement procedures against all 27 Member States for failing to fully transpose the recast Energy Performance of Buildings Directive into national law by the required deadline (European Commission, 2026a). Although delayed transposition does not necessarily indicate opposition to the Directive's objectives, it illustrates the difficulties involved in translating EU-level climate ambition into timely and effective national implementation.

Taken together, these developments point to a broader shift in the European climate policy debate. The discussion is no longer focused primarily on setting progressively more ambitious emissions-reduction targets. Increasing attention is instead being given to how climate objectives can be reconciled with energy affordability, security and resilience, social acceptance, and the economic and industrial competitiveness of the EU. This shift does not necessarily represent an abandonment of the EU's climate-neutrality objective. It does, however, create greater uncertainty regarding the timing, strength, and implementation of the policies required to achieve it.

Against this background, the present study develops and analyses scenarios closely connected to the evolving real-world policy debate in the EU. The analysis is organised around four research questions:

1. Under what conditions can the EU achieve climate neutrality, and what transformations of the energy system, costs, investments, and wider economic impacts would this require?
2. What environmental, energy-system, and economic impacts would result from a rollback of the EU's climate ambition, particularly its NDC commitments and long-term climate-neutrality objective?

3. Could the EU still achieve climate neutrality if climate policy is delayed over the next decade, and what additional costs, investments, and economic impacts would such a delay create?
4. Under a broader rollback of climate ambition, to what extent could continued investment in renewable energy, storage, and electrification mitigate the resulting environmental, energy-system, and economic impacts?

These research questions represent a modest refinement of the focus originally established in the project's task description, which called for an analysis of policies supporting a net-zero transition in the EU. This refinement was made to ensure that the study remains closely aligned with the current EU policy debate and that its model-based analysis provides useful and actionable insights for EU policymakers and other relevant stakeholders. The study continues to assess the requirements and implications of the EU's transition to climate neutrality, as originally envisaged. However, it places additional emphasis on the environmental, energy-system, and economic consequences of climate policy rollback and delayed action.

The remainder of the study is structured as follows. Section 1.2 describes the models and scenarios used in the analysis. Section 1.3 presents the main results, focusing on EU emissions, sectoral transformations, the energy-system transition, and economic implications. Section 1.4 concludes with a discussion of the main policy implications of the findings.

1.2 Methods

1.2.1 Models

This analysis relies on a multi-model comparison of six established integrated assessment models to investigate how different trajectories of EU climate policy could unfold in the coming decades. The six models, GEM-E3, IMACLIM, IMAGE, OPEN-PROM, REMIND-MAGPIE, and WITCH, differ in their underlying structure, solution concept and sectoral detail, ranging from optimisation-based general-equilibrium frameworks to recursive dynamic simulations. The remainder of this section provides a short description of each of the six models, covering their objective, core mechanisms and typical applications.

1.2.1.1 IMACLIM 2.0

IMACLIM-R is developed by CIREN and partner French research institutions. It is intended to study the interactions between energy systems and the economy, in order to assess the feasibility of low-carbon development strategies and the transition pathway toward a low-carbon future (Bibas et al., 2022). IMACLIM-R is a hybrid dynamic general-equilibrium model. Each year, a static equilibrium module determines relative prices, wages, physical flows, capacity utilisation, profit rates and savings from the short-term supply-demand balance across goods, capital and labour markets. The model is implemented in Scilab and solved with a nonlinear-equation solver. It explicitly represents market imperfections, underutilised production factors and imperfect investment foresight, rather than assuming frictionless adjustment (Méjean et al., 2019).

Recursive dynamics link successive years. Sector-specific reduced-form technology modules take each year's static equilibrium as input and simulate how technical systems such as power generation, buildings and transport respond to the resulting price and demand signals. These

modules then feed updated input-output coefficients back into the equilibrium calculation for the following year. This structure allows IMACLIM-R to capture both short-run market rigidities and longer-run technology adjustment, and the model is regularly used to assess the macroeconomic costs and co-benefits of climate mitigation pathways under realistic, imperfect-foresight conditions.

1.2.1.2 IMAGE 3.4

IMAGE (Integrated Model to Assess the Global Environment) is developed by PBL Netherlands Environmental Assessment Agency. The model is designed to understand how global, long-term environmental change unfolds as a consequence of human activity. It has three explicit aims. The first is to analyse human-environment interactions in order to understand global environmental change. The second is to assess response strategies by representing and analyzing climate change mitigation and adaptation options. The third is to indicate the key inter-linkages and uncertainties between climate-related and other environmental processes and human activities (Stehfest et al., 2014).

Rather than solving for an optimum, IMAGE is a simulation model that projects socio-economic pathways forward without foresight. It represents a partial-equilibrium system with price-elastic demand, in which technology and land-use choices respond to relative costs through a multinomial-logit substitution mechanism. A simplified climate emulator, FAIR, can be run in advance to supply climate data for policy scenarios. The framework combines a detailed energy and land-use system with an earth-system component covering the carbon and hydrological cycles and climate change, linked through hard-coded and soft-linked connections, including coupled models for biodiversity, flood risk and human development, which exchange information through shared code or data files. This structure makes IMAGE a standard tool for assessing climate change, air pollution, land-use change, biodiversity loss and water scarcity within a single consistent framework.

1.2.1.3 OPEN-PROM 2.2

OPEN-PROM is a global, open-source energy system simulation model based on the PROMETHEUS modelling framework, developed by E3Modelling (Fragkos et al., 2015). The model simulates the evolution of energy demand, energy supply, technology deployment and emissions under alternative socioeconomic, technological and policy assumptions. It runs as a recursive dynamic model, calibrated on 2023 historical data and simulating year-by-year developments to 2100, representing path dependencies and transition dynamics rather than solving for an inter-temporal optimum.

The model provides a detailed representation of energy demand across industry, transport and residential sectors, alongside energy supply, power generation and fuel-transformation technologies, capturing interactions between energy consumption, fuel use, industrial production and technology adoption. Technology turnover and competition for new and replacement capacity are governed by a cost-based gap-and-substitution mechanism that accounts for technology maturity, existing capital stock, premature scrapping and policy-driven shifts in relative competitiveness. This allows the model to capture both short-term inertia from existing infrastructure and the gradual diffusion of low-carbon technologies, making OPEN-PROM well suited to analysing industrial decarbonisation pathways, resource-efficiency measures, energy transitions and climate policy scenarios.

1.2.1.4 REMIND-MAgPIE 3.7-4.14

REMIND (REgional Model of Investment and Development) is developed at the Potsdam Institute for Climate Impact Research (PIK). The goal of REMIND is to find the welfare-optimal mix of investment in the economy and the energy sectors of each of its twelve world regions, given a set of population, technology, policy and climate constraints. The model also accounts for regional trade in goods, energy carriers and emissions allowances (Baumstark et al., 2021). The macroeconomic core of REMIND is a Ramsey-type growth model with perfect foresight (Leimbach et al., 2010, Luderer et al., 2013). A nested CES production function determines final energy demand from capital, labour and energy inputs. More than fifty conversion technologies translate fossil, nuclear, biogenic and renewable resources into secondary and final energy. The model represents energy-system inertia through capacity vintage structures, technological learning curves and adjustment costs for rapid technology scale-up, as well as policy instruments such as fuel taxes and subsidies. This makes REMIND well suited to analysing technology options and policy proposals for climate change mitigation.

Land-use dynamics are supplied by MAgPIE, a cost-minimising global land-allocation model coupled to the grid-based vegetation model LPJmL. MAgPIE derives land-use patterns and production costs from food-energy demand and land-constrained agricultural yields. Technological change in agriculture responds endogenously to land scarcity (Dietrich et al., 2019). REMIND and MAgPIE are soft-linked and solved iteratively. REMIND passes bioenergy demand and GHG price assumptions to MAgPIE, and MAgPIE returns updated bioenergy prices, land-use emissions and production costs. REMIND solves as a general-equilibrium optimisation, while MAgPIE solves as a partial-equilibrium cost-minimisation problem.

1.2.1.5 WITCH 6.0-EU28

WITCH (World Induced Technical Change Hybrid) is maintained by the RFF-CMCC European Institute on Economics and the Environment (EIEE). WITCH evaluates the impacts of climate policies on global and regional economic systems and derives the optimal response of each region to climate change. It explicitly accounts for the positive externalities generated by learning-by-doing and learning-by-researching in technological change (Emmerling et al., 2016). WITCH is a hard-linked hybrid model. An inter-temporal optimal-growth representation of the economy is integrated directly with a bottom-up energy sector, so that energy-investment and resource choices are optimised jointly with the rest of the economy, rather than passed between separate models. Each region's economy is structured around one final good and seven energy sectors, namely coal, oil, gas, wind and solar, nuclear, electricity and biofuels.

Each region's forward-looking agent maximises inter-temporal welfare simultaneously with the others. By default, the model solves as a non-cooperative open-loop Nash equilibrium, though regions can also be grouped into coalitions to compute a cooperative solution instead. Climate outcomes are generated through coupling with the MAGICC climate model, and land-use and forestry dynamics enter through a soft link to GLOBIOM. WITCH also represents a range of climate policy instruments, including carbon taxes and tradable emissions-permit markets, which makes it particularly suited to questions where the pace and direction of technological change is itself a policy-relevant variable.

1.2.1.6 GEM-E3

GEM-E3 (General Equilibrium Model for Economy-Energy-Environment) is a multi-regional, multi-sectoral, recursive dynamic computable general-equilibrium model developed and maintained by E3Modelling. It is designed to analyse interactions between the economy, the energy system and the environment, with a particular focus on the macroeconomic and distributional impacts of energy, climate and environmental policies (Capros et al., 2013). In each period, firms minimise production costs and households maximise utility, while prices adjust endogenously to clear markets for goods and services, labour, capital and energy. Countries and regions are connected through bilateral trade in energy and non-energy commodities.

Production is represented through nested constant-elasticity-of-substitution functions combining capital, labour, energy and intermediate inputs. Successive periods are linked recursively through investment and capital accumulation, with current investment decisions determining the capital stock available in the following period. The model also represents energy use, greenhouse-gas emissions, fuel and input substitution, and policy instruments such as carbon pricing, emissions trading, energy taxes and subsidies. This structure makes GEM-E3 particularly suited to assessing the economy-wide implications of climate policy, including effects on GDP, welfare, employment, trade, sectoral production and industrial competitiveness.

1.2.2 Scenario Design

The PRISMA scenario design is structured as a progressive sequence of mitigation pathways that move from stated national climate ambition, as expressed with the NDCs and Long-Term strategies, to delayed and weakened ambition, to renewed climate policy acceleration, and finally to a low regret transition strategy under continued political disruption. The purpose is not only to compare alternative futures, but also to isolate the consequences of losing climate policy momentum and to assess whether delayed action can be compensated later, either through stronger future mitigation efforts or through continued deployment of key clean energy technologies. The scenarios are developed and quantified using global integrated assessment models, in which all world regions are represented at the same time, and while they are designed as alternative global futures, the current report focuses specifically on their impacts for the EU's climate transition. The scenarios therefore build on each other in a stepwise way, first defining a reference pathway in which all countries meet their announced climate goals in the medium and long term, then introducing asymmetric regional rollbacks with delays in climate policy implementation, differentiated according to each region's fossil fuel wealth, renewable energy momentum, and the greenhouse gas intensity of its economy, then testing the feasibility and cost of catching up efforts to meet the climate targets, and finally examining whether selected low regret clean energy investments can reduce the impacts caused by delayed climate ambition. Each of these four steps is implemented as a distinct scenario, described below with a focus on how it plays out specifically for the EU.

1.2.2.1 Meet Aspirations

In this scenario, all countries are assumed to meet their own stated NDC and long term strategy goals. For the EU specifically, this means meeting its stated climate objectives for 2030 and 2035 (as stated in its new NDC target of 66.25% to 72.5% emissions reduction in

2035 compared to 1990), before reaching net-zero greenhouse gas emissions by 2050 as included in the EU Climate Law. This pathway reflects the implementation of announced European climate ambition and provides the benchmark for the future evolution of emissions, energy-system transformation, technology deployment, investment needs and policy costs. It is used as the central comparison point for other scenarios.

1.2.2.2 Asymmetric Roll-Back

This scenario introduces a delay in climate ambition and implementation. Since Europe is the focus of this study, the scenario can be interpreted as a European policy rollback from the stated 2030, 2035 and 2050 climate goals. The European climate goals are delayed by 10 years compared to the Meet Aspirations pathway. In addition, the net-zero ambition is weakened to 80% of the current emission level, which corresponds to approximately 550 MtCO₂eq. This scenario captures a case where policy uncertainty, weaker implementation capacity and reduced political commitment slows down the European transition. It is used to quantify the consequences of delayed action in terms of cumulative emissions, technology deployment, investment deferral, energy-system costs and the later massive effort required to decarbonise.

1.2.2.3 Late Reawakening

This scenario examines whether Europe can make up for the lost time after a period of weakened ambition. It builds directly on the Asymmetric Roll-back scenario, as Europe initially follows the weakened policy pathway of the Asymmetric Roll-Back scenario until 2035. From 2040 onwards, climate ambition is restored and the system attempts to return to the original long-term objective of net-zero greenhouse gas emissions by 2050, or as close to it as remains technically and economically feasible. Compared with the Meet Aspirations pathway, this scenario is expected to require faster emissions reductions after the delay, more rapid clean-technology deployment, higher carbon prices or policy effort, and potentially higher energy-system adjustment costs. If the 2050 net-zero target becomes infeasible after the rollback period, the infeasibility should be explicitly reported by the models and the net-zero year can be shifted forward in five-year increments.

1.2.2.4 Staying Alive

The fourth scenario keeps the weaker policy ambition of the rollback scenario but assumes that selected low-regret clean technologies and transition strategies continue to progress. In this case, Europe does not fully maintain its original climate policy ambition, but investments in key technologies such as renewables, energy storage, grid expansion and transport electrification through electric vehicles continue at the levels observed in the Meet Aspirations scenario. The purpose is to test whether maintaining momentum in economically attractive and strategically important technologies can reduce the impacts caused by broader climate policy rollback. This scenario is especially relevant for Europe, where renewables, electrification of transport and grid development may continue to be supported not only by climate objectives, but also due to energy security, competitiveness and reduced fossil fuel dependence concerns of EU policymakers.

1.2.2.5 Asymmetric Roll-Back w/ High Costs

The final scenario is an additional stress-test variant of the standard rollback scenario. It follows the same weakened European climate policy ambition as Asymmetric Roll-Back,

meaning that progress toward the 2030, 2035 and 2050 net-zero pathway is delayed. However, it adds a more adverse transition environment by assuming continued geopolitical tensions, regional fragmentation, and lack of international cooperation. In particular, this narrative is operationalised in the Integrated Assessment Models by assuming no innovation spillovers or knowledge transfers, higher clean-technology costs due to supply-chain constraints, and increased financing costs that reflect capital-market fragmentation and higher investment risks. This scenario therefore tests whether the costs of delayed ambition are amplified in a world of continued geopolitical tensions where clean technologies become more expensive, technological learning is more fragmented, and low-carbon investments are harder to finance.

1.3 Results

This section presents the major findings of the analysis, drawn from the comparison across all models and scenarios for the European Union. The analysis is split into subsections covering the most important environmental, energy system, technological and socio-economic indicators of the energy transition. Each subsection reports the scenario ensemble picture that carries the headline message, together with the model-by-model detailed behaviour. The analysis focuses on the four core scenarios. The stress-test variant, Asymmetric Roll-Back w/ High Costs, is reported in Appendix A, since it is available for only part of the ensemble (GEM-E3, OPEN-PROM, WITCH).

1.3.1 Emissions

1.3.1.1 GHG Emissions

Focusing on Greenhouse Gas (GHG) emissions, Figure 1 shows that, on average, models achieve drastic emissions reductions and reach close to net-zero emissions (but still showing small remaining GHG quantities) in 2050 in the Meet Aspirations scenario. The ensemble mean reaches net zero after 2060, which is an indication of the high ambition level of EU targets. At the individual model level, only IMAGE achieves the net-zero target, and it does so even before 2050, as a consequence of increased use of CDR technologies (Figure 7), whereas WITCH and REMIND-MAgPIE do not reach net zero within the modelled period. Considering a rollback in climate ambition has an adverse effect on GHG emissions as, on average, models do not achieve net zero even by the end of the century, in line with scenario protocol specifications. Accelerating efforts after 2035 (Late Reawakening), leads to a faster rate of decarbonisation than in Meet Aspirations, pushing the system to reach net-zero GHG emissions around the same year as Meet Aspirations. This acceleration is more prominent in GEM-E3, OPEN-PROM and WITCH, and less effective in REMIND-MAgPIE and IMAGE.

Continuous investment in clean technologies (Staying Alive) has a very slight effect on EU GHG emissions in most models, while in IMAGE, it leads to a slightly improved effort. Overall, accelerating efforts leads to a convergence towards Meet Aspiration levels after mid-century, while early investment support in clean technologies has little effect on the long-term emissions in Europe.

Emissions|Kyoto Gases (EU, ensemble)

5 of 6 models — IMACLIM not reporting

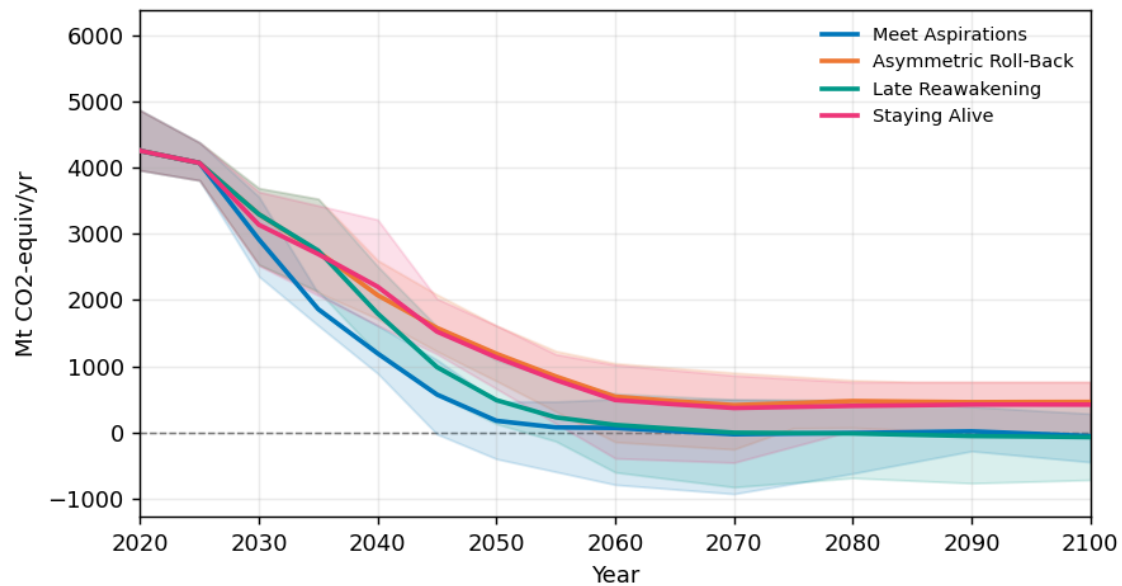


Figure 1: EU Kyoto GHG emissions by scenario, ensemble mean and model range. The shaded band shows the min-max range across models.

Emissions|Kyoto Gases: per model, all scenarios



Figure 2: EU Kyoto GHG emissions by model, all scenarios.

Figure 3 shows the distribution of each model's GHG emissions at selected snapshot years. In 2030, none of the models achieves the EU NDC target of 2093 Mt CO₂eq, even though WITCH and GEM-E3 come closer to the target. This is a clear indication of the relatively high ambition of the EU NDC targets requiring accelerated emissions reduction efforts in a short period of time. GEM-E3 generally lies at the lower end of the model range in 2030, as it decarbonises faster in the early modelling years, while WITCH reports the lowest emissions

under Meet Aspirations. Under Meet Aspirations, emissions decline sharply across all models by 2050. IMAGE reaches net-negative emissions, while the remaining models retain varying levels of positive residual emissions, with REMIND-MagPIE reporting the highest level. Outcomes are substantially less favourable under Asymmetric Roll-Back. By 2060, IMAGE is net-negative, but GEM-E3, OPEN-PROM, WITCH and REMIND-MagPIE continue to report positive residual emissions, with the largest values projected by REMIND-MagPIE and WITCH. Late Reawakening produces a marked reduction relative to Asymmetric Roll-Back by 2050 and 2060 across all models, while Staying Alive lies between the ambitious and rollback pathways, but remains closer to Asymmetric Roll-Back.

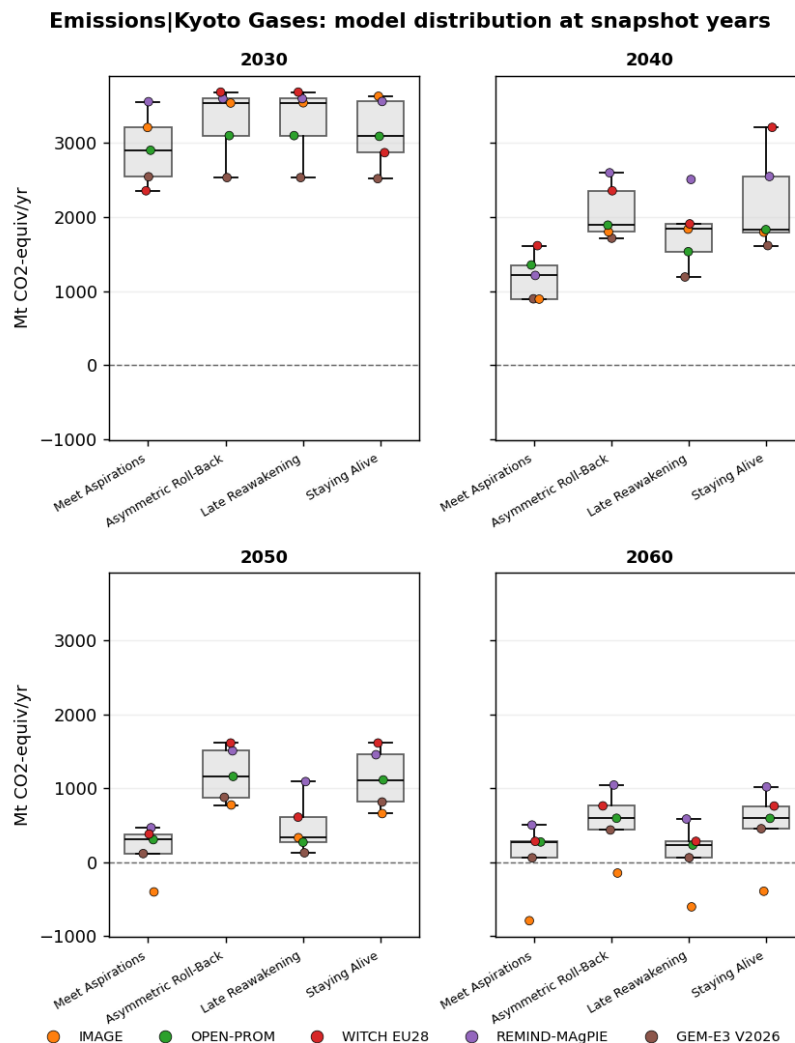


Figure 3: Distribution of EU Kyoto GHG emissions across models, by scenario and snapshot year.

1.3.1.2 CO₂ Emissions

Turning to CO₂ emissions (Figure 4), the Meet Aspirations scenario reaches slightly negative emissions already before 2050 in the ensemble mean and remains below net zero thereafter. In the Asymmetric Roll-Back scenario, EU net CO₂ emissions remain above the Meet Aspirations pathway throughout all years. By 2035, ensemble mean net CO₂ is about 2,600 Mt CO₂/yr under the rollback compared with about 1,400 Mt CO₂/yr in the Meet Aspiration. Per scenario protocol,

EU would be off track for its 2035 NDC commitment and would place the achievement of its 2040 and 2050 climate objectives at significant risk. By 2050, Meet Aspirations reaches net zero in the ensemble mean, while the rollback still emits about 670 Mt CO₂/yr, implying high challenges to meet EU's net-zero goal in this scenario. The net-zero target is never reached throughout the century, even though each individual model decarbonises at a different rate. More specifically, IMAGE reaches net-negative CO₂ emissions shortly after 2040, while the rest of the models decarbonise close to 2050. The only exception is IMACLIM, which faces difficulty to reach net-zero CO₂ emissions. Late Reawakening initially follows the rollback pathway until 2035 but starts closing the gap with the Aspirations scenario in the policy re-acceleration period. However, average emissions do not reach net-zero in 2050, but the target is reached around 2055.

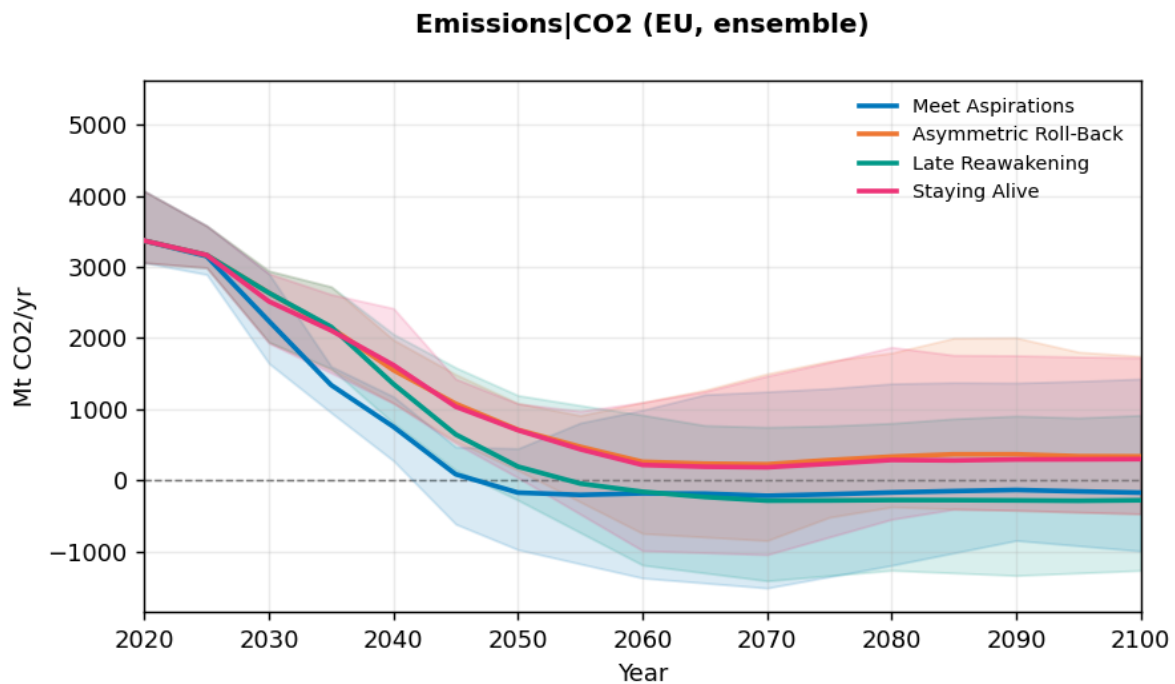


Figure 4: EU net CO₂ emissions by scenario, ensemble mean and model range. The shaded band shows the min-max range across models.

Emissions|CO2: per model, all scenarios

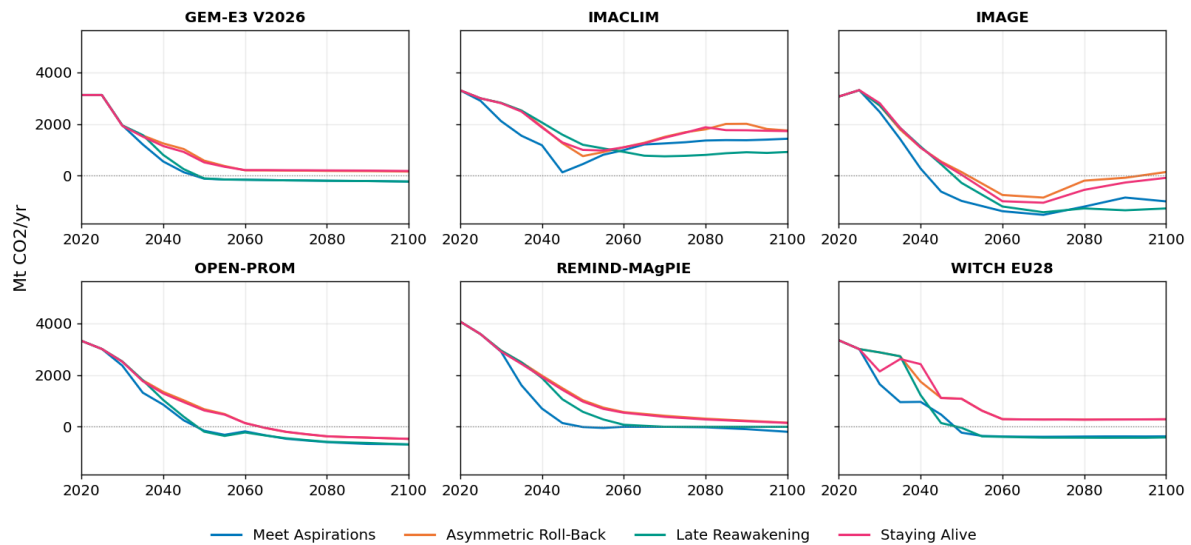


Figure 5: Distribution of EU net CO2 emissions across models, by scenario and snapshot year.

Another interesting result is how models differentiate in their net CO2 emissions compared to the Meet Aspirations scenario, which can indicate how fast decarbonization happens (Figure 6). In 2030, Asymmetric Roll-Back raises the ensemble mean by around 400 Mt CO2/yr, although responses vary substantially, from almost no change in REMIND-MagPIE and GEM-E3 to more than 1.2 Gt CO2/yr in WITCH. Late Reawakening shows an almost identical pattern in 2030 because it follows the rollback pathway until 2035, but by 2050 renewed climate action considerably narrows the emissions gap, particularly in OPEN-PROM, GEM-E3 and WITCH. Staying Alive reduces the average gap relative to Asymmetric Roll-Back in 2030, largely due to WITCH, but offers little additional improvement by 2050. Overall, the results indicate that delayed action has strongly model-dependent consequences and that later policy acceleration can recover part, but not necessarily all, of the emissions reductions achieved under early and sustained climate action.

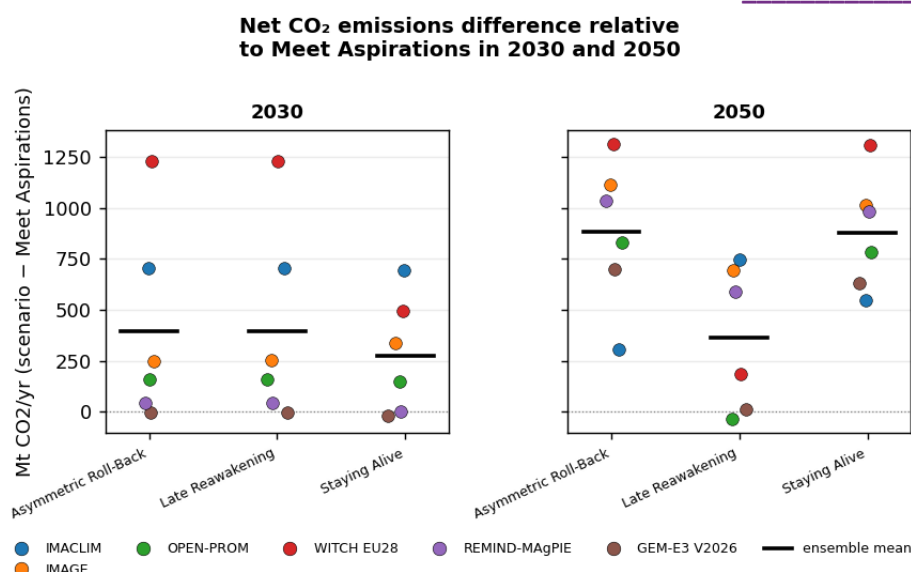


Figure 6: Difference in EU net CO₂ emissions relative to Meet Aspirations, by model and scenario. Positive values indicate higher emissions.

1.3.1.3 Carbon Dioxide Removal (CDR)

The mechanisms through which models close their emissions gaps are reflected in both total CO₂ captured and the composition of projected carbon-removal portfolios across scenarios (Figure 7 and Figure 8). Before comparing the results, it should be noted that carbon capture and removal variables are not reported consistently across models, reflecting differences in technology coverage, system boundaries and aggregation. Absolute levels are therefore not fully comparable, and the discussion focuses primarily on within-model scenario differences. Total CO₂ capture is highest in IMAGE, reaching around 1.9 Gt CO₂/yr in the most ambitious pathways, consistent with the model's strongly net-negative emissions later in the century. OPEN-PROM and REMIND-MAGPIE scale up capture more gradually, while WITCH remains at lower levels and IMACLIM displays a pronounced but short-lived mid-century peak. In 2050, Meet Aspirations produces more carbon removal than Asymmetric Roll-Back in every model (Figure 9), with the largest differences in IMAGE and OPEN-PROM, at approximately 565 and 521 Mt CO₂/yr, respectively. IMAGE reports the largest overall removal portfolio under Meet Aspirations, at around 1.5 Gt CO₂/yr, dominated by BECCS and supplemented by re/afforestation and carbon stored in long-lived materials, mainly timber. OPEN-PROM relies predominantly on geological storage, while REMIND-MAGPIE combines BECCS, re/afforestation and timber storage. WITCH follows a distinct pathway centred on ocean alkalinity, with smaller contributions from enhanced weathering and geological storage. Late Reawakening generally produces intermediate removal levels, although OPEN-PROM returns close to its Meet Aspirations level, whereas Staying Alive remains much closer to Asymmetric Roll-Back in most models. Overall, the results suggest that stronger climate policy ambition, rather than support for mature clean technologies alone, is the main driver of large-scale carbon-removal deployment.

Total CO2 captured: per model, all scenarios

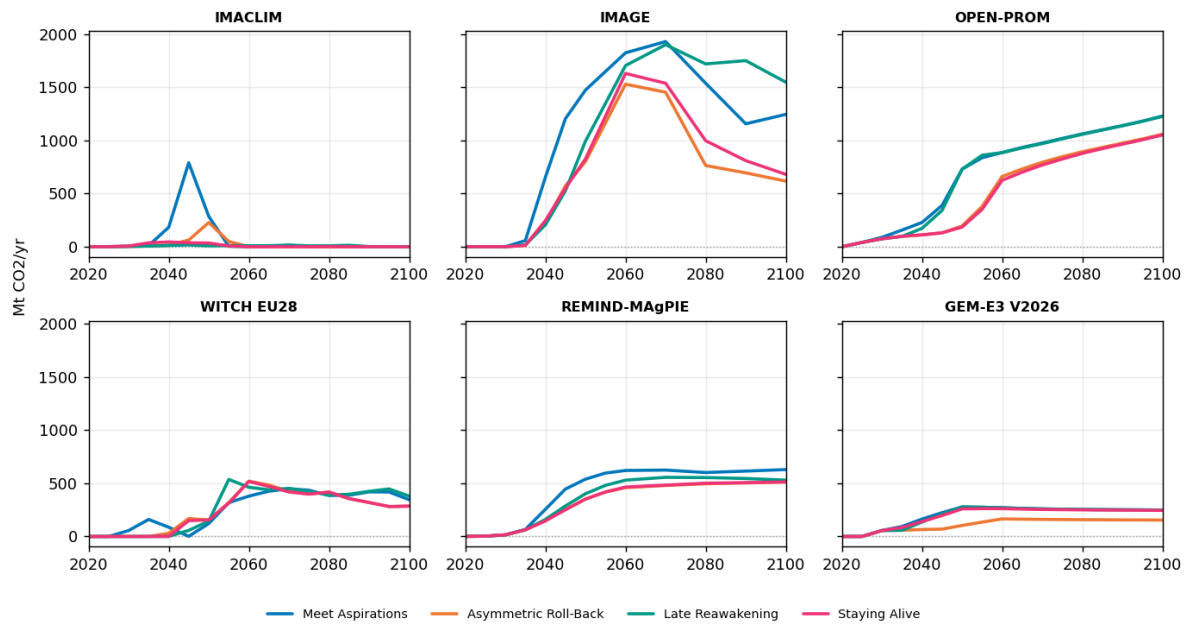


Figure 7: Total CO2 captured by model and scenario.

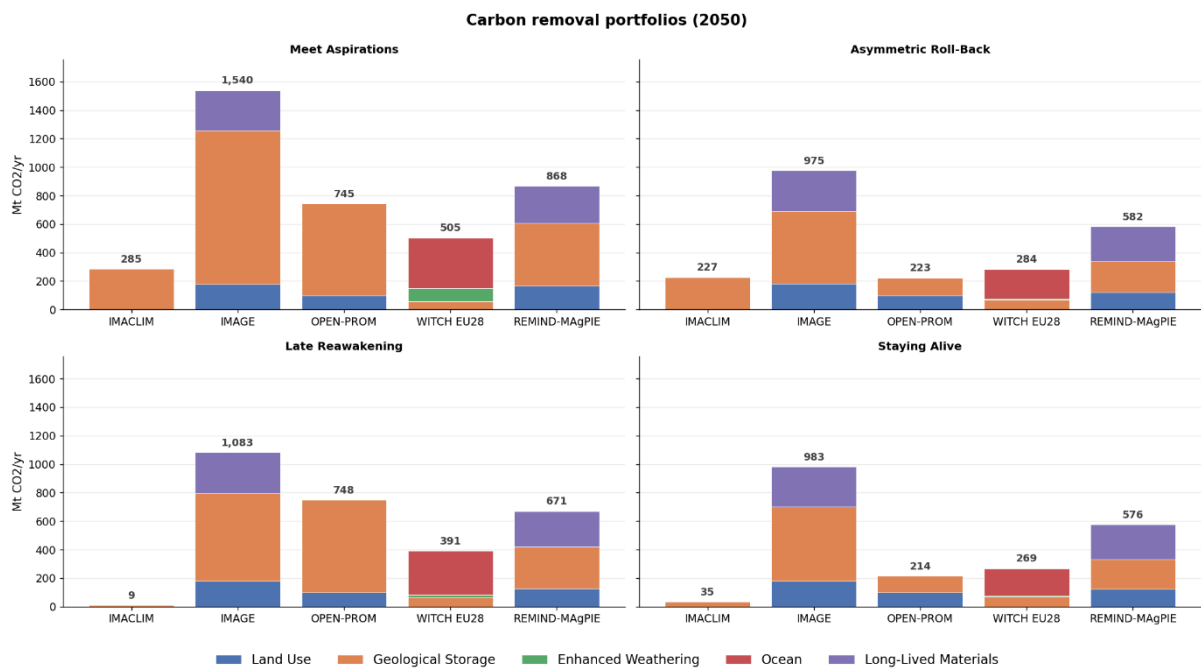


Figure 8: Carbon removal in 2050 by origin, model and scenario (Mt CO2/yr). Totals are shown above each bar. GEM-E3 is not shown, as they do not report detailed carbon removal breakdown.

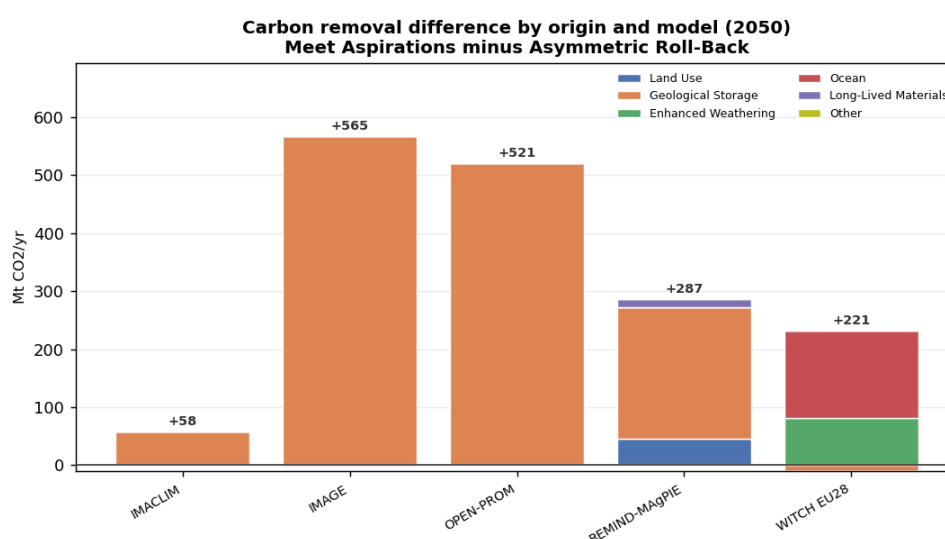


Figure 9: Difference in carbon removal in 2050 by origin and model, Meet Aspirations minus Asymmetric Roll-Back (Mt CO₂/yr). Positive values indicate more removal under Meet Aspirations.

1.3.2 Sectoral Analysis

This subsection uses the sectoral results from the modelling ensemble to answer two questions. First, it identifies which sectors account for the additional emissions generated by delayed and weakened climate ambition under Asymmetric Roll-Back. Second, it assesses how far renewed ambition under Late Reawakening can reduce these additional emissions and return individual sectors towards the Meet Aspirations pathway by 2050. The two questions require different comparisons. Asymmetric Roll-Back is compared with Meet Aspirations to quantify the consequences of continued rollback, while Late Reawakening is compared with both Meet Aspirations and Asymmetric Roll-Back to evaluate the success and value of the catch-up effort. The analysis first presents the ensemble-level results and then examines differences across individual models.

1.3.2.1 Most impact by the rollback

The emissions impact of Asymmetric Roll-Back is distributed unevenly across sectors, and the composition of the gap relative to Meet Aspirations changes over time (Figure 10). In 2035, industry makes the largest absolute contribution to the emissions gap, followed by buildings, transport and power. By 2050, the gaps in industry, buildings and AFOLU have narrowed, whereas those in power, transport and bunkers have widened, making power the largest contributor. Although the total sectoral gap declines from approximately 720 Mt CO₂/yr in 2035 to 640 Mt CO₂/yr in 2050, the combined contribution of power, transport and bunkers increases from around 43% to 58% of the total. The consequences of delayed action therefore become increasingly concentrated in these sectors by mid-century. Since the figure reports absolute differences, it shows each sector's contribution to the overall emissions gap rather than its responsiveness relative to sector size.

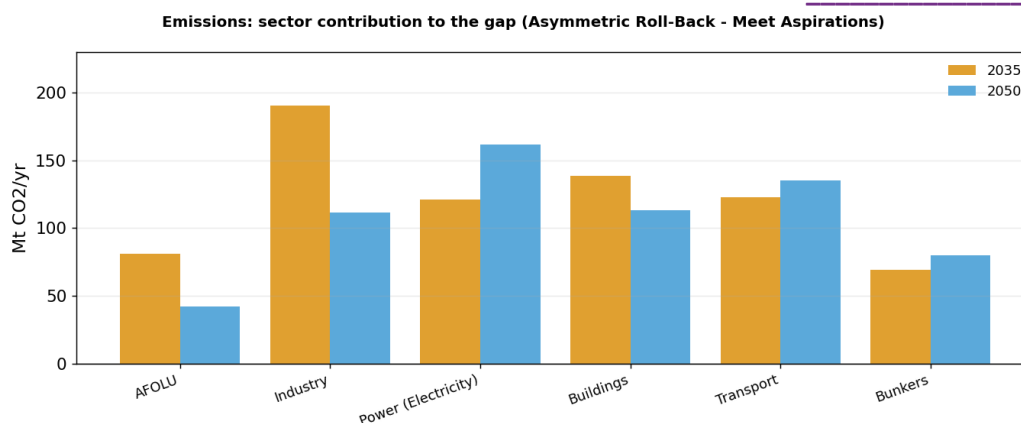


Figure 10: Sectoral contribution to the emissions gap between Asymmetric Roll-Back and Meet Aspirations, ensemble mean, 2035 and 2050.

The model-level results show that the ensemble pattern arises from substantially different sectoral responses (Figure 11). In 2035, IMACLIM concentrates the additional emissions in industry and transport, while WITCH reports particularly large gaps in power, industry and buildings. REMIND-MAGPIE shows its largest difference in AFOLU, whereas OPEN-PROM distributes the rollback impact more evenly across supply and demand sectors. IMAGE initially reports comparatively small differences outside transport, while GEM-E3 shows its largest gaps in buildings and transport.

By 2050, the sectoral patterns have changed considerably. Power becomes the dominant source of additional emissions in IMAGE and OPEN-PROM. In WITCH, the gap shifts away from power and becomes concentrated in transport, buildings and industry. GEM-E3 reports its largest gaps in transport and bunkers, while the differences in IMACLIM span across all reported sectors. REMIND-MAGPIE retains a broad-based emissions gap, with AFOLU remaining its largest contributor. No single sector therefore dominates the impact of rollback across all models and years. Similar aggregate emissions gaps can instead arise from substantially different sectoral transition pathways.

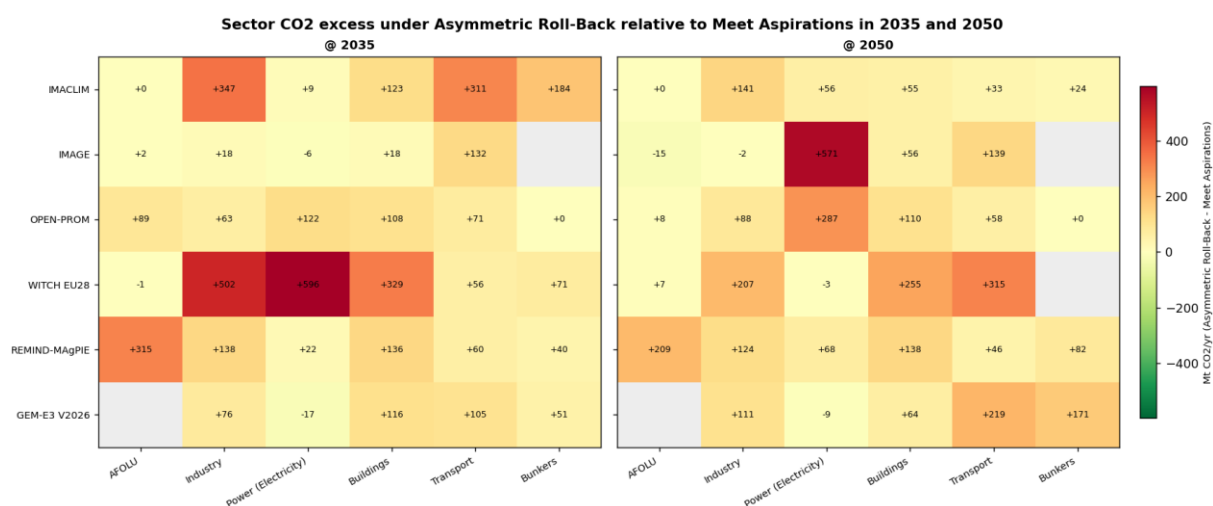


Figure 11: Sectoral CO₂ excess under Asymmetric Roll-Back relative to Meet Aspirations, by model and sector, 2035 and 2050 (Mt CO₂/yr). Red indicates higher emissions than the reference and green lower. Grey indicates not reported.

1.3.2.2 Ability to recover after the rollback

The ability to make up for lost time is assessed through two complementary comparisons. Figure 12 shows the sectoral gap between Late Reawakening and Meet Aspirations at the start of the catch-up period in 2035 and the residual gap in 2050. Since Late Reawakening follows the rollback pathway until 2035, the left panel represents the emissions backlog inherited when ambition is restored. The right panel shows how much of that backlog remains by the original 2050 target year.

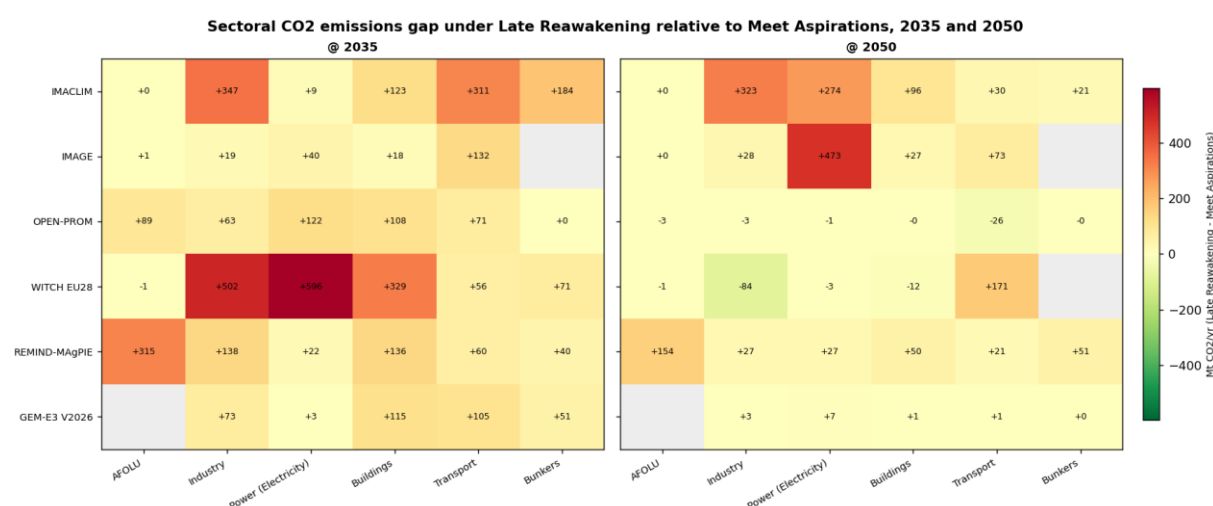


Figure 12: Sectoral CO₂ gap under Late Reawakening relative to Meet Aspirations, by model and sector (Mt CO₂/yr). The left panel shows the backlog at 2035 and the right panel the residual gap at 2050. Grey indicates not reported.

The ability to return towards the Meet Aspirations pathway differs substantially across models and sectors. OPEN-PROM closes almost its entire gap by 2050 across all reported sectors, while GEM-E3 also returns close to the reference pathway. WITCH closes or slightly overcompensates for its initial gaps in industry, power and buildings, but retains a substantial transport gap of approximately 171 Mt CO₂/yr. REMIND-MagPIE narrows its gaps across most sectors but continues to report residual emissions, particularly in AFOLU. In contrast, IMAGE retains a large power-sector gap of approximately 473 Mt CO₂/yr, while IMACLIM remains above Meet Aspirations in industry and power by approximately 323 and 274 Mt CO₂/yr, respectively. Delayed action can therefore be largely recovered in some models, but it leaves substantial residual gaps in others.

Figure 13 compares Late Reawakening directly with continued Asymmetric Roll-Back in 2050, thereby isolating the emissions benefit of restoring climate ambition. The direct comparison with continued rollback confirms that renewed ambition generally reduces emissions, although the magnitude and sectoral distribution of the benefit remain strongly model dependent. Across the available model results, the largest average reductions occur in transport and buildings, at approximately 90 and 86 Mt CO₂/yr, respectively, followed by industry at around 63 Mt CO₂/yr. The average power-sector benefit is smaller, at approximately 32 Mt CO₂/yr, because large reductions in OPEN-PROM and IMAGE are offset by higher power-sector emissions in IMACLIM and limited changes in WITCH and GEM-E3.

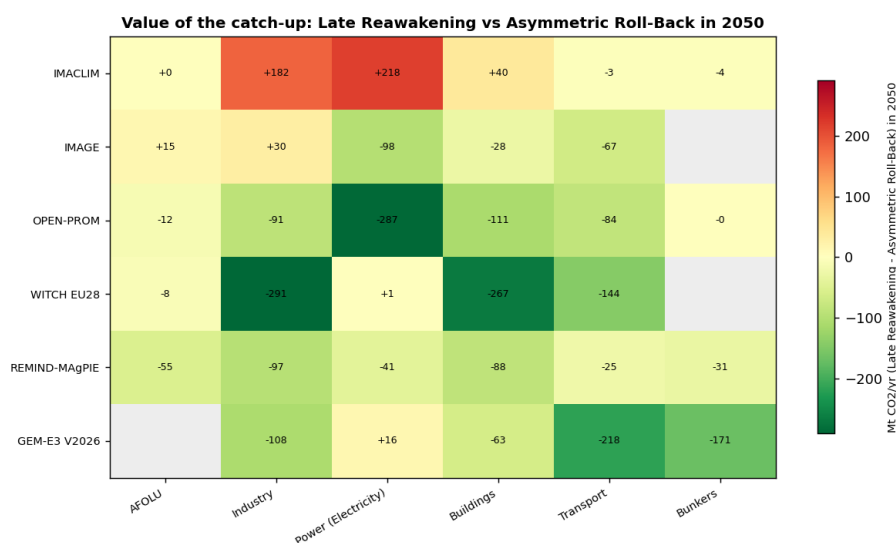


Figure 13: Reduction in sectoral CO₂ emissions at 2050 under Late Reawakening relative to Asymmetric Roll-Back, by model and sector (Mt CO₂/yr). Negative values indicate that renewed ambition reduced emissions. Grey indicates not reported.

At the model level, OPEN-PROM records broad reductions across almost all sectors, with the largest benefit occurring in power. WITCH reports particularly large reductions in industry, buildings and transport, while GEM-E3 achieves its largest gains in transport and bunkers. REMIND-MAGPIE shows more moderate but broadly distributed reductions. IMAGE also lowers emissions in power, buildings and transport. IMACLIM is the principal exception, reporting higher emissions under Late Reawakening in industry, power and buildings than under continued rollback, despite small reductions in transport and bunkers. Power displays the widest disagreement across models, ranging from a reduction of approximately 287 Mt CO₂/yr in OPEN-PROM to an increase of approximately 218 Mt CO₂/yr in IMACLIM. Overall, restoring ambition delivers substantial emissions benefits, but neither the speed nor the sectoral source of recovery is consistent across models.

Overall, the differences across models reflect variations in model structure, foresight, technology representation and adjustment dynamics. When ambition is restored, models therefore rely on different combinations of power-sector decarbonisation, electrification, fuel substitution, demand reduction and carbon removal. These results represent alternative internally consistent transition pathways rather than uncertainty around a single common response.

1.3.3 Energy system transformation

The energy system transformation can first be examined through the primary and final energy mixes, which show how each model rebuilds EU supply and demand on the way to net zero (Figure 14 and Figure 15). Two robust messages emerge. First, all models point in the same direction. Stronger climate ambition reduces fossil fuel dependence in primary energy and increases the role of electricity in final demand. Meet Aspirations generally delivers the fastest transformation, while Asymmetric Roll-Back retains higher fossil fuel shares and lower electrification for longer. Late Reawakening moves most models back towards the ambitious pathway after 2035, whereas Staying Alive generally remains closer to the rollback pathway. Second, there is no single technology portfolio for delivering this transition. Differences across models are often larger than differences between scenarios within the same model, reflecting

alternative representations of technology competition, capital-stock turnover, resource availability, technology costs, learning, demand and deployment constraints.

1.3.3.1 Primary Energy

In the primary energy mix, coal declines first and most sharply across the ensemble, while oil and gas remain more persistent through and beyond mid-century (Figure 14). Under Meet Aspirations, WITCH and REMIND-MagPIE rely most strongly on wind and solar, which become the dominant primary-energy sources by around 2050. The transition is particularly rapid in WITCH, where the mix shifts sharply towards variable renewables between 2040 and 2050. GEM-E3 also expands wind and solar substantially, while retaining a more mixed portfolio of biomass and residual fossil fuels. IMACLIM and IMAGE assign a larger role to biomass, which becomes one of their principal primary-energy sources. OPEN-PROM follows a more diversified pathway combining biomass, wind, solar and nuclear contribution.

Oil and gas remain present in every model, particularly under Asymmetric Roll-Back and Staying Alive. Their persistence is consistent with continued fuel demand in hard-to-abate sectors and may also reflect the roles assigned to gas-based technologies, hydrogen production and carbon capture in individual models. In IMACLIM, and more mildly in IMAGE, Meet Aspirations and Late Reawakening show a post-2050 stabilisation or partial recovery of gas in the primary energy mix after a much stronger decline up to mid-century. A weaker late-century stabilisation is also visible in some other models, but it is most evident in IMACLIM. Since the figure reports shares, this should not automatically be interpreted as an increase in absolute gas consumption. Rather, it indicates that these models retain some role for gas after the main decarbonisation effort to 2050 through model-specific, cost-responsive adjustments in the energy mix.



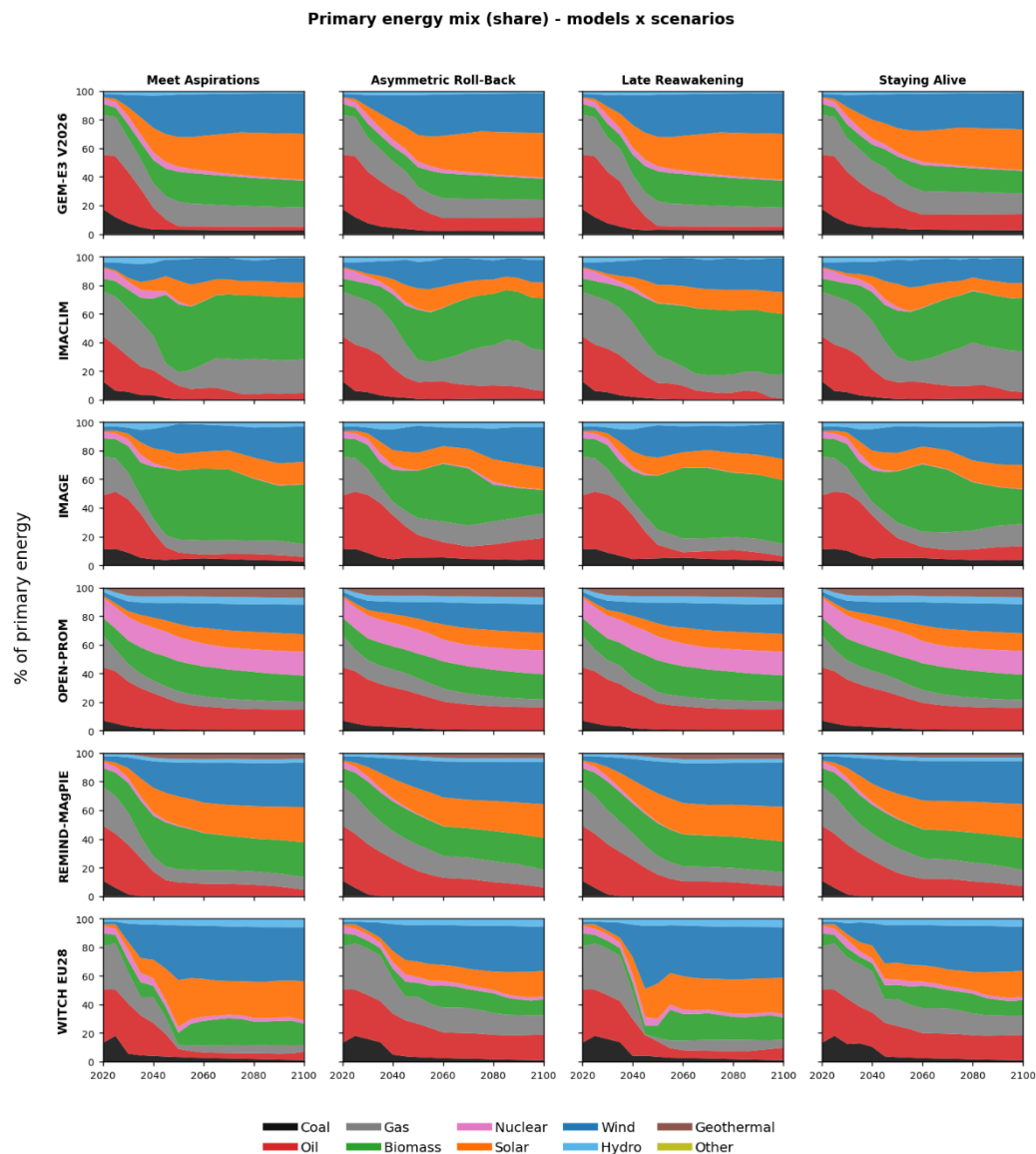


Figure 14: Primary energy mix by model and scenario.

1.3.3.2 Final Energy

The final energy mix shows the corresponding transformation on the demand side (Figure 15). Electricity becomes the largest final-energy carrier in every model and scenario by around mid-century, confirming electrification as one of the most robust features of the transition. WITCH and GEM-E3 push direct electrification furthest, with WITCH again showing a significant and abrupt increase around 2050 under Meet Aspirations and Late Reawakening. IMAGE, OPEN-PROM and REMIND-MAGPIE also expand electricity substantially, but through more gradual pathways. IMACCLIM shows a strong increase up to mid-century, followed by a partial decline in electricity's share as gases regain importance later in the century.

The models differ more clearly in how they meet demand that is not directly electrified. OPEN-PROM assigns the largest role to hydrogen, with smaller contributions also visible in REMIND-

MAGPIE and GEM-E3. Liquid fuels remain comparatively important in IMACLIM, IMAGE and REMIND-MAGPIE, while gases retain a notable role in several models, particularly IMACLIM. These differences represent alternative strategies for decarbonising difficult-to-electrify uses through direct electricity, hydrogen, low-carbon gases, biofuels or synthetic liquids. The policy conclusion is therefore robust even though the precise technology mix remains uncertain. Ambitious pathways are consistently characterised by rapid renewable deployment, greater electrification and declining direct fossil fuel use. The main disagreement concerns how far direct electrification can proceed and which low-carbon fuels and technologies should complement it.

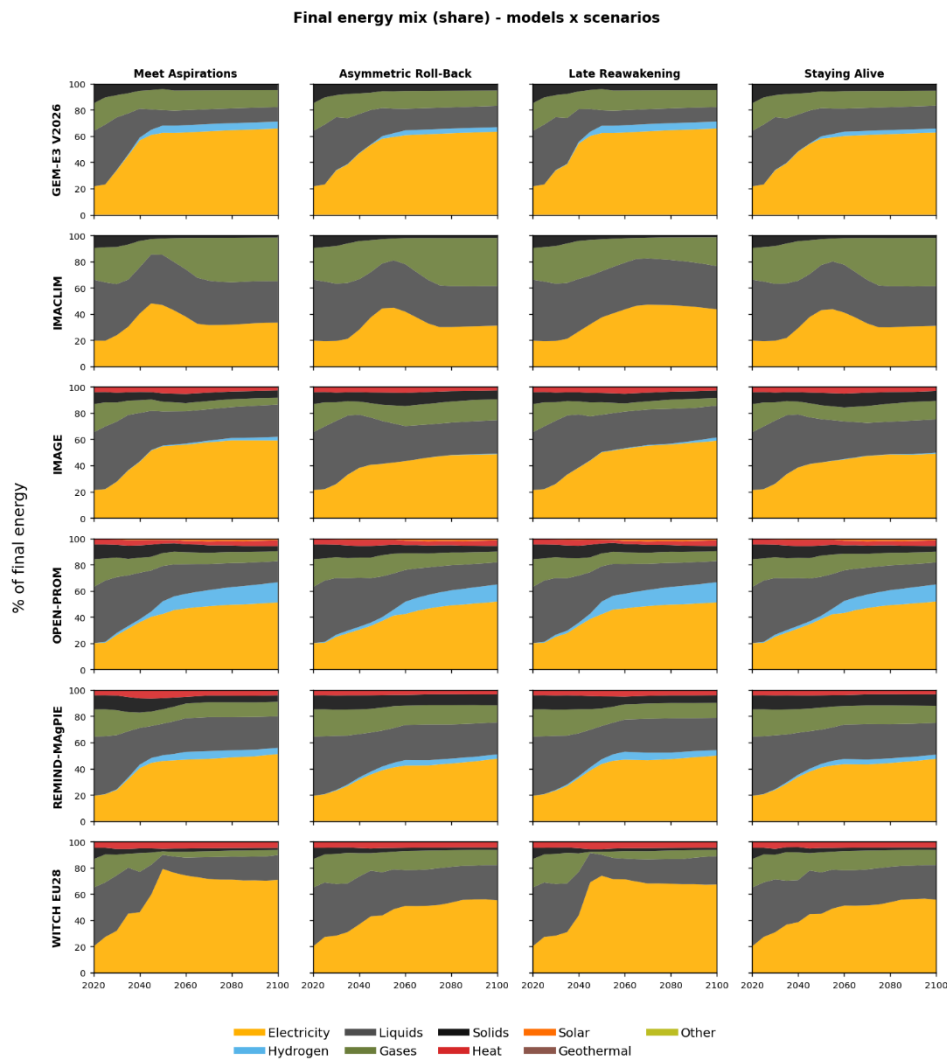


Figure 15: Final energy mix, as a share of final energy, by model and scenario.

1.3.3.3 Fossil share of primary energy

Focusing on the fossil share of primary energy, the ensemble declines from approximately 76% in 2020 to around 20% by 2050 under Meet Aspirations (Figure 16). Under Asymmetric Roll-Back and Staying Alive, fossil fuels still account for roughly 35% of primary energy in 2050, while Late Reawakening reduces the share to about 25%. Renewed ambition therefore closes

much, but not all, of the mid-century gap created by the initial rollback. The robust message across the ensemble is that delayed ambition prolongs the role of fossil fuels in the EU energy mix, even when technological progress continues.

The model-level results reveal substantial differences in the speed and scenario sensitivity of this transition (Figure 17). WITCH shows the strongest contrast: its fossil share falls to around 14–17% by 2050 under Meet Aspirations and Late Reawakening but remains above 40% under Asymmetric Roll-Back and Staying Alive. GEM-E3 also shows a clear separation between the scenarios, reaching 20% range under Meet Aspirations and Late Reawakening, compared with around 40–45% under the weaker-ambition pathways. IMAGE and IMACLIM similarly retain substantially higher fossil shares under Asymmetric Roll-Back and Staying Alive, although IMACLIM also shows some stabilisation or recovery after its mid-century decline. OPEN-PROM and REMIND-MAGPIE show smoother and more gradual declines with smaller differences across scenarios. The models therefore agree that stronger policy reduces fossil dependence, but differ considerably in how rapidly the transition occurs and how strongly it responds to changes in ambition. Moreover, since the figures report shares, changes may also reflect developments in total primary-energy demand and should not be interpreted directly as changes in absolute fossil fuel consumption.

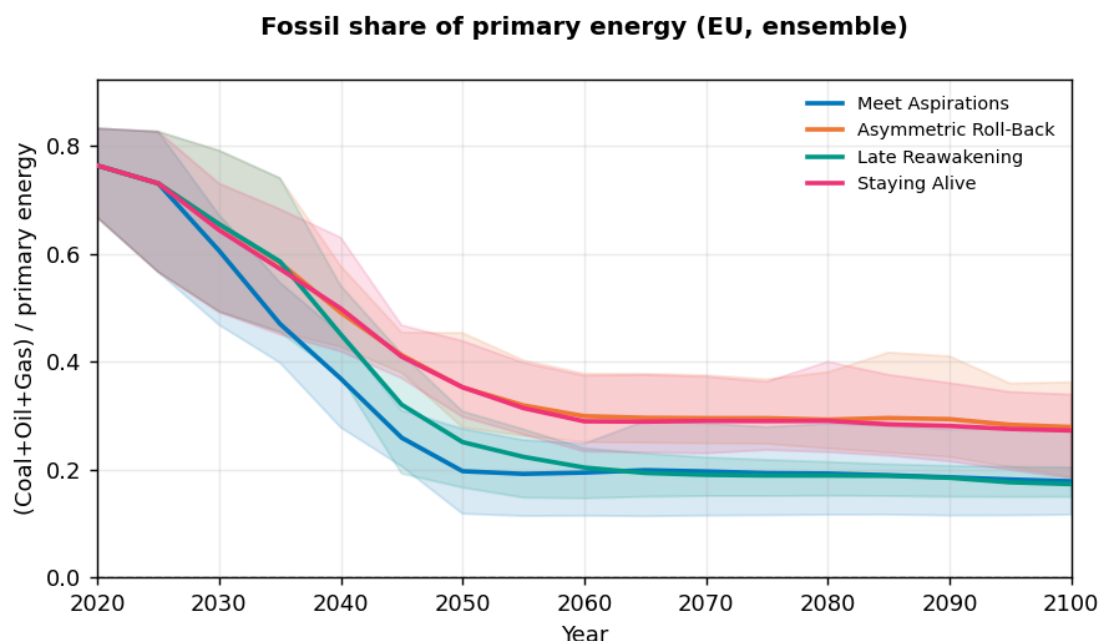


Figure 16: Fossil share of EU primary energy by scenario, ensemble mean.

Fossil share of primary energy: per model, all scenarios

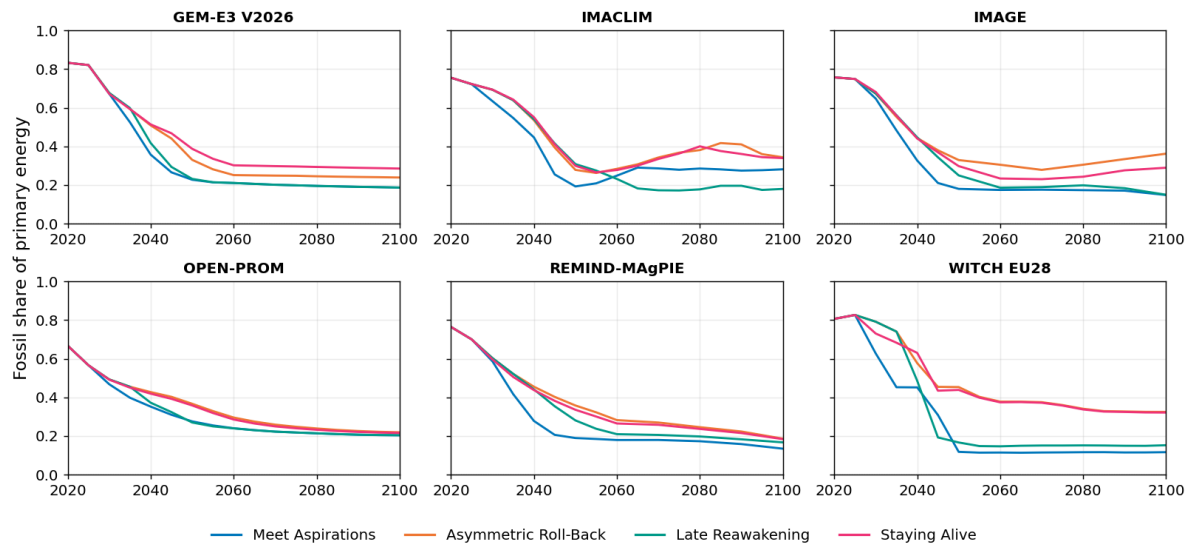


Figure 17: Fossil share of EU primary energy by model, all scenarios.

1.3.3.4 Electrification rate

Electrification provides a complementary mechanism to reduce emissions (Figure 18). In Meet Aspirations, end-use electrification rises faster through the 2030s and approaches about 54% of final energy by 2050, based on the model ensemble mean. Under Asymmetric Roll-Back, the 2050 value remains lower, at about 44%. Late Reawakening accelerates after 2035 and reaches approximately 51% by mid-century, closing most of the gap with Meet Aspirations but compressing the transition into a shorter period. Finally, even though Staying Alive maintains support for transport electrification before 2035, its economy-wide electrification rate remains close to Asymmetric Roll-Back and below Late Reawakening by 2050.

It could seem likely that Staying Alive, by maintaining electrification momentum, should achieve greater electrification than Late Reawakening. However, the data show that the broader decarbonisation effort introduced under Late Reawakening leads to a higher electrification rate by 2050. This is consistent with renewed mitigation effort driving the replacement of fossil fuel use across buildings, industry and transport, rather than supporting electrification only in selected areas. The result suggests that late policy acceleration can recover much of the electrification gap, but requires a more compressed transition than the smoother pathway observed under Meet Aspirations.

The per-model view (Figure 19) shows that the electrification response differs strongly across models. WITCH electrifies fastest and reaches the highest mid-century shares, especially in Meet Aspirations and Late Reawakening, followed by a moderate decline after 2050. This is consistent with the final-energy-mix results discussed earlier, where electricity loses some share after the target year under these scenarios. GEM-E3 also reaches high electrification levels, exceeding 60% later in the century, with Late Reawakening eventually slightly exceeding Meet Aspirations. OPEN-PROM shows the opposite behaviour, as electrification is comparatively gradual. IMACLIM electrifies earlier under Meet Aspirations but shows a pronounced decline after its mid-century peak, while Late Reawakening continues to increase

and eventually becomes the most electrified pathway. IMAGE and REMIND-MAgPIE show smoother increases, with Meet Aspirations generally remaining above the rollback cases and Late Reawakening closing part of the gap after 2035. Overall, the rollback delays electrification in the models where scenario differences are visible, although the timing and persistence of this effect vary substantially across models.

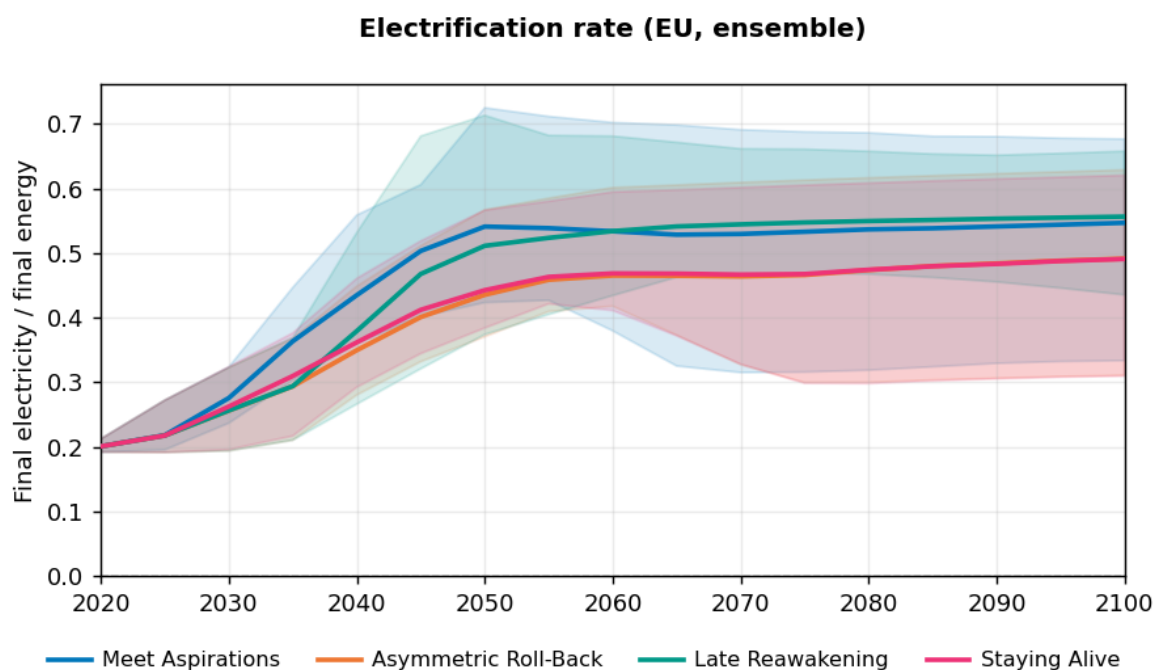


Figure 18: End-use electrification, as a share of final energy, by scenario, ensemble mean.

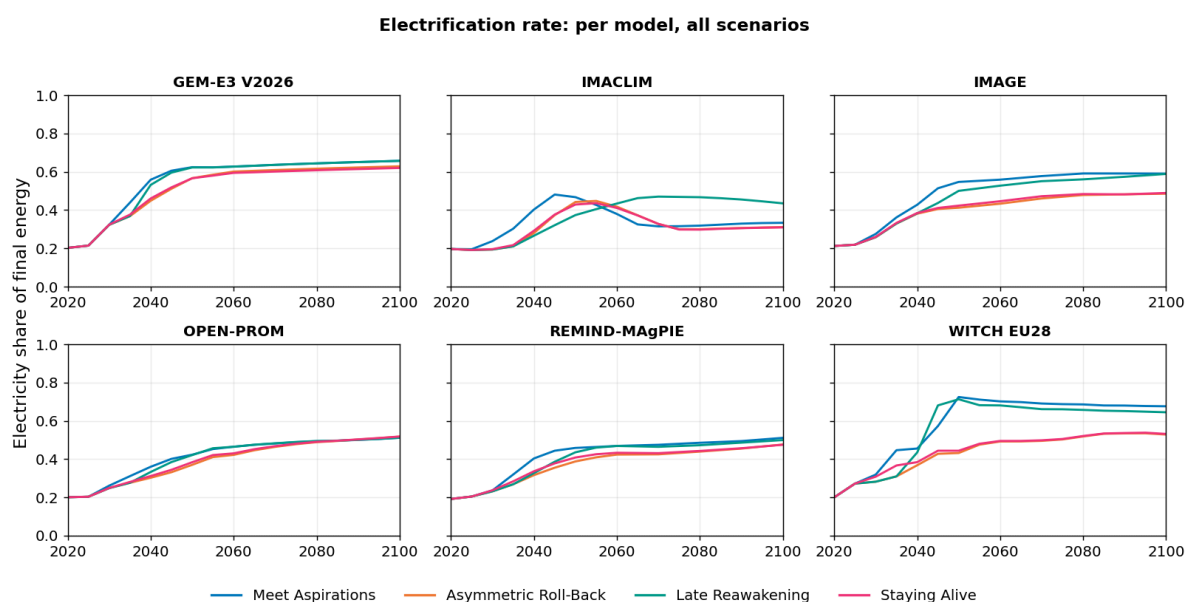


Figure 19: End-use electrification by model, all scenarios.

1.3.4 Energy security implications

Energy security has moved to the centre of European climate policy. Geopolitical tensions repeatedly disrupt oil and gas markets, and the resulting price shocks pass quickly into inflation, trade balances and household incomes. The EU produces only a small share of the fossil fuels it consumes, so phasing out fossil fuels also removes a strategic vulnerability. Renewables, electrification and low-carbon carriers are supplied predominantly from within the Union, which makes the pace of the fossil phase-out a security indicator as much as a climate one.

1.3.4.1 Fossil phase out

Figure 20 reports the first year in which each fuel falls below its threshold share of total EU primary energy, which indicates a relative phase-down rather than the end of fuel use. The models agree on the order in which fossil fuels lose structural importance, with coal declining first, gas second and oil last, but they differ widely on timing and several never cross the threshold at all.

Coal crosses the 1% threshold in only two models. REMIND-MAgPIE crosses in the mid-2030s in every scenario, while OPEN-PROM crosses around 2050 under Meet Aspirations and Late Reawakening and roughly eight years later under the two rollback scenarios. IMACLIM, IMAGE, WITCH and GEM-E3 remain above the threshold to 2100.

Gas crossings are more numerous and cluster between the late 2030s and the mid-2050s, although five of the six crossings that later reverse concern gas, including IMAGE in all four scenarios. Oil is slower and less robust, with crossings spread from the 2040s to beyond 2090 and at least one model failing to cross in every scenario. The rollback generally delays both fuels, but not uniformly.

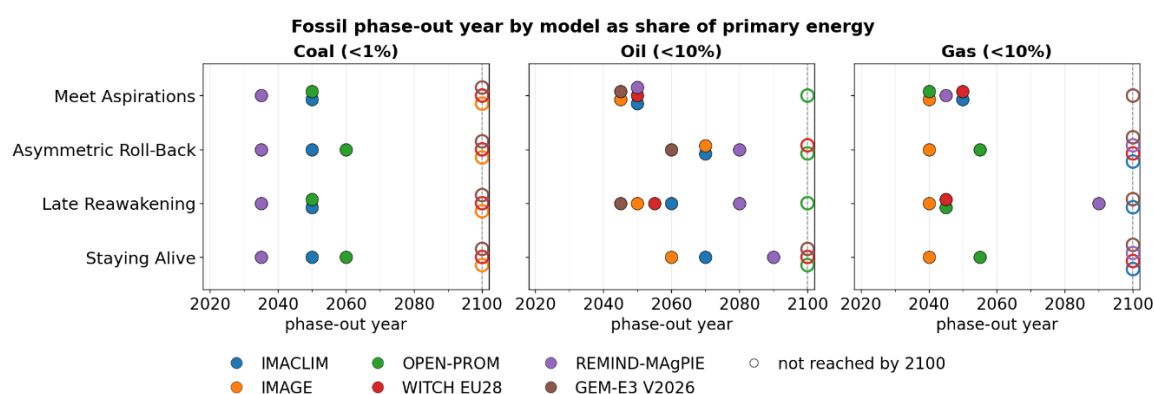


Figure 20: Fossil phase-out year by model, fuel and scenario. The first year in which each fuel's share of total EU primary energy falls at or below a fixed threshold (coal below 1%, oil and gas below 10%). Hollow markers denote combinations that never fall below the threshold by 2100. Six crossings later reverse, five of them for gas.

1.3.4.2 Fossil import reliance

Fossil import reliance provides a more direct indicator of energy security and geopolitical exposure than the fossil share of primary energy. It measures net imports of oil, gas and coal relative to total primary energy, showing how much of the EU energy system remains dependent on external fossil fuel suppliers. Only OPEN-PROM and REMIND-MAgPIE report this indicator consistently, so the results are not ensemble-wide. Both models show a substantial

long-term reduction in external fossil dependence (Figure 21). Coal import reliance approaches zero rapidly, while gas dependence also declines strongly. Oil remains the largest and most persistent source of import exposure, reflecting the continued difficulty of replacing oil in transport and other hard-to-abate uses. Meet Aspirations generally reduces oil and gas import dependence faster than Asymmetric Roll-Back, while Late Reawakening recovers part of the lost progress after 2035. Staying Alive also reduces dependence over time but remains closer to the rollback pathway. Lower import dependence reduces exposure to external supply restrictions, disruptions and imported fuel-price volatility.

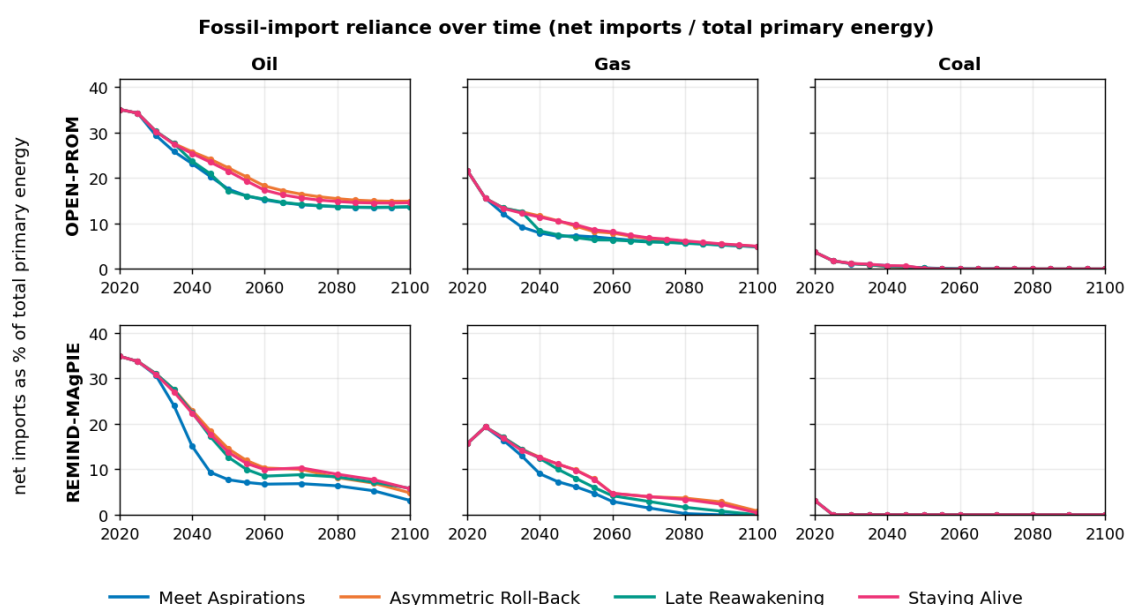


Figure 21: EU fossil-import reliance by model, fuel and scenario. Net imports of oil, gas and coal as a share of total primary energy, reported by OPEN-PROM and REMIND-MAGPIE only.

1.3.5 Economic impacts

1.3.5.1 Carbon Price

The carbon price is one of the clearest economic indicators of the mitigation pressure associated with the alternative pathways. Figure 22 presents the modelled EU carbon price trajectories under the four scenarios. In Meet Aspirations, the ensemble mean rises sharply during the 2030s and peaks at around 900 USD₂₀₁₀/tCO₂ in 2035 before declining to approximately 600 USD₂₀₁₀/tCO₂ by 2050. However, both the peak and the very wide model spread are largely driven by IMACLIM, which reports a carbon price of around 3,000 USD₂₀₁₀/tCO₂ in 2035, while the other models remain substantially lower. As each model treats the carbon price mechanism differently, the ensemble mean should not be interpreted as a representative price followed by all models. Under Asymmetric Roll-Back and Staying Alive, prices increase more gradually and remain around 250–300 USD₂₀₁₀/tCO₂ in 2050, reflecting weaker immediate mitigation pressure. Late Reawakening illustrates the cost of catching up: after remaining relatively low during the rollback period, its ensemble-mean price rises sharply to around 750 USD₂₀₁₀/tCO₂ in 2050, exceeding Meet Aspirations at the target year. This increase is supported by high prices in IMAGE and OPEN-PROM, as well as elevated values in IMACLIM and GEM-E3, and indicates that restoring ambition after 2035 requires a

stronger and more compressed carbon-price signal. The broad and overlapping shaded ranges nevertheless show that the magnitude of the required price remains highly model-dependent.

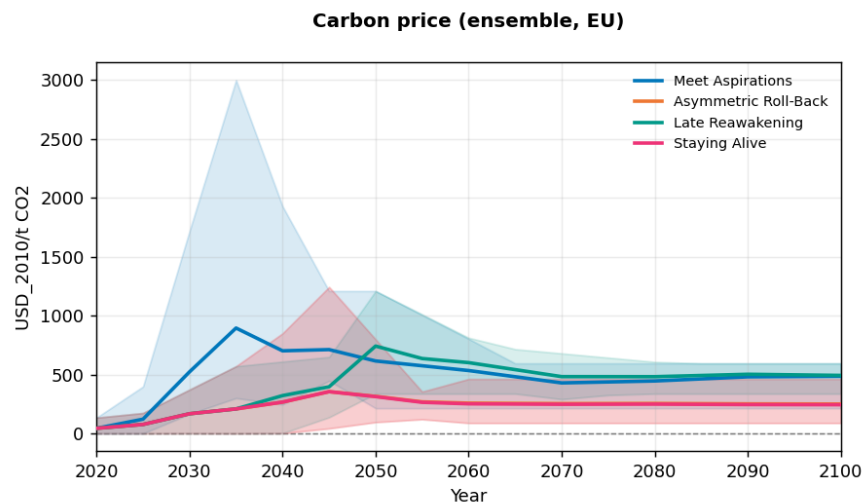


Figure 22: EU carbon price by scenario, ensemble mean. WITCH is excluded because it does not report carbon price consistently.

The ensemble mean combines five distinct pricing behaviours (Figure 23). IMACLIM reports the highest and earliest peak, reaching around 3,000 USD₂₀₁₀/tCO₂ under Meet Aspirations in 2035, which may reflect the strong pressure to meet the EU NDC. OPEN-PROM instead records its highest price under Late Reawakening in 2050, at around 900 USD₂₀₁₀/tCO₂, reflecting the compressed effort required to approach the original 2050 target after the rollback period. IMAGE also concentrates much of its mitigation pressure around the target years, with a strong Meet Aspirations increase before 2050 and a Late Reawakening peak around 2050. GEM-E3 and REMIND-MagPIE display smoother and more stable increases, without similarly abrupt peaks. Overall, carbon prices tend to rise around the years in which binding emissions objectives must be achieved, but their timing and magnitude depend strongly on how each model represents policy constraints, foresight, technology adjustment and the availability of mitigation options.

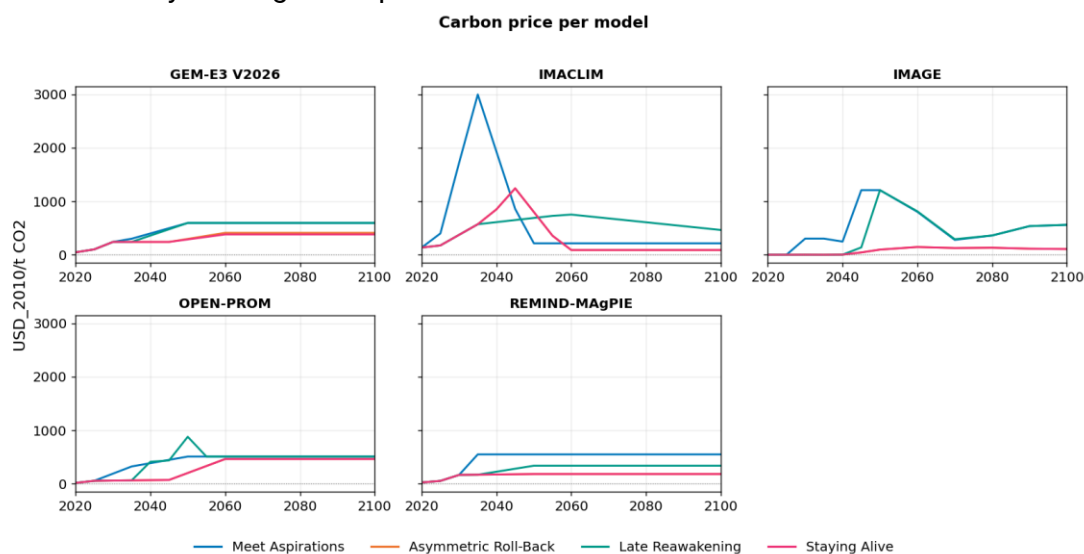


Figure 23: Carbon price by model, all scenarios. WITCH is excluded because it does not report carbon price consistently.

1.3.5.2 Electricity Price

As electricity prices are reported differently across models, the focus of this analysis is on their evolution over time and on how scenario assumptions affect prices within each model. As Figure 24 shows, Meet Aspirations produces somewhat higher electricity prices before mid-century in several models, but the differences are generally small. The main exception is IMACLIM, where Meet Aspirations leads to a pronounced price peak around 2040 before the scenario pathways converge. In OPEN-PROM and WITCH, electricity prices are almost identical across scenarios, while IMAGE and REMIND-MagPIE show only modest and temporary differences. Lower carbon-price paths under the rollback scenarios may partly explain their lower electricity prices in some periods, although this relationship is not consistent across all models.

Notably, the limited scenario variation outside IMACLIM is an important finding for households and industry. It suggests that raising the EU's climate ambition does not need to come with a cost to electricity prices for industry and households. The continued deployment of cost-competitive renewable technologies can counterbalance the effect of higher carbon prices and keep modelled electricity prices broadly similar even under more ambitious pathways. However, these results concern modelled electricity price indicators rather than final household or industrial prices.

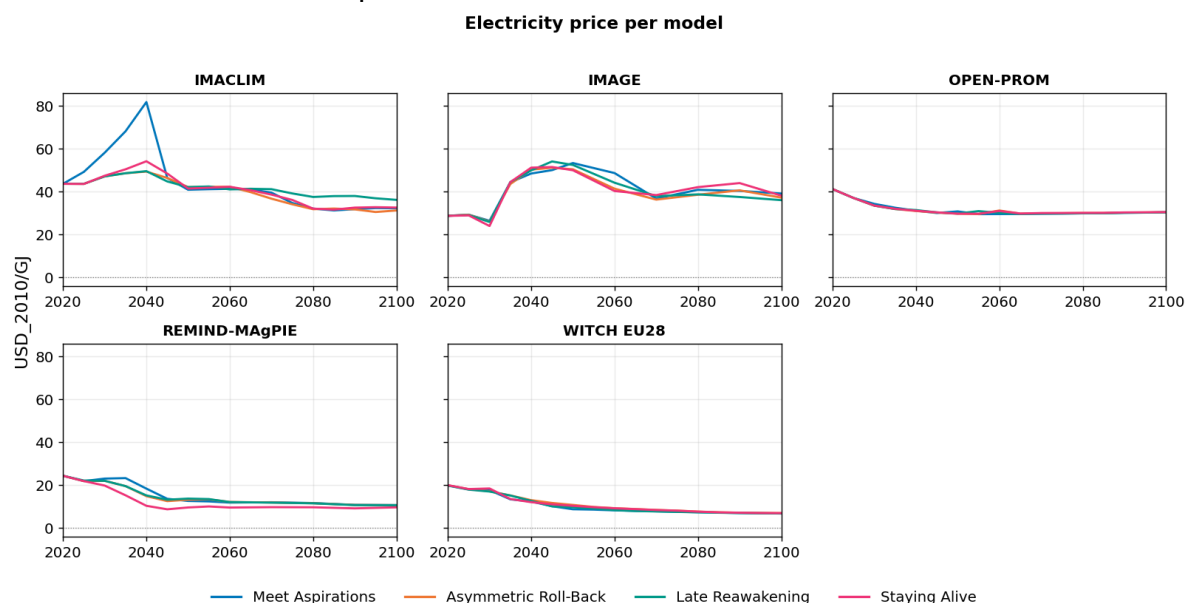


Figure 24: Electricity price by model and scenario.

1.3.5.3 Clean Technology Investments

Since investment coverage differs across models, the results are best interpreted through within model scenario differences rather than absolute comparisons between models. Figure 25 reports cumulative investment in the protocol's specified clean technologies over 2025 – 2050, while Figure 26 breaks down the individual investments in solar, wind and, where available, storage and transmission and distribution. Wind accounts for the largest share in most models, while solar is also substantial, particularly in IMAGE and WITCH. Storage and network investment are reported by only a subset of models, which partly explains the large differences in total investment levels across the ensemble.

Within models, Meet Aspirations generally requires the highest cumulative investment, particularly in IMAGE, OPEN-PROM and WITCH, while Asymmetric Roll-Back is the lowest or close to the lowest pathway in all models. Late Reawakening exceeds Asymmetric Roll-Back in five of the six models, reflecting additional investment once ambition is restored, although it generally remains below Meet Aspirations because some early investment cannot be fully recovered after 2035. Staying Alive also requires more investment than Asymmetric Roll-Back in every model that reports it, consistent with continued support for renewables, grids, storage and electrification. However, it does not follow a uniform ranking relative to Meet Aspirations or Late Reawakening: it remains lower in IMAGE, OPEN-PROM and WITCH, but is comparatively high in REMIND-MAgPIE and GEM-E3. Overall, the results suggest that maintaining clean-technology momentum reduces investment deferral under rollback, but the total capital response depends strongly on model-specific technology coverage, costs and deployment timing.

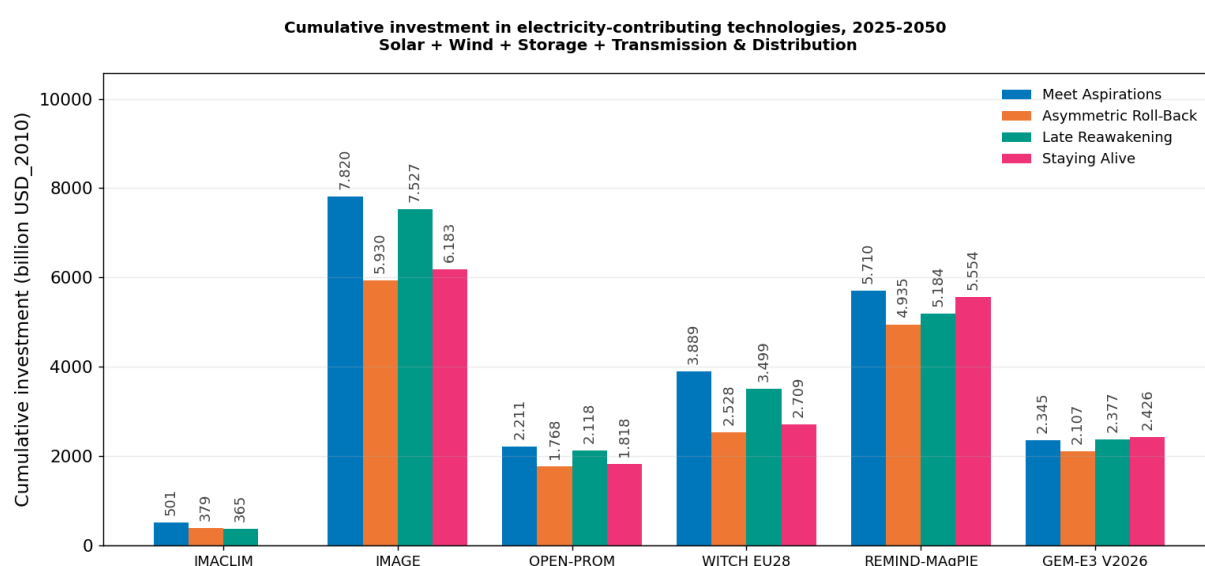


Figure 25: Cumulative clean-technology investment over 2025-2050 by model and scenario.

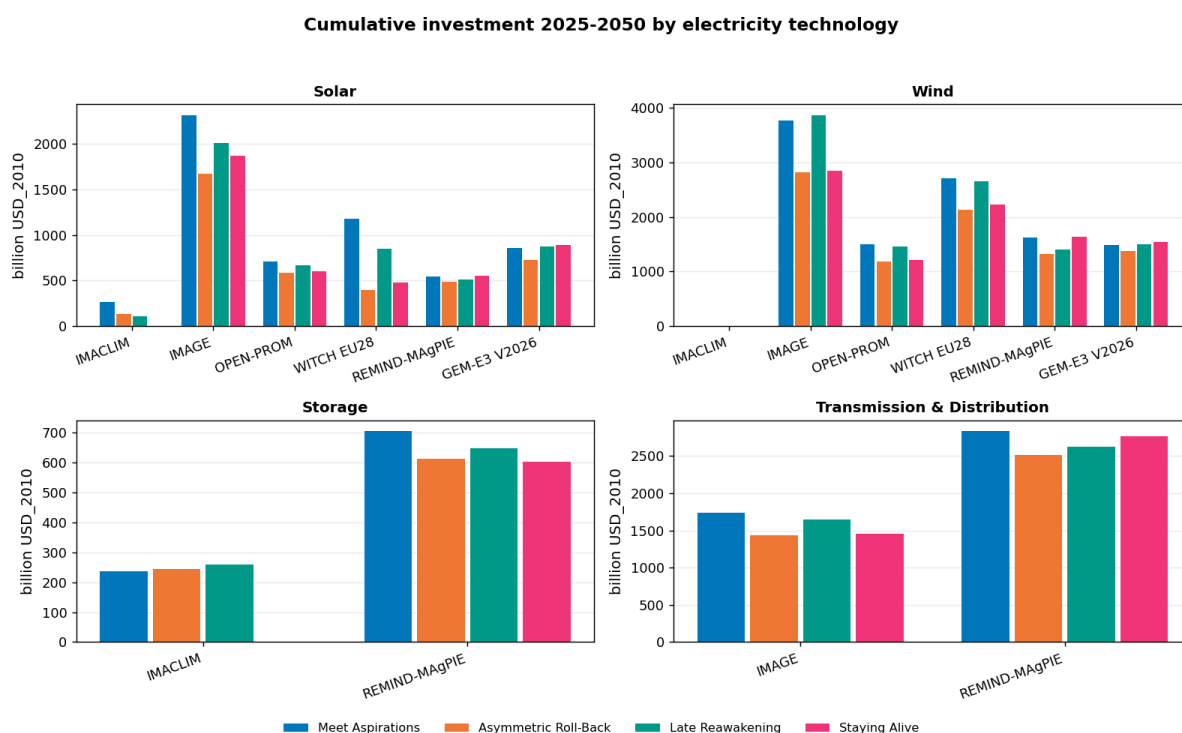


Figure 26: Cumulative clean-technology investment over 2025-2050 by technology, model and scenario.

1.4 Conclusions

This study examined how different trajectories of European climate ambition could affect emissions, sectoral decarbonisation, energy system transformation, investment requirements, prices and energy security. The analysis is particularly relevant to the current EU policy debate, in which the climate-neutrality objective must increasingly be reconciled with concerns over affordability, industrial competitiveness, implementation capacity, social acceptance and geopolitical resilience. Rather than treating climate policy rollback as a simple postponement, the scenarios assess whether lost momentum changes the feasibility, timing and character of the transition itself.

Across the modelling ensemble, the results show that deep decarbonisation is possible, but achieving the EU's stated climate neutrality target remains highly demanding. Even under Meet Aspirations, the ensemble reaches net-zero GHG emissions only after 2060, with only IMAGE achieving net-zero before mid-century. The models nevertheless agree on the main direction of transformation, which consists of a rapid decline in fossil fuel use, substantial renewable energy deployment, greater electrification of final demand and continued investment in power generation, networks and storage. Carbon removal also becomes important for offsetting residual emissions, although its scale and technological composition differ considerably across models. Climate neutrality therefore depends not on one specific technology portfolio, but on combining rapid clean energy deployment with broad reductions in fossil fuel demand and measures addressing residual emissions.

Delaying or weakening climate policy has consequences beyond a temporary deviation from the reference pathway. Under Asymmetric Roll-Back, emissions remain substantially above

Meet Aspirations throughout the transition. By 2050, the ensemble approaches net zero CO₂ under Meet Aspirations, while the rollback pathway still emits around 670 Mt CO₂/yr and does not subsequently achieve net zero within the modelled horizon. Delayed action also maintains higher fossil fuel shares, reduces electrification and postpones clean-technology investment. The sectoral composition of this gap changes over time. Industry accounts for the largest contribution in 2035, whereas power, transport and bunkers become increasingly important by mid-century. This indicates that the consequences of rollback gradually shift towards sectors in which infrastructure turnover, fuel substitution and the development of low-carbon alternatives require longer time.

Late Reawakening demonstrates that a substantial part of the lost emissions reduction can still be recovered when ambition is restored, but the recovery is neither complete nor uniform. Electrification accelerates sharply after 2035 and reaches around 51% of final energy by 2050, closing most of the gap with Meet Aspirations but concentrating the transformation into a shorter period. Several models return close to the reference pathway in many sectors, while others retain significant residual gaps in power, industry, transport or AFOLU. The economic indicators reinforce this result: Late Reawakening requires a sharper carbon price signal around 2050 and generally higher clean technology investment than continued rollback, although investment remains below Meet Aspirations in several models. Delayed action can therefore be partly corrected, but only through a faster and more concentrated adjustment.

Continued support for selected clean technologies under Staying Alive provides some protection against a rollback, but does not replace broader climate policy ambition. Maintaining investment in renewables, grids, storage and electric vehicles preserves part of the transition momentum. However, emissions and electrification generally remain much closer to Asymmetric Roll-Back than to Meet Aspirations. Support for mature clean technologies is therefore a useful low-regret strategy during periods of political uncertainty, but it is insufficient on its own to deliver climate neutrality.

The results also address the concerns that stronger climate ambition could lead to increased electricity costs for households and industry. Besides the pronounced IMACLIM peak, differences in modelled electricity prices across scenarios are generally modest, with almost no variation in OPEN-PROM and WITCH and only temporary differences in IMAGE and REMIND-MAgPIE. This suggests that the deployment of cost-competitive renewable technologies can partly offset the effects of higher carbon prices. It should be noted that the reported values may not be the end-consumer prices, but the results provide no indication of increased electricity prices due to stronger ambition.

Finally, higher ambition also strengthens energy security. As reliance on imported fossil fuels diminishes, EU becomes less exposed to supply disruptions, sudden price shocks and broader geopolitical tensions. In this analysis, oil remained the most persistent source of this vulnerability, which points to transport and other hard-to-electrify sectors as continuing priorities for both climate and energy-security policy.

Although individual results vary because the models differ in their assumptions, technology coverage and adjustment mechanisms, the general direction is consistent. Early and sustained ambition produces a smoother and more feasible transition, while delay raises emissions, preserves fossil dependence and shifts a larger adjustment burden into the period after 2035.

References

- Baumstark, L., Bauer, N., Benke, F., Bertram, C., Bi, S., Gong, C. C., Dietrich, J. P., Dirnaichner, A., Giannousakis, A., Hilaire, J., Klein, D., Koch, J., Leimbach, M., Levesque, A., Madeddu, S., Malik, A., Merfort, A., Merfort, L., Odenweller, A., ... Luderer, G. (2021). REMIND2.1: Transformation and innovation dynamics of the energy-economic system within climate and sustainability limits. *Geoscientific Model Development*, 14(10), 6571–6603. <https://doi.org/10.5194/gmd-14-6571-2021>
- Bibas, R., Cassen, C., Crassous, R., Guivarch, C., Hamdi-Cherif, M., Hourcade, J. C., Leblanc, F., Méjean, A., Ó Broin, E., Rozenberg, J., Sassi, O., & Vogt-Schilb, A. (2022). *IMpact assessment of CLIMate policies with IMACLIM-R 1.1: Model documentation, version 1.1* (CIRED Working Paper No. hal-03702627). HAL. <https://hal.science/hal-03702627>
- Capros, P., Van Regemorter, D., Paroussos, L., Karkatsoulis, P., Fragkiadakis, C., Tsani, S., Charalampidis, I., & Revesz, T. (2013). GEM-E3 model documentation. Publications Office of the European Union. <https://doi.org/10.2788/47872>
- Council of the European Union. (2026, March 5). *2040 climate target: Council gives final green light* [Press release]. <https://www.consilium.europa.eu/en/press/press-releases/2026/03/05/2040-climate-target-council-gives-final-green-light/>
- Dietrich, J. P., Bodirsky, B. L., Humpenöder, F., Weindl, I., Stevanović, M., Karstens, K., Kreidenweis, U., Wang, X., Mishra, A., Klein, D., Ambrósio, G., Araujo, E., Yalew, A. W., Baumstark, L., Wirth, S., Giannousakis, A., Beier, F., Chen, D. M.-C., Lotze-Campen, H., & Popp, A. (2019). MAgPIE 4: A modular open-source framework for modeling global land systems. *Geoscientific Model Development*, 12(4), 1299–1317. <https://doi.org/10.5194/gmd-12-1299-2019>
- Draghi, M. (2024). *The future of European competitiveness*. European Commission. https://commission.europa.eu/topics/competitiveness/draghi-report_en
- Emmerling, J., Drouet, L., Reis, L. A., Bevione, M., Berger, L., Bosetti, V., Carrara, S., De Cian, E., De Maere d'Aertrycke, G., Longden, T., Malpede, M., Marangoni, G., Sfera, F., Tavoni, M., Witajewski-Baltviks, J., & Havlík, P. (2016). *The WITCH 2016 model: Documentation and implementation of the Shared Socioeconomic Pathways* (FEEM Working Paper No. 42.2016). Fondazione Eni Enrico Mattei. <https://doi.org/10.2139/ssrn.2800970>
- European Commission. (2021). Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality (European Climate Law). *Official Journal of the European Union*, L 243, 1–17. <https://eur-lex.europa.eu/eli/reg/2021/1119/oj/eng>
- European Commission. (2022, May 18). *REPowerEU plan* (COM(2022) 230 final). <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN>
- European Commission. (2024). Regulation (EU) 2024/1735 of the European Parliament and of the Council of 13 June 2024 establishing a framework of measures for strengthening Europe's net-zero technology products manufacturing ecosystem (Net-Zero Industry Act). *Official Journal of the European Union*. https://commission.europa.eu/topics/competitiveness/green-deal-industrial-plan/net-zero-industry-act_en
- European Commission. (2026a, July 16). *Commission boosts Europe's competitiveness, decarbonisation and independence with Electrification Action Plan and ETS review* [Press release]. https://ec.europa.eu/commission/presscorner/detail/en/ip_26_1596
- European Commission. (2026b, July 15). *The Commission calls on EU countries to transpose the reinforced rules on the energy performance of buildings* [News announcement].



https://energy.ec.europa.eu/news/commission-calls-eu-countries-transpose-reinforced-rules-energy-performance-buildings-2026-07-15_en

- European Scientific Advisory Board on Climate Change. (2023). *Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030 to 2050*. <https://climate-advisory-board.europa.eu/news/eu-climate-advisory-board-recommends-ambitious-2040-climate-target-and-urgent-transitions-for-the-european-union>
- Fragkos, P., Kouvaritakis, N., & Capros, P. (2015). Incorporating uncertainty into world energy modelling: The PROMETHEUS model. *Environmental Modeling & Assessment*, 20, 549–569. <https://doi.org/10.1007/s10666-015-9442-x>
- IAMC Documentation Wiki. (2026). *Reference cards and model documentation for IMAGE, WITCH, REMIND-MAgPIE, and IMACLIM*. <https://www.iamcdocumentation.eu>
- Leimbach, M., Bauer, N., Baumstark, L., & Edenhofer, O. (2010). Mitigation costs in a globalized world: Climate policy analysis with REMIND-R. *Environmental Modeling & Assessment*, 15, 155–173. <https://doi.org/10.1007/s10666-009-9204-8>
- Luderer, G., Leimbach, M., Bauer, N., Kriegler, E., Aboumahboub, T., Curras, T. A., Baumstark, L., Bertram, C., Giannousakis, A., Hilaire, J., Klein, D., Mouratiadou, I., Pietzcker, R. C., Piontek, F., Roming, N., Schultes, A., Schwanitz, V. J., & Strefler, J. (2013). *Description of the REMIND model (Version 1.5)*. SSRN. <https://doi.org/10.2139/ssrn.2312844>
- Méjean, A., Guivarch, C., Lefèvre, J., & Hamdi-Cherif, M. (2019). The transition in energy demand sectors to limit global warming to 1.5°C. *Energy Efficiency*, 12(2), 441–462. <https://doi.org/10.1007/s12053-018-9682-0>
- Stehfest, E., van Vuuren, D., Kram, T., & Bouwman, L. (Eds.). (2014). *Integrated assessment of global environmental change with IMAGE 3.0: Model description and policy applications*. PBL Netherlands Environmental Assessment Agency.



Appendix

A. Asymmetric Roll-Back w/ High Costs

A1. Scope

The stress-test variant, Asymmetric Roll-Back with High Costs, applies the same policy assumptions as Asymmetric Roll-Back, including an identical carbon price trajectory, and differs from it only on the cost side. Changes include innovation spillover mechanisms and knowledge transfer between regions being deactivated to represent low international collaboration. Capital costs are increased for solar photovoltaics, batteries and onshore and offshore wind to represent supply chain constraints. Financing cost markups are applied on top of baseline costs of capital to represent capital market fragmentation and higher risk premiums on clean technology, differentiated by region. The policy signal is therefore held constant and what changes is the cost of responding to it. This scenario is reported by three models only, namely GEM-E3, OPEN-PROM and WITCH, so the ensemble means in this appendix are not comparable with those in the main results. In several figures the Asymmetric Roll-Back line is hidden beneath the high-cost variant because the two pathways almost coincide, which is a result rather than a plotting omission. The subsequent sections are structured slightly differently compared to the main manuscript, due to the nature of the scenario.

A2. Emissions

The high-cost variant is effectively indistinguishable from the standard rollback across the whole horizon (Figure 27). Both remain near 1,500 Mt CO₂eq/yr in 2045 and decline slowly to roughly 350 Mt CO₂eq/yr by 2100, while Meet Aspirations and Late Reawakening converge near zero shortly after mid-century. The snapshot distributions confirm this, with median differences of roughly 50 Mt CO₂eq/yr in 2030 and 2040 falling to about 30 in 2050 and 10 in 2060 (Figure 28). Against a gap to Meet Aspirations of close to 890 Mt CO₂eq/yr at 2050, these differences are marginal. This is close to what the scenario design implies, since the carbon price trajectory is unchanged and it is the policy signal rather than the cost of technology that drives the emissions outcome. Higher costs change how the models meet that signal rather than the level they meet it at.

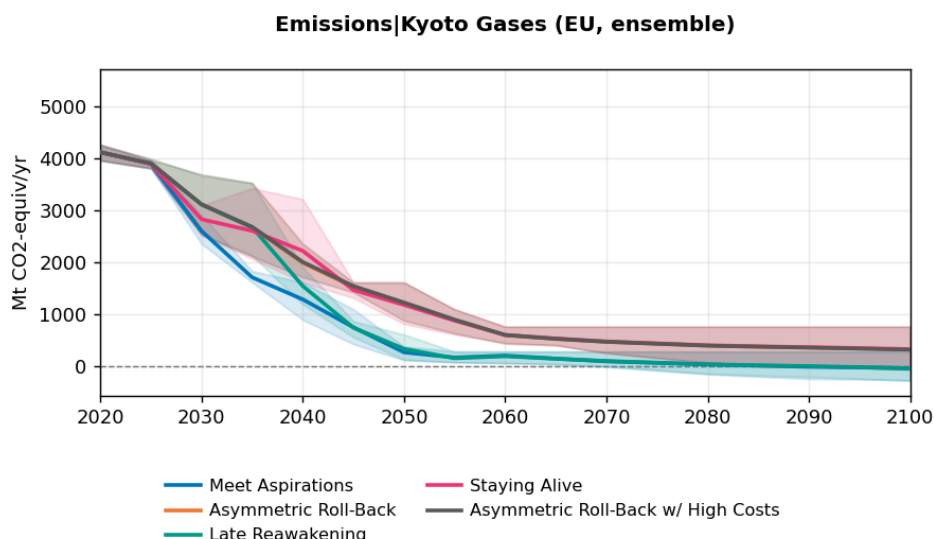


Figure 27: EU Kyoto GHG emissions by scenario, ensemble mean and model range (Mt CO₂eq/yr).

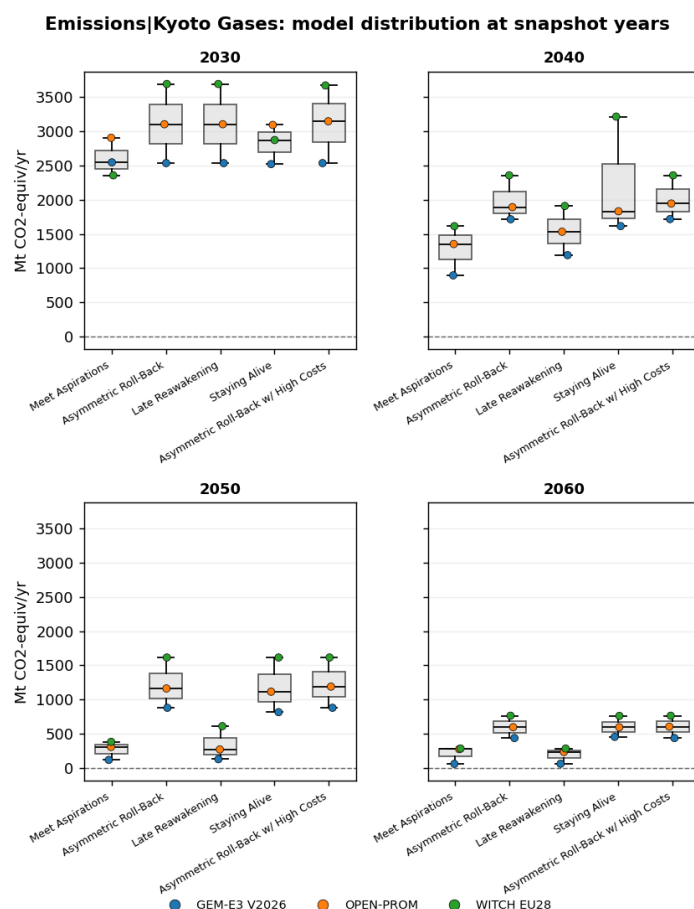


Figure 28: Distribution of EU Kyoto GHG emissions across models, by scenario and snapshot year (Mt CO₂eq/yr).

The sectoral decomposition of the rollback gap reproduces the pattern reported in the main text (Figure 29). The total gap narrows from approximately 790 Mt CO₂/yr in 2035 to 670 in 2050, while the combined share of power, transport and bunkers rises from roughly 44% to 58%. The composition is worth noting, since power falls sharply from 233 to 92 Mt CO₂/yr while transport rises from 77 to 198 and bunkers from 41 to 98. The late-period concentration is therefore driven by transport and international bunkers rather than by power

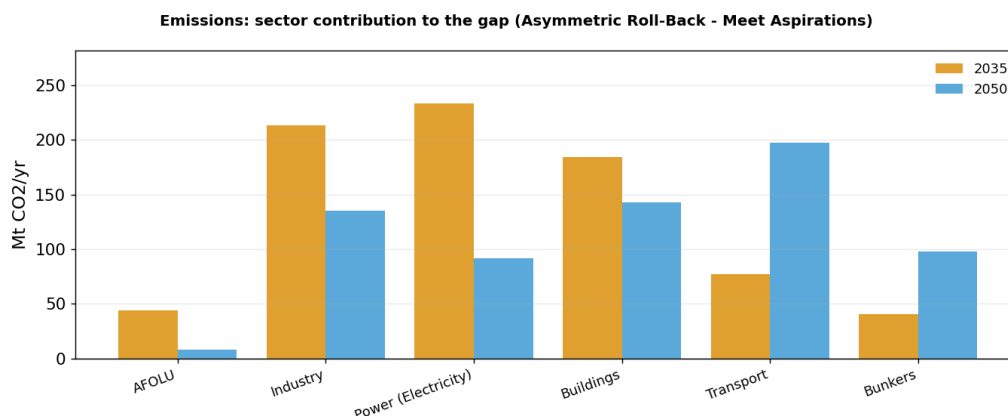


Figure 29: Sectoral contribution to the emissions gap, Asymmetric Roll-Back minus Meet Aspirations, ensemble mean, 2035 and 2050 (Mt CO₂/yr).

A3. Carbon capture

Carbon capture is the first indicator where the variant departs from the standard rollback, and the models disagree on the direction (Figure 30). GEM-E3 captures substantially less, plateauing near 155 Mt CO₂/yr against roughly 255 in every other scenario. WITCH captures more, peaking above 600 Mt CO₂/yr around 2060 and ending as the highest of any pathway in that model. OPEN-PROM sits slightly above the standard rollback from mid-century onwards. Both directions are consistent with the design. Capture is itself capital-intensive, so higher financing costs discourage it, while an unchanged carbon price still requires the emissions outcome to be met, which encourages it where other options have become more expensive. GEM-E3 resolves this tension in the first direction and WITCH in the second. With three models reporting and no agreement between them, no ensemble conclusion can be drawn.

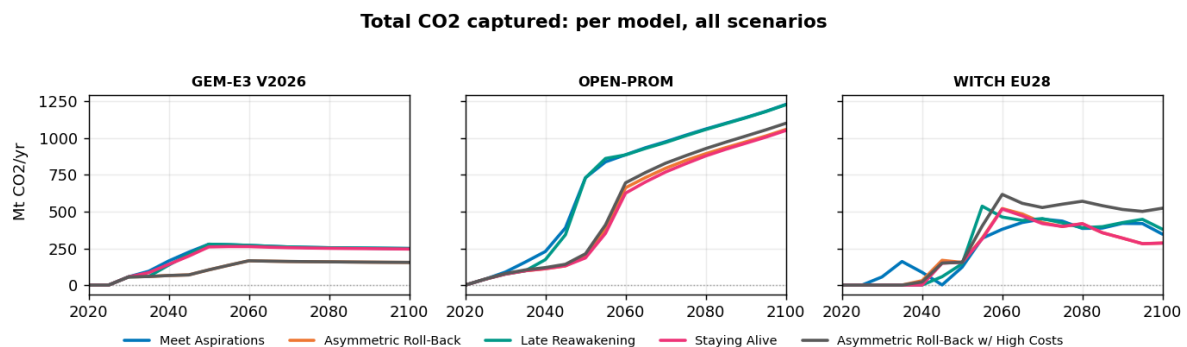


Figure 30: Total CO₂ captured by model and scenario (Mt CO₂/yr).

A4. Energy system

The primary energy mix under the variant closely resembles the standard rollback in GEM-E3 and OPEN-PROM (Figure 31). WITCH is the exception, retaining a markedly larger gas share through the second half of the century.

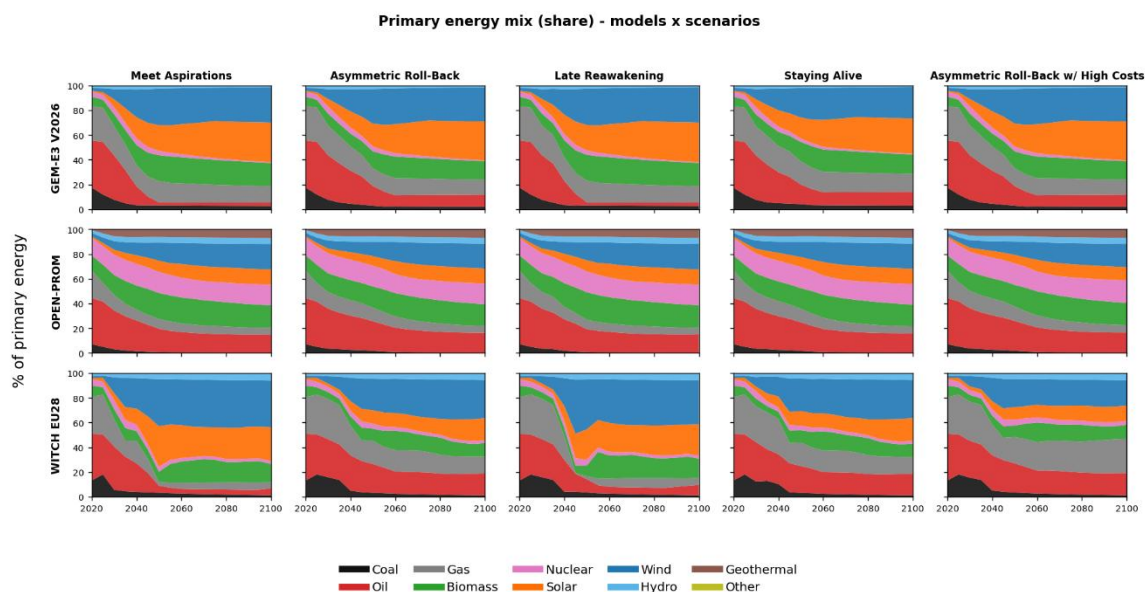


Figure 31: Primary energy mix by model and scenario, share of primary energy

The final energy mix separates the models more clearly than the primary mix does (Figure 32). Electricity dominates in all three, but the level differs. GEM-E3 reaches roughly 62% of final energy under the variant against 65% under Meet Aspirations, and OPEN-PROM is close to 50% in every scenario, with hydrogen reaching around 15% by the end of the century and appearing at scale in no other model. WITCH again shows the widest spread, with electricity near 45% under the variant against about 70% under Meet Aspirations, the difference being taken up mainly by liquids and gases. Liquids remain a substantial share under all three rollback pathways in every model, which is consistent with the persistence of oil reported in the phase-down results.

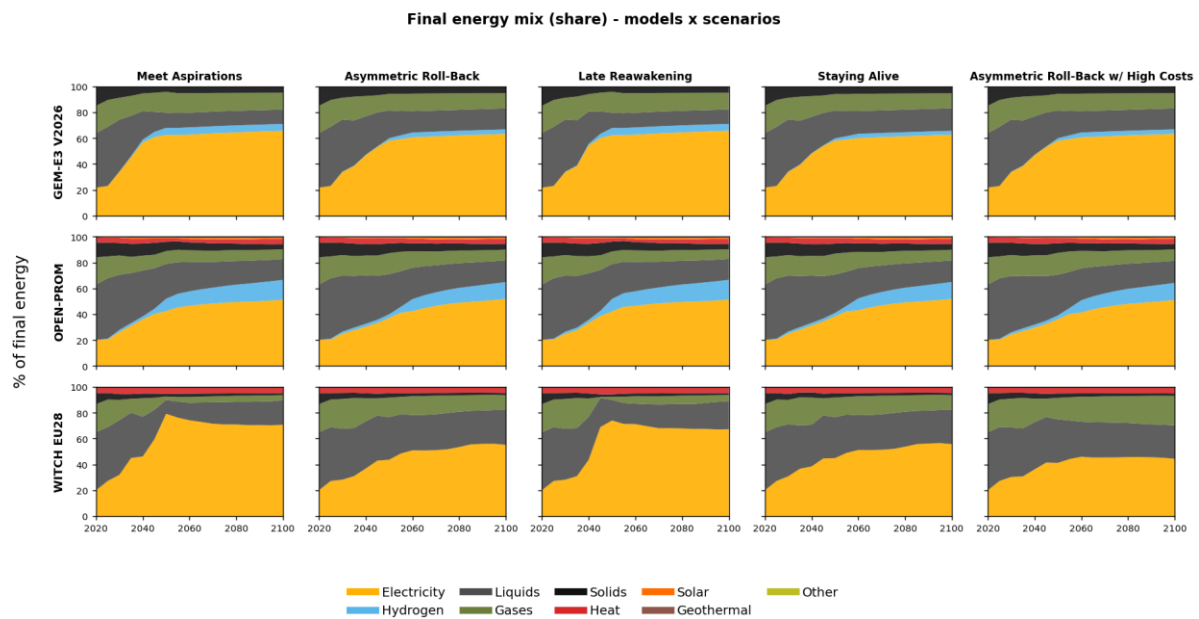
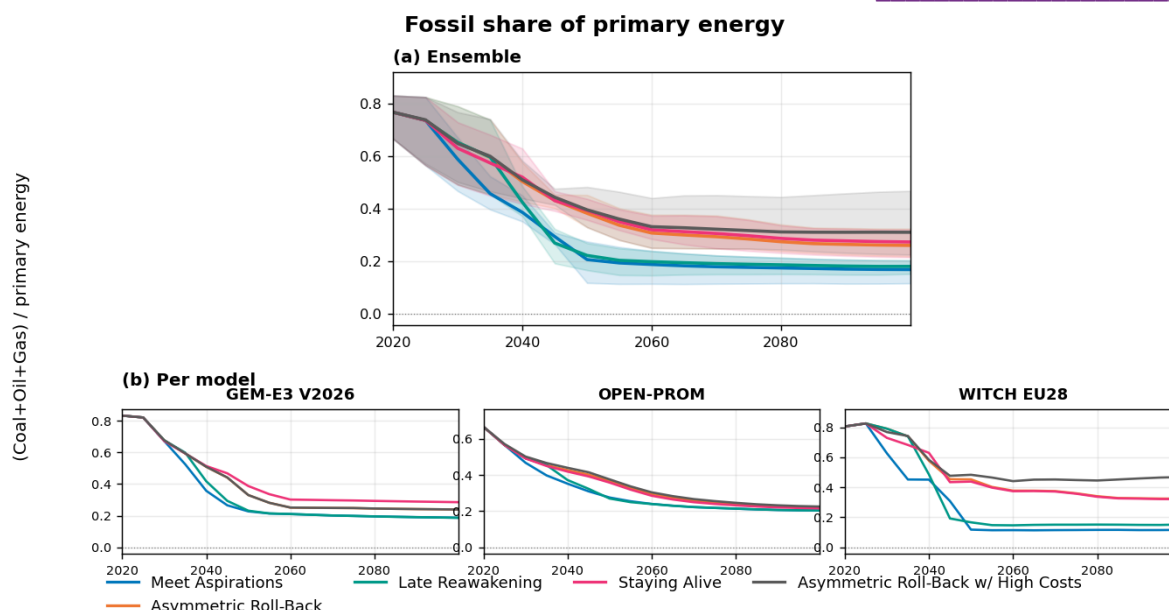
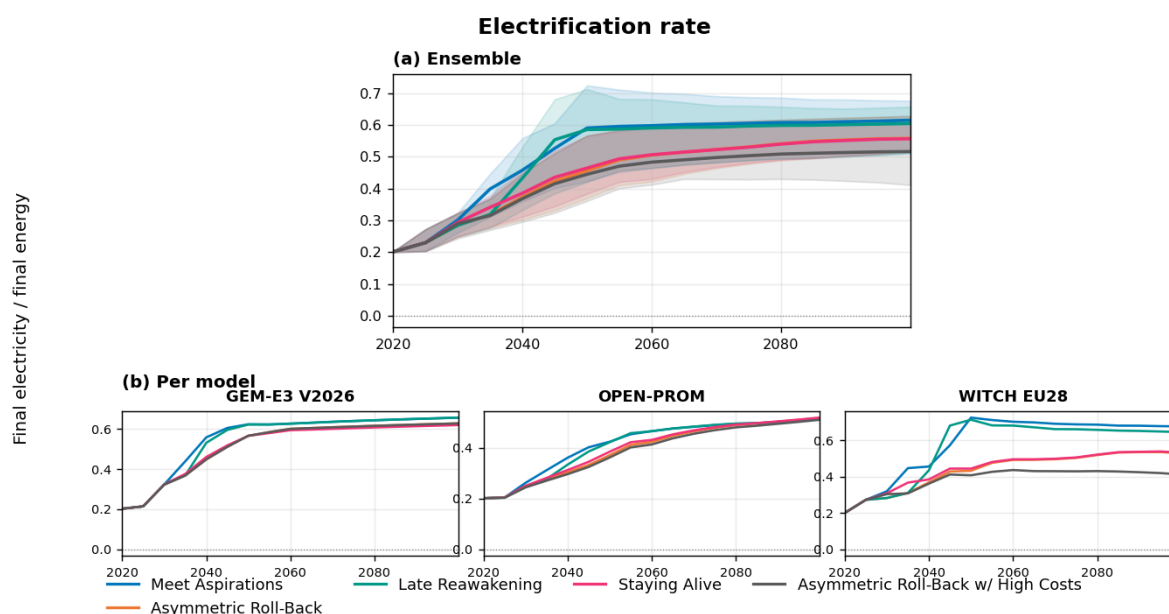


Figure 32: Final energy mix by model and scenario, share of final energy.

The fossil share of primary energy shows the same result (Figure 33). At the ensemble level the variant plateaus near 31% against roughly 26% under the standard rollback and 17% under Meet Aspirations, and the range across models is very wide by the end of the century. The spread is driven almost entirely by WITCH, where the variant ends near 47% against 32% under Staying Alive and 12% under Meet Aspirations. GEM-E3 and OPEN-PROM show differences of only a few percentage points.



Electrification behaves symmetrically (Figure 34). The variant reaches approximately 52% of final energy by 2100 against 56% under Staying Alive and 61% under Meet Aspirations, and once again the separation is concentrated in WITCH, where it plateaus near 41%.



A5. Costs and investment

With the carbon price held constant, the remaining question is what the transition costs to build. Cumulative investment in electricity-contributing technologies over 2025 to 2050 is the clearest economic signature of the variant (Figure 35). It exceeds the standard rollback in all three models, marginally in GEM-E3 at 2,113 against 2,107 billion USD₂₀₁₀, by roughly 5% in

OPEN-PROM at 1,852 against 1,768, and by approximately 17% in WITCH at 2,958 against 2,528. This indicator covers solar and wind, since storage and transmission investments are not reported by any of the three models. These are the technologies whose costs the variant inflates, so the higher spending reflects higher unit costs rather than greater deployment. Read together with the lower electrification rate and the higher fossil share, the variant therefore buys less clean capacity for more money while delivering no additional emissions reduction, which is the essential result of the stress test.

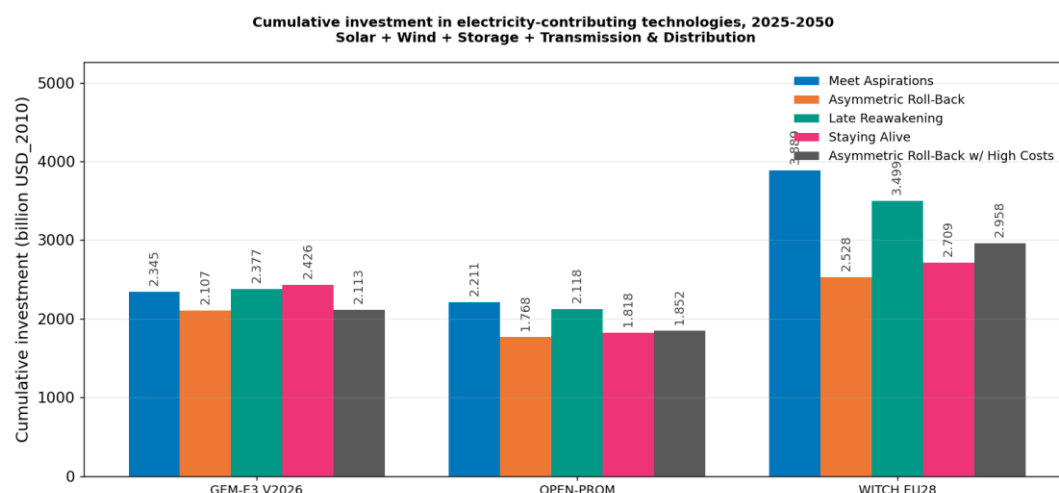


Figure 35: Cumulative investment in electricity-contributing technologies, 2025 to 2050, by model and scenario (billion USD2010). Covers solar and wind.

A6. Summary

The stress test does not change the emissions outcome of a rollback. Trajectories, snapshot distributions and the sectoral pattern are effectively identical to the standard rollback, with differences two orders of magnitude smaller than the gap to Meet Aspirations. It does change the cost and structure of the energy system. Because the carbon price is unchanged, the models must still meet the same signal, but higher financing costs, more expensive clean technology and the absence of knowledge spillovers together penalise capital-intensive options relative to fuel-intensive ones. The result is a system that is more fossil-intensive, less electrified and more expensive to build. The reading for the main analysis is that supply chain constraints, capital market fragmentation and weak international collaboration are not an additional emissions risk on top of a rollback, since the carbon price already determines the emissions outcome. They are a cost and energy-security risk, and they fall on precisely the indicators most often invoked to justify slowing the transition.

2 Extension of the DPET online tool

2.1 DPET tool overview

The INNOPATHS Decarbonization Policy Evaluation Tool (DPET, <https://dpet.innopaths.eu/#>) is an online database and interface that presents the results of work carried out under the EU H2020-funded project INNOPATHS. The purpose of the tool is to present in an easily searchable manner the results of a systematic review of existing evidence on the impacts of decarbonisation policies published by the INNOPATHS team members (Peñasco et al., 2021). The review included 281 policy evaluations contained in 211 peer-reviewed scientific articles and policy evaluation reports published in 2000-2018. It covered 10 types of decarbonisation policy instruments across 7 types of policy outcomes. The following types of policy instruments were considered: building codes and standards; renewable portfolio standards (RPS), also known as renewable energy obligations (RO); government procurement; public research and development (R&D) funding; feed-in tariffs or premiums (FITs/FIPs); renewable energy capacity auctions; energy-related taxes and tax exemptions; greenhouse gas (GHG) emissions trading schemes (ETS), also known as cap-and-trade schemes; tradable green certificates (TGC) associated with renewable energy; and white certificates associated with energy efficiency standards. The seven categories of outcomes analysed were environmental, technological, cost-related, innovation, competitiveness, distributional, and other social outcomes.

As part of Task 2.4, the PRISMA project set the goal of extending the coverage of DPET to add more policy types (e.g., in transportation and appliances) and a more granular understanding of different types of distributional outcomes by societal groups, with a focus on vulnerable communities and different geographies. The next two subsections describe the work conducted in these two directions by the University of Cambridge team.

Importantly, it proved to be not feasible to update the contents of the existing online DPET platform with the results of this work. This is due to the nature of the tool that, while being openly accessible in its present form, was developed by a commercial contractor in a way that did not include an option for direct updating of the underlying data by the project team. Any subsequent updates could be made only through the former contractor. In the past 5 years since the DPET launch, the platform also experienced a loss of its domain name for about a year (restored in 2025) and a loss of the original database underlying DPET due to a data storage failure. The database was eventually restored by web scraping from the DPET website. However, these incidents demonstrated that DPET in its current form is not a sustainable solution for long-term provision of up-to-date evidence on the impacts of decarbonisation policies to the public and policymakers. Upon discussion, the PRISMA consortium concluded that a new, scalable platform based on the principles of open science and living systematic reviews that would build on and expand the corpus of evidence contained in DPET – “DPET 2.0” – would be a better fit for the purpose than the current closed-source platform.

As the development of the new platform is not in the scope of the PRISMA project, the resources for this undertaking are being sought elsewhere. As a result, the DPET-related part of Task 2.4 has focused on expanding and bringing up to date the corpus of evidence provided in the current version of DPET. Specifically, the University of Cambridge team worked on 1) a new systematic literature review on innovation and environmental outcomes of 14 types of

road transportation policy instruments (section 2.2); and 2) updating and expanding the systematic review on the distributional outcomes of 10 types of decarbonisation policy instruments, first presented as part of Peñasco et al. (2021) in DPET, with recent evidence published in 2019-2026, additionally focusing on developing more granular understanding of different types of distributional outcomes (section 2.3).

2.2 Systematic review of transportation policy instruments

Road transportation policies can drive innovation in environmentally sustainable vehicle and fuel technologies but may have unintended consequences. To synthesise and assess existing evidence on their impacts on technology innovation, greenhouse gas emissions, air pollution, and land use, we systematically reviewed and analysed peer-reviewed literature on the outcomes of 14 road transportation policy instruments, including fuel economy, vehicle emissions and low-carbon fuel standards; biofuel and zero emission vehicle (ZEV) mandates; vehicle, road, and fuel taxes; vehicle and biofuel subsidies; scrappage incentives; charging infrastructure investment; and technology investment through R&D funding and public procurement. The results of the systematic literature review were published in Nature Communications in 2025 (Ma et al., 2025) and are summarised in Figure 36 below.

The systematic review considered two types of policy outcomes—on technological innovation and the environment—represented by the following indicators: innovation outcomes—modular improvements (MI), fuel economy (FE), vehicle sales (SA), biofuel production (BP), technology transfer (TT), and cost reductions (CR); environmental outcomes—greenhouse gas emissions (GG), air pollution (AP), and land use (LU). In addition, innovation inputs and outputs were also tracked through R&D spending (RD) and patents, publications and prototypes (PA).

The corpus of literature for the systematic review was constructed by identifying, collecting, screening and analysing relevant scientific sources indexed by the Web of Science Core Collection. Articles published between 1975 and 2022 were considered to ensure the broadest possible historical coverage, including from the pre-electric vehicle (EV) era. In choosing the sources for inclusion, we followed the CIMO framework, focusing on the context (C), intervention (I), mechanism (M) and outcome (O) when constructing the search query (Denyer et al., 2008). The initial search yielded 18,335 papers. After removing duplicates, applying the inclusion and exclusion criteria for titles, abstracts, and the main text to these papers, as well as including additional studies from outside the initial search results, a final set of 468 peer-reviewed studies comprising more than 1000 individual policy evaluations was obtained.

Figure 36 presents an overview of the policy instruments, outcomes, number of evaluations, and the types of impacts that we extracted and coded from these sources. There are marked differences between the outcomes that have been studied for different policy instruments, and there are numerous combinations of policy instruments and outcomes with little to no evidence. While a majority of the studies identifies broadly positive effects on the outcomes considered, the figure highlights several areas in which there are conflicting results in terms of the direction of the impact of policy instruments. For example, for vehicle taxes and air pollution, there are both positive and negative impact evaluations (panel f), and for biofuel mandates and greenhouse gas emissions, ex ante evidence is mixed while ex post evidence is negative (panel e). In general, ex post evidence suggests that policy instruments expanding first-generation biofuel production have increased greenhouse gas emissions and land use

(panel k). With some exceptions, ex ante and ex post evaluations are broadly consistent in terms of the direction of the impact across most policy instruments and outcomes.

We further explored tensions between policy instrument impacts by considering the interactions between individual policy instruments. Based on the evidence in our sample, we identified six types of positive, negative, and neutral relationships between road transportation policy instruments:

1. Pre-condition: a positive interaction in which one policy instrument acts as a pre-condition to another instrument
2. Synergy: a positive interaction in which one policy instrument reinforces another instrument such that the overall impact of the two instruments together is greater than the sum of the impacts of the individual instruments
3. Addition: a neutral relationship between policy instruments, when there is no clear interaction between the two policy instruments such that their overall impact is roughly the sum of their individual impacts; the instruments remain generally independent and auxiliary to each other.
4. Overlap: a negative interaction in which the aim or effect of one policy instrument coincides or conflicts with that of another, resulting in the combined effect of two instruments being smaller than the sum of their effects in isolation
5. Trade-off: a negative interaction in which a better outcome in one area is associated with a worse outcome in another area
6. Backfire: a negative interaction in which the combined effect of two instruments is worse than that of the best instrument alone

Using this typology, we analysed in detail the interactions between individual policy instruments on both innovation and environmental outcomes (see Tables 4 and 5 in Ma et al., 2025). The resulting evidence indicates that multiple policy instruments in concert can be more effective for promoting technology innovation and environmental sustainability in road transportation than single instruments alone. It is possible for a mix of policy instruments to act together to achieve the levels of stringency necessary to meet desired targets without placing the burden of doing so on a single instrument, while increasing public acceptance, political feasibility, and the potential for successful implementation. Some policy instruments can be successful only in combination with or subsequent to the implementation of another instrument, as illustrated by electric vehicle subsidies and support for charging infrastructure in the earliest stages of EV deployment. However, additional policy instruments sometimes trade off or backfire. Alongside binding biofuel mandates, subsidies for biofuel production increase greenhouse gas emissions by lowering fuel prices, and electric vehicle subsidies and mandates trade off with fleet-wide internal combustion engine vehicle performance standards by allowing automakers to comply with the latter using weaker improvements in conventional vehicle emissions and fuel efficiency. Reducing cross-compliance between policy instruments targeting conventional as opposed to advanced technologies could allow larger improvements in both categories.

Overall, our analysis highlights the complex task faced by policymakers in balancing different technology and environmental priorities, adapting to technological uncertainty, and managing interference from powerful industry actors, challenges which are experienced in other sectors beyond road transportation (e.g., shipping, aviation, and agri-food production and

consumption). In particular, technology-specific policy instruments can lead to early technological lock-in of more mature but flawed alternative technologies, even when the intention is for the technology-ready solution to serve as an intermediate to more advanced solutions. This is most evident in our analysis of the outcomes of conventional biofuel mandates and subsidies, which the evidence suggests are a factor in the lagging development of cellulosic biofuels, an advanced biofuel technology that must overcome the lock-in not only of incumbent fossil fuels but also of mature first-generation biofuels while competing with increasing road vehicle electrification, all of which receive government support. The experience with biofuels to date offers potential lessons for the design of other technology-specific policy instruments, like ZEV mandates, where proactive efforts to manage renewable electricity integration, vehicle energy consumption, and supply chain sustainability are becoming increasingly important as EVs achieve higher market penetration. Policy instruments with high technology specificity may benefit from clear and responsive revisions in technology selection criteria or performance-based elements that require improvements in a technology's life-cycle environmental impacts over time.

To conclude, in this systematic literature review (Ma et al., 2025), we synthesised existing evidence on the environmental and innovation outcomes of 14 road transportation policy instruments. Out of these instruments, only two – R&D funding and public procurement – were previously covered by DPET, and it was done without specific focus on transportation. Integrating these results into the DPET database would thus enable a major expansion of the evidence on the outcomes of decarbonisation policies in different sectors available to policymakers and the public via the DPET tool. Therefore, such integration should be a part of any future work on DPET 2.0 development. However, beyond DPET, which primarily focuses on the outcomes of individual policy instruments, our review also provides rich and detailed insights into the interactions between individual instruments and the factors that make decarbonisation policy mixes successful in the transportation sector.



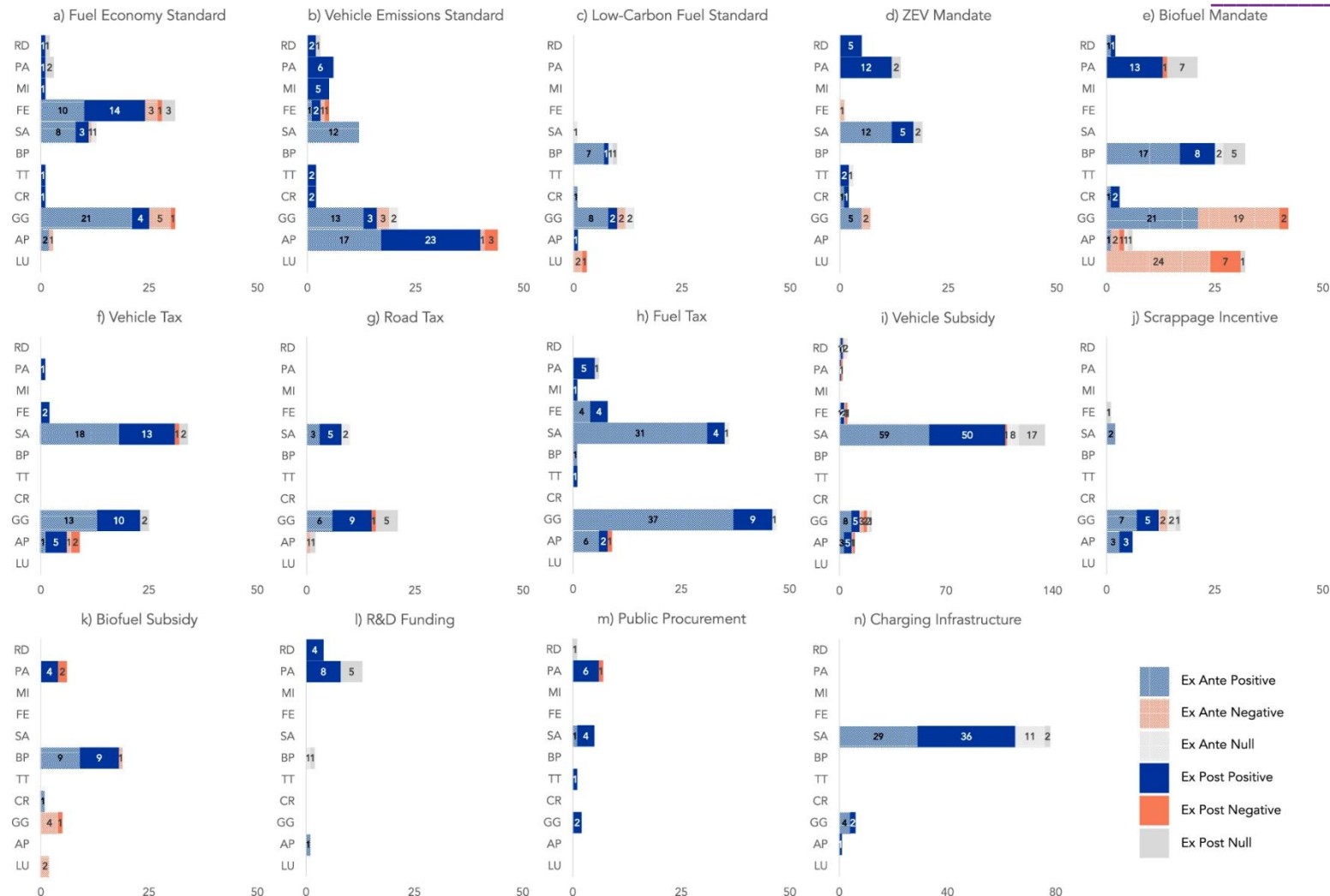


Figure 36: Overview of road transportation policy instrument impacts on technology innovation and environmental indicators. Source: Ma et al. (2025)

2.3 Distributional outcomes of decarbonisation policy instruments

Another direction in the work on expanding the evidence base of DPET is more directly linked to its existing content, focusing specifically on updating the systematic review on the distributional outcomes of 10 types of decarbonisation policy instruments included in Peñasco et al. (2021). With DPET covering the sources published between 2000 and 2018, the aim of this systematic review is to update the evidence corpus with more recent sources published between 2019 and 2026. In addition, we are interested in developing more granular understanding of different types of distributional outcomes, as there is substantial diversity of the outcomes discussed in the literature, which is determined by the incidence of the policy effect (e.g., spatial, income group, or other social group incidence) and a variety of potential inequity types involved (e.g., energy poverty, access issues, distributional justice and fairness). The diversity of these distributional outcomes makes it important to differentiate between different outcome types when analysing the evidence aggregated across multiple sources for specific policy instruments

For context, among 281 policy evaluations contained in 211 peer-reviewed sources previously synthesised in Peñasco et al. (2021) and included in DPET, only 74 evaluations contained in 58 sources considered distributional outcomes. Among those, 38 (51%) were ex-ante assessments, 22 (30%) were qualitative ex-post evaluations, and 14 (19%) were quantitative ex-post evaluations. This distribution showed a lack of quantitative ex-post evidence on the distributional outcomes of decarbonisation policies that would enable large-scale quantitative meta-analyses of policy impact.

The top policies represented in the original dataset (Peñasco et al., 2021) were taxes and tax exemptions (17 evaluations), FITs/FIPs (13), tradeable green certificates (12), and renewable portfolio standards (8). Only 5 evaluations considered emission trading schemes (ETS). The systematic review identified many instances of the negative distributional impacts of these policies, often demonstrating the regressive nature of their effect, particularly on low-income populations. The evidence on negative outcomes was particularly strong on FITs, TGCs, auctions, and more mixed (but still predominantly negative) on taxes, RPS, and ETS schemes. Only building codes, R&D funding, and government procurement had evidence of only positive distributional outcomes; however, these observations were made on a very small number of sources – three or less.

With the need for more high-quality evidence on the distributional outcomes of decarbonisation policies, it was reasonable to expect more attention to the problem in the recent scholarly and policy literature. This called for an update of evidence provided in DPET, as it was based on the sources which were all published before 2019.

In the new systematic review presented in this section, we generally built on the methodology used in Peñasco et al. (2021) for the construction of the literature corpus for the systematic review. We used the same data source – Scopus bibliometric database (<https://www.scopus.com>) – and the same original search queries for the same policy instruments as a starting point. Two notable modifications were made compared to the original search process. First, as our focus is on, specifically, distributional outcomes, we followed the CIMO framework (Denyer et al., 2008) to narrow-down the initial broad search

queries by adding the terms related specifically to the distributional outcomes, their synonyms, and related phenomena (e.g., “distributional”, “distributive”, “allocative”, “equity”, “equality”, “inequality”, “vulnerable population”, or “vulnerable group”). On several occasions, we also optimised original multiple queries for the same policy type by combining them into a single search query. The resulting search queries are provided in Table A1 in the Appendix for the following 10 types of policy instruments: 1) carbon / emissions / fuel taxes; 2) emission trading schemes (ETS); 3) public funding, grants, subsidies (e.g., for R&D and innovation in green technologies or deployment of energy-efficient building retrofits); 4) FIT / FIT / CfD (Contracts-for-Differences); 5) renewable energy auctions; 6) green public procurement; 7) tradable green certificates (TGC); 8) renewable energy obligations (RO) / renewable portfolio standards (RPS); 9) building codes; 10) white certificates / energy efficiency certificates. Following the evidence provided in DPET, we also included loans / loan guarantees as an additional policy instrument and a separate search category. Importantly, we also expanded the scope of grants and subsidies as a policy instrument from just R&D funding (as not a single relevant paper was identified for this policy instrument in a corresponding research query) to broader grants and subsidies targeting innovation and deployment of low-carbon technologies. The search was limited to journal articles, conference papers and reviews published between January 2019 and May 2026.

A total of 309 literature sources were identified with this approach. All sources were reviewed for relevance to the scope of the review using publication abstracts and titles. Among these sources, 73 also required a full-paper review to make a final inclusion or exclusion decision. Following the two review rounds, we excluded irrelevant and duplicate sources, and included 9 additional relevant sources identified via citations in the reviewed sources. This resulted in 88 publications identified as relevant to the scope of our review. We further excluded 2 sources without full-text access, and 1 source that evaluated large-scale policy mixes in a way that did not allow us to identify the effects or contributions of individual policies. Our final core dataset consists of 85 unique sources providing 108 assessments or evaluations of individual policies or distinct policy mixes. The details of the search and selection process for each individual search query are provided in Table A2 in the Appendix. The list of all 85 sources included in the evidence corpus is provided at the end of the Appendix.

Importantly, the number of sources identified—85, which accumulated in just over 7 recent years—is already higher than the total number of publications on distributional outcomes that were included in DPET over a much longer period of 19 years (2000-2018) – 58. This confirms our initial expectations about the accelerated growth of literature on the distributional outcomes of decarbonisation policies. However, a detailed breakdown of this number by the policy type (Figure 37) and evaluation method (Figure 38) reveals a pattern of a very skewed scholarly attention to the topic.



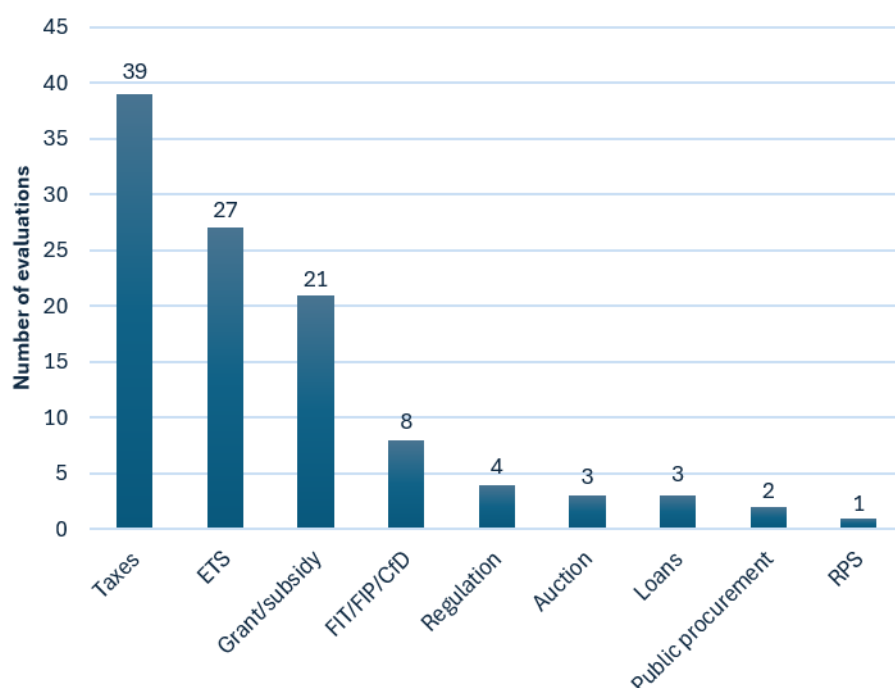


Figure 37: Number of decarbonisation policy evaluations identified in this systematic review, split by the policy type. Total number of evaluations: 108. Source: own elaboration.

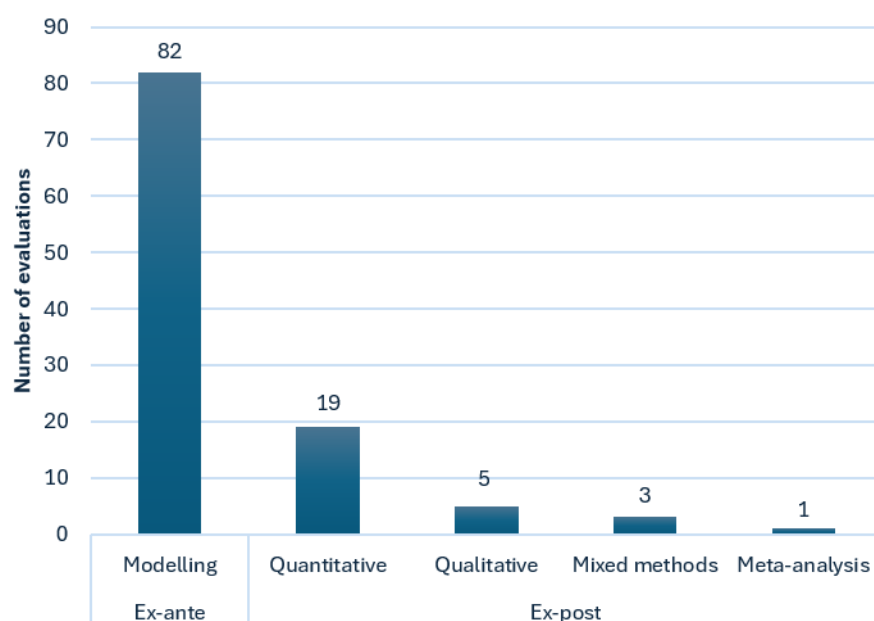


Figure 38: Number of decarbonisation policy evaluations identified in this systematic review, split by the type of evaluation methodology. Total number of policies evaluated: 108. Note: the numbers do not add up to the total as two policies are assessed in both ex-ante and ex-post fashion. Source: own elaboration.

Compared to the original dataset (see Figure 5 in Peñasco et al., 2021), the distribution of evaluations across different policy types (see Figure 37) dramatically shifted over time. A majority of present evaluations are focused on carbon pricing instruments, with 39 evaluations

for taxes (dominated, specifically, by carbon taxes) and 27 for ETS, together accounting for 61% of the dataset. They are followed by grants and subsidies (previously considered only within a narrower scope of R&D subsidies, now expanded to also cover broader low-carbon innovation and technology deployment subsidies), with 21 evaluations (19%). For all other policies, the numbers roughly stayed the same or declined, compared to DPET. Three policy types previously represented in DPET – building codes, TGC and white certificates – are completely absent in the updated dataset. Instead, two new policy types are represented (albeit in small numbers) that were previously missing in DPET: loans and loan guarantees, and regulation – an umbrella term for fossil fuel bans and phase out.

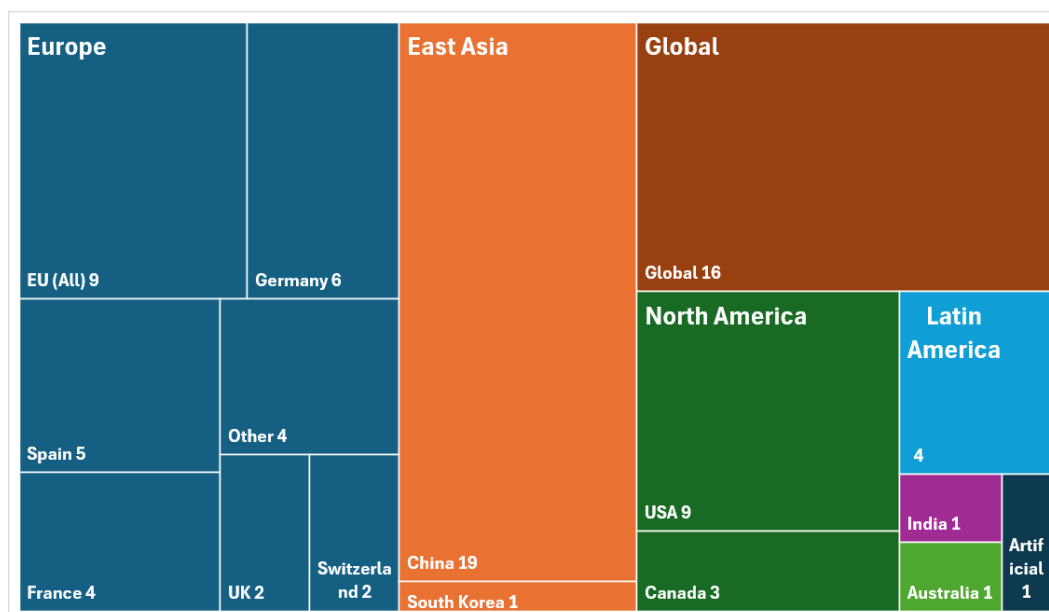


Figure 39: Number of publications identified in the systematic review, split by region and country. Total number of publications: 85. Note: the numbers do not add up to the total as several publications consider multiple geographies.

An even higher degree of concentration is observed among the evaluation methodologies employed in the dataset. The number of quantitative ex post evaluations remained roughly at the same level as in DPET – 20 (18%), if one meta-analysis is included. However, the share of qualitative methods dramatically declined from 30% to less than 5% (5 evaluations). Instead, the share of ex ante assessment by mathematical and computational modelling increased from 51% to 75% (82 evaluations). It appears that the dramatic increase in the number of modelling studies is the main driver of the growth of evidence in this field. Modelling not only increased its relative share among other methodologies, but also masked the decline of qualitative studies that often provide essential context for the interpretation of quantitative and modelling studies that otherwise lack such context. Among the modelling methodologies, the most popular ones are computable general equilibrium (CGE) models, integrated assessment models (IAM), microsimulations, followed by agent-based models (ABM) and various hybrid approaches that combine different types of mathematical and computational models.

Overall, it appears that the single most important factor explaining what appears to be a growth in the total number of policy evaluations in this field is the sharp increase in ex ante modelling

of the impacts of carbon pricing instruments, i.e., carbon taxes and ETS schemes. For other types of policies and evaluation methodologies, the numbers remain stagnant or decline compared to pre-2019 evidence covered in DPET. This means that, despite the importance and prevalence of the decarbonisation policy instruments that are not focused on carbon pricing in real-world policy mixes, the gap in the provision of robust empirical evidence on critically important distributional outcomes of these policy instruments persists.

Another persistent gap in evidence is the geographical one. As can be seen in Figure 39, the main geographies covered by our corpus are China (19 publications), the US (9) and the EU (9). Sixteen studies also have a global scope. Completely missing in the corpus are Africa and the Middle East, while the rest of Asia outside China is represented only by two studies. This means that the problem with insufficient evidence provision on the distributional outcomes of decarbonisation policies in less developed global regions persists.

Despite these major gaps in evidence identified, 108 policy evaluations contained in 85 studies are still a substantial number for the analysis. To identify the types of distributional outcomes and the direction of impact of decarbonisation policies on these outcomes, we analysed the full texts of all 85 publications, extracting information on the types of populations affected by a policy, the indicators of the distributional outcomes of the policy, and the effects of the policy on these populations measured by these indicators. We also tracked whether the policy was evaluated individually, or as part of a broader policy mix. We then manually classified these effects into distinct groups of distributional outcomes, based on the type of incidence (e.g., spatial, income group, etc.) and/or the type of inequality or disparity caused or addressed by the policy (e.g., income inequality, energy poverty, distributional fairness). For each observation of a specific distributional outcome of the policy, we also coded the direction of its effect, distinguishing between negative effects (i.e., those that increase inequality, disparity, or regressivity of the policy, or decrease its fairness), positive effects (i.e., those that decrease inequality or disparities or increase the progressiveness or fairness of the policy), neutral effects (no significant effect of the policy found on inequality in a given area), or mixed effects (i.e., heterogeneous effects of the policy on different population groups without clear trends).

In total, our dataset includes 370 distinct distributional outcomes identified in 108 policy evaluations. Such a large number of distinct outcomes can be primarily explained by two factors. First, many policy evaluations consider multiple types of distributional outcomes of a single policy. For example, a single study can consider income inequality both within and between countries, as well as assess more fine-grained disparities in income and energy poverty between rural and urban households within countries, resulting in 4 distinct distributional outcomes assessed in the study. Second, and more specific to decarbonisation policy, many recent publications do not stop at identifying a single negative distributional outcome of a baseline policy (e.g., a simple carbon tax, well-known for its regressiveness), but also assess different designs of the same policy (e.g., different revenue redistribution mechanisms) that aim to mitigate the baseline negative effect of the policy, often resulting in multiple distinct outcomes identified for the same policy in different design options in a single study.



Table 1: Distributional outcomes of decarbonisation policies assessed in 108 policy evaluations included in the study, grouped by the type of outcome, with the number of times each type of outcome is observed in the dataset.

Types of distributional outcomes	Number of outcomes
Economic inequality	112
Income inequality	59
Welfare / consumption inequality	43
Wealth inequality	7
Wage inequality	2
Economic development disparities	1
Spatial / regional disparities	80
Geographical disparities	60
Rural / urban inequality	20
Distributional justice	56
Allocation of costs and benefits	46
Public finance burden	8
Intertemporal equity	2
Personal / household characteristics	38
Household composition / vulnerability	12
Gender inequality	8
Housing inequality	5
Education / skills inequality	5
Racial / ethnic inequality	4
Immigrant status	2
Age disparities	2
Poverty	28
Energy poverty	20
Income poverty	5
Food / nutritional poverty	3
Environmental justice	27
Carbon equality	17
Environmental justice	10
Access, inclusion, participation	21
Health disparities	8
Total number of distinct outcomes evaluated	370

Table 1 summarises the 24 types of distributional outcomes found in our dataset, identified inductively during the evidence coding process and then iteratively validated to ensure the consistency of coding in two rounds of review. For practical purposes, we group these outcomes into 8 larger groups guided by the nature of relevant distributional effects and distinct literature clusters. The largest group is economic inequality (112 distinct outcomes), with the differences between specific outcome types determined primarily by the indicators used to measure it: household or firm income, welfare, consumption, expenditures, wealth, wages, or, on a country level, the level of economic development. The second biggest group is spatial / regional disparities (80 outcomes), i.e., the disparities in different indicators observed between different countries, regions, or locations, with a distinct and notable group of assessments dedicated also to rural / urban inequalities. The third group is focused on the distributional justice (56 outcomes), concerned primarily with the fairness of allocation of the social, public and private costs and benefits of policies, as well as, in two cases, intertemporal equity. The next group is concerned with disparities associated with different personal and household characteristics (38 outcomes), including family size and composition, gender, education, race and ethnicity, immigrant status, and age, as well as housing situation and vulnerability status. Poverty (28 outcomes) is often strongly associated with economic inequality, but has multiple other structural dimensions and a distinct way of measurement which necessitates distinguishing it as a separate group. Within this group of outcomes, a majority is focused on energy poverty, with income, food, and nutritional poverty also represented. Environmental justice (27 outcomes) is similarly distinguished from broader distributional justice due to its distinct focus on the fairness of allocation of environmental costs, benefits, and responsibilities associated with the policy. A specific type of outcome in this group is carbon equality, a term that emerged initially in the context of ETS policies in China concerned with fair and equitable allocation of carbon emission quotas. The final two groups are focused on the issues of access, inclusion and participation in policy support programmes (e.g., building retrofit subsidies) (21 outcomes), and health disparities (8 outcomes).

Figure 40 shows the observed directions of the effects identified for each type of distributional outcome among the 8 groups described above, aggregated across all 9 types of decarbonisation policies considered in the study. Panel a), specifically, shows the absolute number of outcomes observed for each type of outcome and the direction of effect, while panel b) shows the relative shares of different effect directions for each type of outcome. From the figure, it is clear that, taken on aggregate, the decarbonisation policies considered in our study tend to have a positive effect on environmental justice and, in a limited number of cases identified, health disparities. At the same time, they tend to have a distinctly negative effect on the distributional justice, and access, inclusion, and participation, which seems to be an important common trend for all decarbonisation policies evaluated. The results for the remaining outcomes (i.e., economic inequality, spatial / regional disparities, personal and household characteristics, and poverty) are roughly split between positive and negative evaluations. These mixed aggregate effects are likely explained by heterogeneity of specific policy instruments and policy mixes classified under different policy types, as described below.

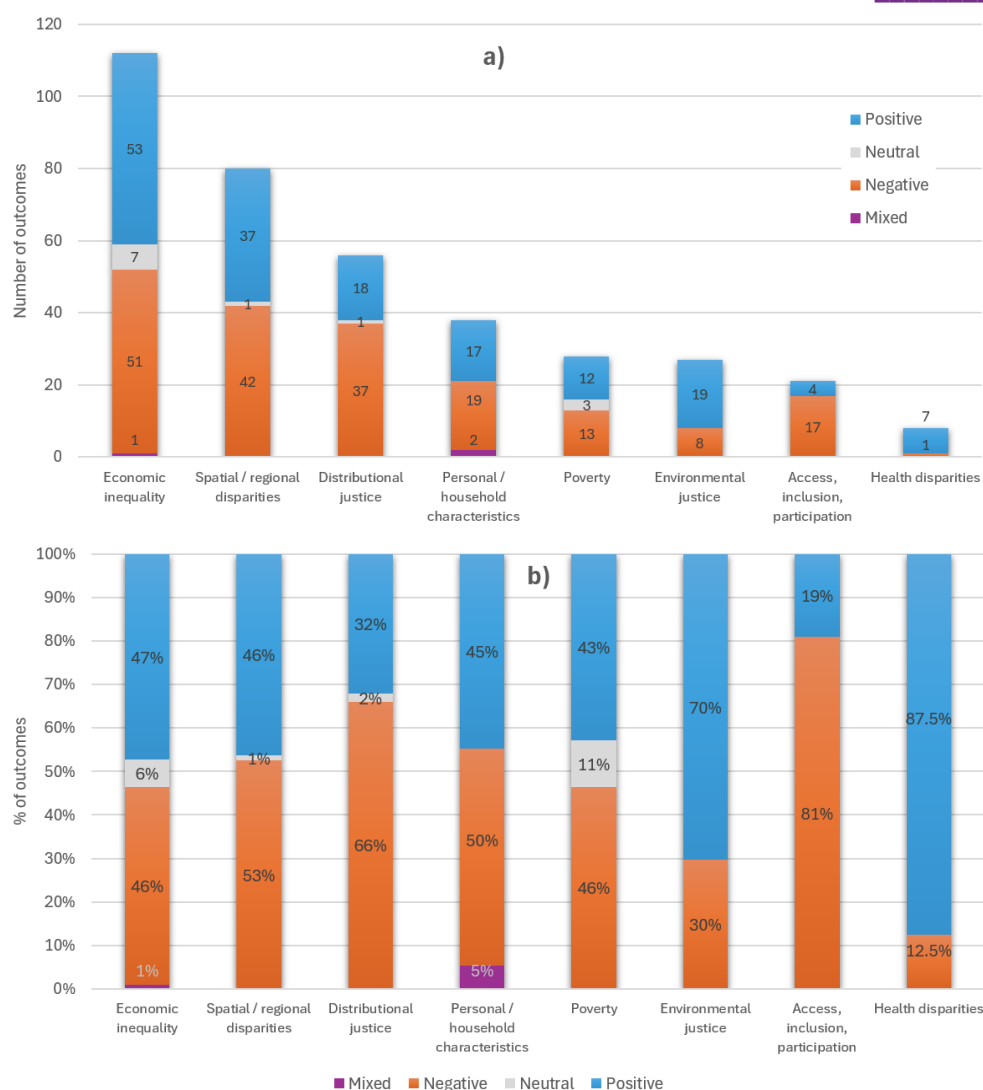


Figure 40: Number of distinct distributional outcomes identified in decarbonisation policy evaluations included in the systematic review, split by the type of outcome and the direction of effect. Panel a) - absolute number of outcomes for each type of outcome and effect; panel b) - same data shown as relative shares of the effect directions for each policy. ETS = emissions trading scheme; FIT = feed-in tariff; FIP = feed-in premium; CfD - contract-for-differences; RPS - renewable portfolio standard. Total number of outcomes = 370. Source: own elaboration.

Figure 41 demonstrates the observed directions of the distributional effects identified for each policy type, aggregated across the outcome types. Panel a) shows the absolute number of outcomes observed for each type of policy and the direction of effect, while panel b) shows the relative shares of different effect directions for each type of policy. One can see that for each of the 9 types of policies included in our dataset, not a single policy succeeds in providing unequivocally positive or negative distributional effects, as the evidence remains overall mixed. In general, the trend in the corpus is towards negative effects, but it hides important heterogeneities both between the policies and within policies. Some policies tend to produce more positive effects (ETS or RPS), others more negative effects (e.g., subsidies, FITs, regulations), and one – taxes – is split in the middle. However, this pattern is primarily explained not by uncertain effects of individual policies, but rather by the differences within each policy group. Specifically, negative assessments tend to be found for standalone policies,

while positive effects are often found for policies operating in policy mixes, which, particularly for carbon tax and ETS, also include various redistributive policy mechanisms that compensate for the negative distributional outcome of standalone policies.

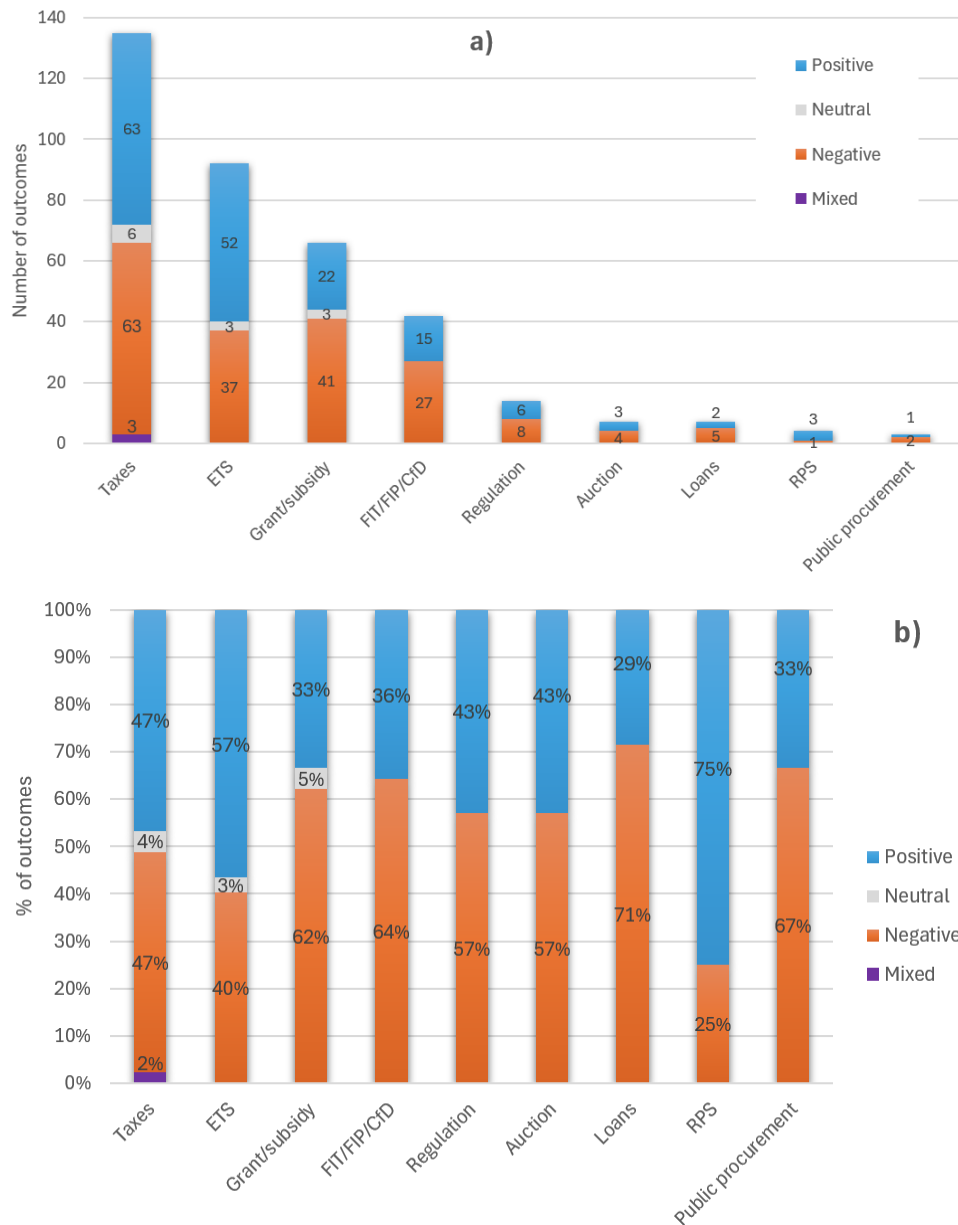


Figure 41: Number of distinct distributional outcomes identified in decarbonisation policy evaluations included in the systematic review, split by the evaluated policy type and the direction of effect. Panel a) - absolute number of outcomes for each type of policy and effect; panel b) - same data shown as relative shares of the effect directions for each policy. ETS = emissions trading scheme; FiT = feed-in tariff; FiP = feed-in premium; CfD = contract-for-differences; RPS = renewable portfolio standard. Total number of outcomes = 370. Source: own elaboration.

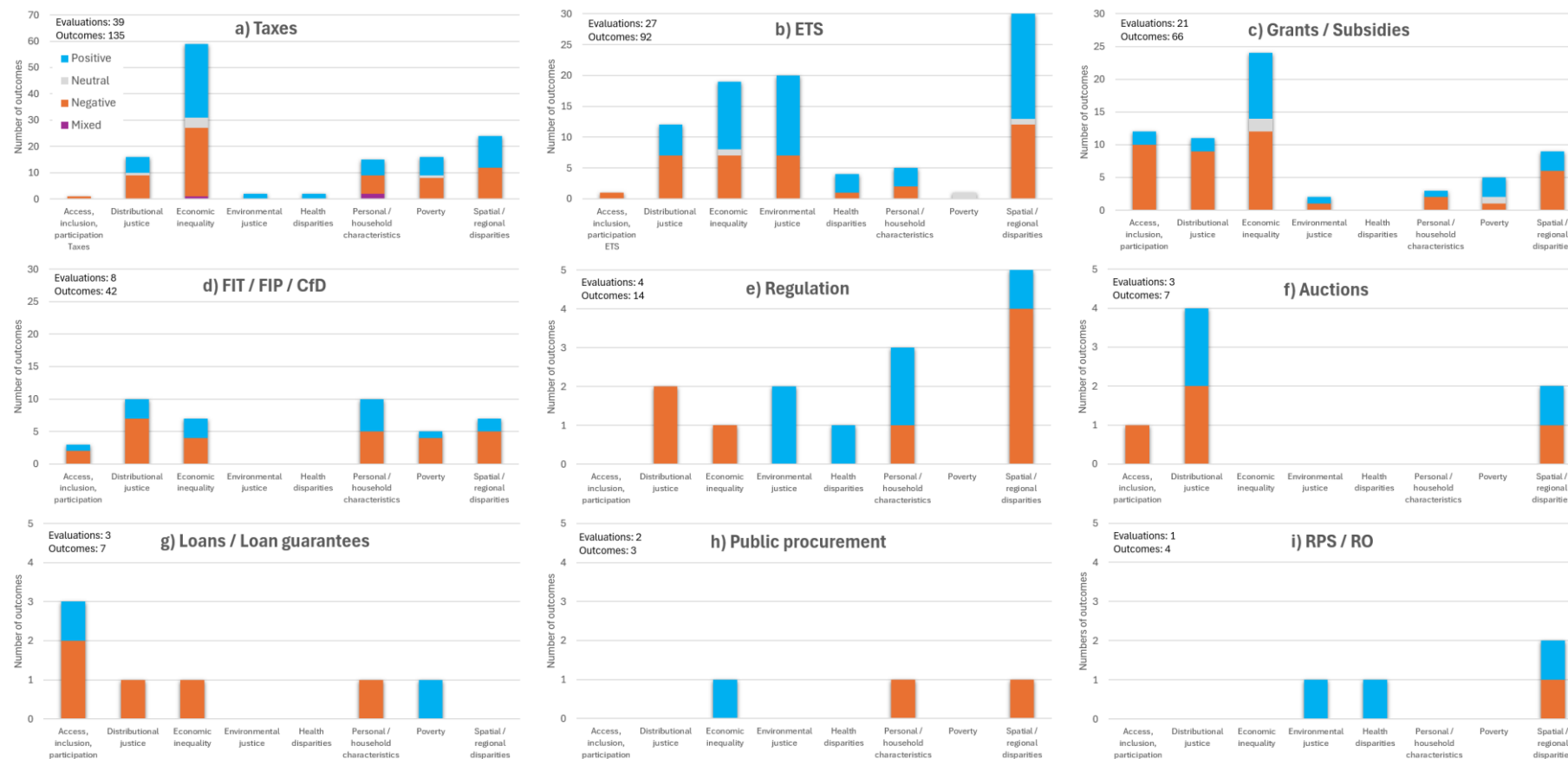


Figure 42: Distributional outcomes of 9 types of decarbonisation policies identified in the systematic review, split by the type of policy, type of distributional outcome, and the effect direction. Positive/negative effects are marked by blue/orange colour; neutral effect by grey colour; mixed effects by purple colour. ETS = emissions trading scheme; FIT = feed-in tariff; FIP = feed-in premium; CfD - contract-for-differences; RPS - renewable portfolio standard; RO - renewable energy obligation. Each panel includes an inset with the total number of evaluations and outcomes for each policy. Total number of evaluations = 108. Total number of outcomes = 370. Note different scales on the vertical axis on different panels. Source: own elaboration.

In Figure 42, we show the detailed results disaggregated by policy type, outcome type, and the policy effect direction. Below, we summarise the main findings of our analysis for each policy type.

Taxes (39 evaluations, 135 outcomes). A majority of the studies in this group are focused on carbon taxes, their negative and regressive distributional outcomes, and various revenue redistribution and compensation mechanisms that seek to address this problem. Correspondingly, the most dominant type of outcome in carbon tax evaluations is economic inequality, with 59 outcomes observed in total. A smaller number of studies also consider the distributional effects on spatial disparities between countries and regions; poverty; distributional justice; and disparities based on personal or household characteristics. The results across all these outcome groups are almost equally split between negative and positive evaluations, with the former mostly covering the regressive effects of a baseline standalone carbon tax, and the latter representing policy mixes of the carbon tax with different revenue redistribution mechanisms and other compensatory policy measures. The evidence on the effect of different tax revenue redistribution schemes agrees that these schemes work, not only reducing the regressive effects of carbon taxes successfully, but in many cases even making their distributional outcomes positive and progressive. However, among different redistribution mechanisms, revenue-neutral equal-per-capita (EPC) lump sum rebates are typically found to be less effective in reducing inequalities than the schemes with progressive rebates, targeted rebates to low-income groups, or the schemes that redistribute the revenue in the form of green subsidies, e.g. for clean heating or cooking, instead of direct cash transfers.

A smaller number of evaluations (5) also consider fuel taxes. Their effects are generally found to be progressive when targeting transportation fuels, and regressive when targeting heating fuel, in the latter case resulting in increased energy poverty among low-income populations.

Emission trading schemes (ETS) (27 evaluations, 92 outcomes). ETS evaluations are dominated by spatial disparities between countries and regions, followed by environmental justice; economic inequality; and distributional justice. For the former three outcomes, the effects are more positive on average, while in the latter case, the effects are more negative. These differences can be explained by the dominant themes among the studies in this group. Specifically, a common theme represented in 17 evaluations is “carbon equality” – an environmental justice outcome concerned with fair allocation of emission quotas and allowances to reduce the inequality in the distribution of the costs and benefits of emission reductions under various ETS schemes. These studies focus either on the provincial allocation of quotas in China or the fairness of the global distribution of national emission reduction targets, attempting to identify the mechanisms and specific policy designs that would maximise the distributional fairness of provincial or country-level allocation of responsibilities under the national ETS scheme in China or a hypothetical global ETS.

Another common theme considers the incidence of ETS on different income groups and populations. The evidence here is less conclusive than for the carbon tax. While a majority of these studies finds the effect of ETS on different income groups to be regressive, there is a notable minority of evaluations that find that ETS can produce progressive effects when a broader set of climate, environmental and health benefits from the policy is considered. Many of these papers also consider how the regressive effects can be mitigated through various redistribution schemes, with findings generally aligning with those for the carbon tax. As part

of the discussion on broader ETS benefits, four studies in the corpus also consider the effect of ETS on health disparities. In three cases, these effects are found to be positive, with the ETS producing substantial health benefits and reducing health disparities.

Grants and subsidies (21 evaluations, 66 outcomes). These evaluations are primarily focused on economic inequality, followed by issues of access, inclusion and participation, distributional justice, and spatial disparities. Negative distributional effects dominate, with a particularly strong consensus reached on access, inclusion and participation, and distributional justice. When looking at the common themes, we find that these studies are focused either on specific “green” subsidy schemes for clean technology deployment (e.g., fuel cell power generation, clean household heating and cooking, building retrofits, or consumer EV purchases), constituting a majority of all ex-post evaluations in the dataset; or on generic economy-wide green subsidies considered in global computational models. The distributional effects of subsidies in the power sector and negative emissions technologies are generally negative and regressive, resulting in increased energy poverty, unequal access to benefits from renewable energy, and excessive burden on public finance. For consumer-oriented subsidies targeting other technologies, the effects depend on the subsidy design. Income-insensitive subsidies generally benefit higher-income populations, while subsidies specifically targeting low-income groups result in improved distributional outcomes in terms of income group incidence and energy savings. In addition, several papers explore combinations of green subsidies with other policy instruments, such as carbon taxes or ETS schemes, finding synergies between the policies. For example, a combination of a modest carbon price with modest green subsidies may produce better distributional outcomes than a high carbon price with no subsidies or a high subsidy with no carbon price, while achieving the same level of emission reductions.

FITs, FIPs, CfD (8 evaluations, 42 outcomes) + **Auctions** (3 evaluations, 7 outcomes). The negative and regressive distributional effects of FITs and renewable energy auctions are well-documented in DPET and broader literature, and some of the newer studies further contribute to this consensus. However, one specific strand of literature that emerged recently, compared to past studies, is how these distributional effects can be mitigated, e.g., either by replacing traditional fixed power purchase payments to auction winners or the electricity surcharge on all households with more efficient schemes like FIPs or CfDs of different designs, or various redistribution mechanisms that directly reduce the burden of these policies on electricity consumers. The success of some of these schemes predicted by computational models may explain less conclusive evidence on the aggregate direction of the distributive effects of FITs and auctions across different types of distributional outcomes in our corpus, compared to the previous study where these effects were found to be overwhelmingly negative (see Figure 5 in Peñasco et al., 2021).

Regulations on fossil fuels (4 evaluations, 14 outcomes). This small and disparate group of studies evaluates either the spatial effects of phasing out fossil fuel power plants, or the incidence and fairness of specific fossil fuel bans or regulations. These effects tend to be negative for spatial disparities and distributional justice. However, some studies also show that these effects can be mitigated by substantial environmental and health co-benefits from reduced air pollution gained by low-income populations and racial / ethnic minorities that historically tend to cluster near the fossil fuel power plants affected by the policy.

Loans and loan guarantees (3 evaluations, 7 outcomes), **public procurement** (2 evaluations, 3 outcomes), and **RPS** (1 evaluation, 4 outcomes). Among the evaluations of policies with low representation in the corpus, loan guarantees are discussed as essential to improving the access of small and medium enterprises (SME) to green finance for clean technology upgrades, which is currently limited, while targeted loans for clean cooking are considered as a way to reduce gender inequality. Other studies find that the benefits of EV adoption from EV public procurement in China are unequally distributed among locations with different population densities, while green public procurement applied in a bounded-rational agent-based model of a hypothetical country reduces wealth inequality at the expense of increased unemployment and consumer prices, which have their own regressive effects on different income groups. Finally, a single ex-ante assessment of a regional RPS scheme in the US focuses on the geographical distribution of substantial health benefits of this scheme, finding that populations living in urban areas and/or next to large fossil fuel power plants receive much higher health benefits than the residents in rural areas far from fossil fuel infrastructure.

To conclude, we conducted a systematic literature review of recent (2019-2026) evidence on the distributional outcomes of 9 types of decarbonisation policy instruments, building on the structured evidence synthesis framework first published by Peñasco et al. (2021) and updating the 2000-2018 dataset on this topic originally included in DPET. In the process of review, we found 85 recent literature sources that contain 108 policy evaluations and 370 distinct distributional outcomes, which we inductively grouped into 24 distinct types of distributional outcomes clustered in 8 groups. Despite the overall growth in the amount of evidence on the distributional outcomes of decarbonisation policies, compared to DPET, we find that this growth was specifically driven by a sharp rise in ex ante computational model assessments of carbon pricing mechanisms at the expense of the sharp decline in ex post qualitative studies that could provide essential context for the interpretation of modelling results. In addition, persistent evidence gaps remain in the lack of quantitative ex-post policy evaluations, as well as in the geographical coverage of existing studies, which remain focused mostly on developed countries and China at the expense of less developed countries and regions where the evidence on the distributional outcomes of climate policies is needed the most.

Our synthesis of evidence across the full corpus of literature analysed in this review reveals that across different types of policies and distributional outcomes considered, decarbonisation policies tend to have negative and regressive distributional effects when implemented on their own. However, implementing them in policy mixes with other complementary decarbonisation policies and redistribution mechanisms can substantially mitigate these negative impacts, and even achieve the “double dividend” of simultaneous reductions in greenhouse gas emissions and inequality. The key takeaway from our review for integrated assessment modelling is the need to incorporate such policy mixes and redistribution mechanisms in the models alongside traditional standalone decarbonisation policies such as carbon pricing.



References

- Denyer, D., Tranfield, D., & Van Aken, J. E. (2008). Developing design propositions through research synthesis. *Organization studies*, 29(3), 393-413.
- Ma, C., Peñasco, C., & Anadón, L. D. (2025). Technology innovation and environmental outcomes of road transportation policy instruments. *Nature Communications*, 16(1), 4467.
- Peñasco, C., Anadón, L. D., & Verdolini, E. (2021). Systematic review of the outcomes and trade-offs of ten types of decarbonization policy instruments. *Nature Climate Change*, 11(3), 257-265.



Appendix

Table A1 – Scopus search queries by policy type

Policy type	Search date	Scopus search query	Number of Scopus sources identified
Carbon / Emissions / Fuel taxes	14/05/2026	TITLE-ABS-KEY (("carbon tax" OR "emission* tax" OR "CO2 tax" OR "fuel tax" OR "gas* tax" OR "energy tax") AND (distributional OR distributive OR allocative OR equit* OR equalit* OR inequit* OR inequalit* OR "vulnerable population" OR "vulnerable group") AND (outcome OR impact OR incidence OR burden OR effect*) AND (evaluation OR assessment OR appraisal OR "ex post")) AND PUBYEAR > 2018 AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "re"))	52
Emission trading scheme (ETS)	24/05/2026	TITLE-ABS-KEY (("cap and trade" OR "cap and invest*" OR (carbon OR "greenhouse gas" OR emission) AND (trading OR allowance OR permit)) OR "EU ETS") AND (distributional OR distributive OR allocative OR equit* OR equalit* OR inequit* OR inequalit* OR "vulnerable population" OR "vulnerable group") AND (outcome OR impact OR incidence OR burden OR effect*) AND (evaluation OR assessment OR appraisal OR "ex post")) AND PUBYEAR > 2018 AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "re"))	91
Public funding, grants, subsidies*	17/05/2026	TITLE-ABS-KEY (((public OR government* OR state) W/5 (funding OR subsidy OR grant OR investment OR incentiv* OR financ*)) AND (energy OR climate OR decarboni* OR "clean tech*" OR "green tech*" OR "clean innovation" OR "green innovation" OR "environmental innovation") AND (distributional OR distributive OR allocative OR equit* OR equalit* OR inequit* OR inequalit* OR "vulnerable population" OR "vulnerable group") AND (outcome OR impact OR incidence OR burden OR effect*) AND (evaluation OR assessment OR appraisal OR "ex post")) AND PUBYEAR > 2018 AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "re"))	100
FIT/FIP/CfD	15/04/2026	TITLE-ABS-KEY (("feed in tariff*" OR "feed in premium*" OR "contract* for difference*") AND (distributional OR distributive OR allocative OR equit* OR equalit* OR inequit* OR inequalit* OR "vulnerable population*" OR "vulnerable group*") AND (outcome OR impact OR incidence OR burden OR effect*) AND (evaluation OR assessment OR appraisal OR "ex post")) AND PUBYEAR > 2018 AND (LIMIT-TO (DOCTYPE,"ar") OR LIMIT-TO (DOCTYPE,"cp") OR LIMIT-TO (DOCTYPE,"re"))	14
Auctions	03/05/2026	TITLE-ABS-KEY ((energy AND (auction OR tender OR bid)) AND (distributional OR distributive OR allocative OR equit* OR equalit* OR inequit* OR inequalit* OR "vulnerable population" OR "vulnerable group") AND (outcome OR impact OR incidence OR burden OR effect*) AND (evaluation OR assessment OR appraisal OR "ex post")) AND PUBYEAR > 2018 AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "re"))	8
Green public procurement	14/05/2026	TITLE-ABS-KEY ((("public procurement" OR "government procurement") AND (green OR environment* OR sustainable OR clean OR "low carbon" OR circular OR innovati* AND (climate OR energy))) AND (distributional OR distributive OR allocative OR equit* OR equalit* OR inequit* OR inequalit* OR "vulnerable population" OR "vulnerable group") AND (outcome OR impact OR incidence OR burden OR effect*) AND (evaluation OR assessment OR appraisal OR "ex post")) AND PUBYEAR > 2018 AND (LIMIT-TO (DOCTYPE,"ar") OR LIMIT-TO (	16

Loans / Loan guarantee	10/06/2026	DOCTYPE,"cp") OR LIMIT-TO (DOCTYPE,"re")) TITLE-ABS-KEY (("decarbonisation polic*" OR "decarbonization polic*" OR "climate polic*" OR "climate change polic*" OR "energy polic*" OR (("climate action" OR "climate mitigation" OR "climate change action" OR "climate change mitigation") AND polic*) OR (("greenhouse gas" OR carbon) AND emission* AND reduc* AND polic*)) AND loan AND (distributional OR distributive OR allocative OR equit* OR equalit* OR inequit* OR inequalit* OR "vulnerable population*" OR "vulnerable group*") AND (outcome OR impact OR incidence OR burden OR effect*) AND (evaluation OR assessment OR appraisal OR "ex post")) AND PUBYEAR > 2018 AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "re"))	5
Tradable green certificates (TGC)	10/05/2026	TITLE-ABS-KEY (("green certificate" OR ("renewable energy" AND certificate) OR "renewable energy credit" OR "tradable renewable certificate" OR "Large-scale generation certificates" OR (renewable AND "guarantee* of origin")) AND (distributional OR distributive OR allocative OR equit* OR equalit* OR inequit* OR inequalit* OR "vulnerable population" OR "vulnerable group") AND (outcome OR impact OR incidence OR burden OR effect*) AND (evaluation OR assessment OR appraisal OR "ex post")) AND PUBYEAR > 2018 AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "re"))	5
Renewable energy obligations / Renewable portfolio standards (RPS)	03/05/2026	TITLE-ABS-KEY (("renewable portfolio standard" OR "renewable energy quota" OR "renewable energy obligation" OR "renewable obligation") AND (distributional OR distributive OR allocative OR equit* OR equalit* OR inequit* OR inequalit* OR "vulnerable population" OR "vulnerable group") AND (outcome OR impact OR incidence OR burden OR effect*) AND (evaluation OR assessment OR appraisal OR "ex post")) AND PUBYEAR > 2018 AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "re"))	1
Building codes	03/05/2026	TITLE-ABS-KEY (("building code") AND (distributional OR distributive OR allocative OR equit* OR equalit* OR inequit* OR inequalit* OR "vulnerable population" OR "vulnerable group") AND (outcome OR impact OR incidence OR burden OR effect*) AND (evaluation OR assessment OR appraisal OR "ex post")) AND PUBYEAR > 2018 AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "re"))	17
White certificates / Energy efficiency certificates	14/05/2026	TITLE-ABS-KEY (("white certificate*" OR "energy savings certificate*" OR "energy efficiency certificate*" OR "energy savings credit*" OR "energy efficiency credit*" OR "white tag") AND (distributional OR distributive OR allocative OR equit* OR equalit* OR inequit* OR inequalit* OR "vulnerable population" OR "vulnerable group") AND (outcome OR impact OR incidence OR burden OR effect*) AND (evaluation OR assessment OR appraisal OR "ex post")) AND PUBYEAR > 2018 AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "re"))	0

* In Peñasco et al. (2021), the search strategy was focused narrowly on R&D funding as a policy instrument. In this work, we expanded the scope of this instrument to include broader public funding and subsidies for innovation and decarbonisation, as not a single relevant publication focused on the distributional outcomes of R&D funding policies published in 2019-2026 was initially identified.



Table A2 – Search strategies and search outcomes by policy type

Scopus search query by policy type	Number of Scopus sources reviewed (title & abstract)	Number of Scopus sources reviewed (full text)	Number of primary sources identified	Number of additional relevant sources found	Total number of sources included
Taxes	52	19	36	4	40
ETS	91	22	29	2	31
Public funding, grants, subsidies	100	22	14	3	17
FIT/FIP/CfD	14	2	6	0	6
Auctions	8	2	3	0	3
Green public procurement	16	2	2	0	2
Loans / Loan guarantee	5	0	1	0	1
TGC	5	3	1	0	1
RPS	1	0	1	0	1
Building codes	17	1	0	0	0
White certificates	0	0	0	0	0
TOTAL	309	73	93	9	102

References – Main corpus of evidence

- Albanese, M., Busato, F., & Cisco, G. (2025). How do up-skilling and skill heterogeneity affect a fair green transition? *Economia Politica*. <https://doi.org/10.1007/s40888-025-00381-2>
- Alvarez, M. (2019). Distributional effects of environmental taxation: An approximation with a meta-regression analysis. *Economic Analysis and Policy*, 62, 382–401. <https://doi.org/10.1016/j.eap.2018.10.003>
- Andreoni, P., Emmerling, J., & Tavoni, M. (2024). Inequality repercussions of financing negative emissions. *Nature Climate Change*, 14(1), 48–54. <https://doi.org/10.1038/s41558-023-01870-7>
- Bahramian, P., Jenkins, G. P., & Milne, F. (2021). A stakeholder analysis of investments in wind power electricity generation in Ontario. *Energy Economics*, 103. <https://doi.org/10.1016/j.eneco.2021.105569>
- Balousha, Z. A. M., Wahab, M. I. M., & Fang, L. (2025). An income-tailored energy efficiency rebate policy: Multi-dimensional benefit evaluation approach for upgrading heating furnaces in Ontario, Canada. *Journal of Environmental Management*, 381. <https://doi.org/10.1016/j.jenvman.2025.125106>
- Bauer, N., Bertram, C., Schultes, A., Klein, D., Luderer, G., Kriegler, E., Popp, A., & Edenhofer, O. (2020). Quantification of an efficiency–sovereignty trade-off in climate policy. *Nature*, 588(7837), 261–266. <https://doi.org/10.1038/s41586-020-2982-5>
- Berberian, A. G., Perera, F., Arunachalam, S., Levy, J. I., Buckley, L., Arter, C., Coomes, K. E., & Buonocore, J. J. (2024). Children’s health impacts from a proposed decarbonization policy in the transportation sector in the Eastern United States. *Environmental Research Letters*, 19(4). <https://doi.org/10.1088/1748-9326/ad2e73>

- Berger, F., Brunzema, I., Rao, S., Vondung, F., Hachenberger, P., & Schlomann, B. (2025). Evaluating co-benefits of energy efficiency policy measures: A holistic framework with case studies from Germany. *Energy Efficiency*, 18(8). <https://doi.org/10.1007/s12053-025-10397-z>
- Böhringer, C., García-Muros, X., & González-Eguino, M. (2022). Who bears the burden of greening electricity? *Energy Economics*, 105. <https://doi.org/10.1016/j.eneco.2021.105705>
- Borenstein, S., & Davis, L. W. (2016). The distributional effects of US clean energy tax credits. *Tax Policy and the Economy*, 30(1), 191–234. <https://doi.org/10.1086/685597>
- Bourgeois, C., Giraudet, L.-G., & Quirion, P. (2019). Social-environmental-economic trade-offs associated with carbon-tax revenue recycling. *Eceee Summer Study Proceedings*, 2019-June, 1365–1372.
- Bourgeois, C., Giraudet, L.-G., & Quirion, P. (2021). Lump-sum vs. Energy-efficiency subsidy recycling of carbon tax revenue in the residential sector: A French assessment. *Ecological Economics*, 184. <https://doi.org/10.1016/j.ecolecon.2021.107006>
- Braumann, W., & Erwin, J. (2020). De-carbonisation, guaranteed: Realising affordable, equitable and long-term financing for industrial SME projects. *Eceee Industrial Summer Study Proceedings*, 2020-September, 359–369.
- Caillavet, F., de Fadhuile, A., & Nichèle, V. (2019). Assessing the distributional effects of carbon taxes on food: Inequalities and nutritional insights in France. *Ecological Economics*, 163, 20–31. <https://doi.org/10.1016/j.ecolecon.2019.04.020>
- Chen, W.-M., & Kim, H. (2020). Energy, economic, and social impacts of a clean energy economic policy: Fuel cells deployment in Delaware. *Energy Policy*, 144. <https://doi.org/10.1016/j.enpol.2020.111617>
- Cheng, Y., Gu, B., Tan, X., Yan, H., & Sheng, Y. (2022). Allocation of provincial carbon emission allowances under China's 2030 carbon peak target: A dynamic multi-criteria decision analysis method. *Science of the Total Environment*, 837. <https://doi.org/10.1016/j.scitotenv.2022.155798>
- Coenen, G., Lozej, M., & Priftis, R. (2024). Macroeconomic effects of carbon transition policies: An assessment based on the ECB's New Area-Wide Model with a disaggregated energy sector. *European Economic Review*, 167. <https://doi.org/10.1016/j.eurocorev.2024.104798>
- Coldrey, O., LaRocco, P., Lant, P., & Allan, D. (2026). What women want: Financing a gender-responsive clean cooking transition. *Energy Research and Social Science*, 132. <https://doi.org/10.1016/j.erss.2026.104538>
- Coomes, K. E., Buonocore, J. J., Levy, J. I., Arter, C., Arunachalam, S., Buckley, L., Berberian, A., Gunasti, J., & Perera, F. (2022). Assessment of the health benefits to children of a transportation climate policy in New York City. *Environmental Research*, 215. <https://doi.org/10.1016/j.envres.2022.114165>
- Cruz, J.-L., & Rossi-Hansberg, E. (2024). The Economic Geography of Global Warming. *Review of Economic Studies*, 91(2), 899–939. <https://doi.org/10.1093/restud/rdad042>
- Douenne, T. (2020). The Vertical and Horizontal Distributive Effects of Energy Taxes: A Case Study of a French Policy. *Energy Journal*, 41(3), 231–246. <https://doi.org/10.5547/01956574.41.3.tdou>
- Đukan, M., & Kitzing, L. (2023). A bigger bang for the buck: The impact of risk reduction on renewable energy support payments in Europe. *Energy Policy*, 173. <https://doi.org/10.1016/j.enpol.2022.113395>



- Emmerling, J., Andreoni, P., & Tavoni, M. (2024). Global inequality consequences of climate policies when accounting for avoided climate impacts. *Cell Reports Sustainability*, 1(1). <https://doi.org/10.1016/j.crsus.2023.100008>
- Feindt, S., Kornek, U., Labeaga, J. M., Sterner, T., & Ward, H. (2021). Understanding regressivity: Challenges and opportunities of European carbon pricing. *Energy Economics*, 103. <https://doi.org/10.1016/j.eneco.2021.105550>
- Frondel, M., Thiel, P., & Vance, C. (2026). The distributional consequences of tax pass-through: The case of Germany's fuel tax discount. *Regional Science and Urban Economics*, 117. <https://doi.org/10.1016/j.regsciurbeco.2025.104183>
- Fujimori, S., Hasegawa, T., Oshiro, K., Zhao, S., Sasaki, K., Takakura, J., & Takahashi, K. (2023). Potential side effects of climate change mitigation on poverty and countermeasures. *Sustainability Science*, 18(5), 2245–2257. <https://doi.org/10.1007/s11625-023-01369-2>
- Georgiadou, M. C., Greenwood, D., Schiano-Phan, R., & Russo, F. (2024). Assessing retrofit policies for fuel-poor homes in London. *Buildings and Cities*, 5(1), 133–149. <https://doi.org/10.5334/bc.416>
- González-Eguino, M., García-Muros, X., Arto, I., & Pizarro-Irizar, C. (2022). Impact evaluation of financing mechanisms for renewable energy in Spain. *Cuadernos Economicos de ICE*, 2022(104), 111–135. <https://doi.org/10.32796/cice.2022.104.7476>
- Grashof, K. (2019). Are auctions likely to deter community wind projects? And would this be problematic? *Energy Policy*, 125, 20–32. <https://doi.org/10.1016/j.enpol.2018.10.010>
- Hashemi, M., Jenkins, G., & Milne, F. (2024). Renewable Energy Support Through Feed-in Tariffs: A Retrospective Stakeholder Analysis. *Journal of Benefit-Cost Analysis*, 15(2), 276–301. <https://doi.org/10.1017/bca.2024.9>
- Howie, P., Gupta, S., Park, H., & Akmetov, D. (2020). Evaluating policy success of emissions trading schemes in emerging economies: Comparing the experiences of Korea and Kazakhstan. *Climate Policy*, 20(5), 577–592. <https://doi.org/10.1080/14693062.2020.1751030>
- Huang, H., Roland-Holst, D., Springer, C., Lin, J., Cai, W., & Wang, C. (2019). Emissions trading systems and social equity: A CGE assessment for China. *Applied Energy*, 235, 1254–1265. <https://doi.org/10.1016/j.apenergy.2018.11.056>
- Huang, Y., & Li, S. (2022). Can Marketization of Environmental Governance Improve Public Health?—Empirical Analysis Based on the Emission Trading System. *International Journal of Environmental Research and Public Health*, 19(23). <https://doi.org/10.3390/ijerph192315518>
- Ibañez Iralde, N. S., Pascual, J., & Martí Audí, N. (2026). Evaluating the effectiveness of public subsidies for energy-efficient retrofit: A comparative study of two next-generation programs with standard market interventions in Catalonia. *Energy and Buildings*, 352. <https://doi.org/10.1016/j.enbuild.2025.116858>
- Jacobs, L., Quack, L., & Mechtel, M. (2022). Distributional effects of carbon pricing by transport fuel taxation. *Energy Economics*, 114. <https://doi.org/10.1016/j.eneco.2022.106290>
- Jordan, K. H., Dennin, L. R., Adams, P. J., Jaramillo, P., & Muller, N. Z. (2024). Climate Policy Reduces Racial Disparities in Air Pollution from Transportation and Power Generation. *Environmental Science and Technology*, 58(49), 21510–21522. <https://doi.org/10.1021/acs.est.4c03719>
- Konc, T., Drews, S., Savin, I., & van den Bergh, J. C. J. M. (2022). Co-dynamics of climate policy stringency and public support. *Global Environmental Change*, 74. <https://doi.org/10.1016/j.gloenvcha.2022.102528>



- Lin, B., & Zhao, H. (2024). Threatening the Poor? The economic impacts of carbon border adjustment mechanism on developing countries. *Structural Change and Economic Dynamics*, 71, 582–593. <https://doi.org/10.1016/j.strueco.2024.09.005>
- Meus, J., Pittomvils, H., Proost, S., & Delarue, E. (2022). Distortions of National Policies to Renewable Energy Cooperation Mechanisms. *Energy Journal*, 43(4), 95–126. <https://doi.org/10.5547/01956574.43.4.jmeu>
- Mi, Z., Liao, H., Coffman, D. M., & Wei, Y.-M. (2019). Assessment of equity principles for international climate policy based on an integrated assessment model. *Natural Hazards*, 95(1–2), 309–323. <https://doi.org/10.1007/s11069-018-3408-7>
- Monasterolo, I., Dunz, N., Mazzocchi, A., & Gourd, R. (2022). Derisking the low-carbon transition: Investors’ reaction to climate policies, decarbonization and distributive effects. *Review of Evolutionary Political Economy*, 3(1), 31–71. <https://doi.org/10.1007/s43253-021-00062-3>
- Moz-Christofolletti, M. A., & Pereda, P. C. (2021). Distributional welfare and emission effects of energy tax policies in Brazil. *Energy Economics*, 104. <https://doi.org/10.1016/j.eneco.2021.105616>
- Nelson, T., & Dodd, T. (2023). Contracts-for-Difference: An assessment of social equity considerations in the renewable energy transition. *Energy Policy*, 183. <https://doi.org/10.1016/j.enpol.2023.113829>
- Oikonomou, V., Tourkolias, C., Perotti, A., Szabo, J. L., Spyridakos, S., & Ebrahimigharehbaghi, S. (2026). Can tax credit schemes support energy efficiency measures in residential buildings? A case study for Greece. *Energy Efficiency*, 19(5), 33. <https://doi.org/10.1007/s12053-026-10429-2>
- O’Ryan, R., Nasirov, S., & Osorio, H. (2023). Assessment of the potential impacts of a carbon tax in Chile using dynamic CGE model. *Journal of Cleaner Production*, 403. <https://doi.org/10.1016/j.jclepro.2023.136694>
- Perdana, S., & Vielle, M. (2026). Regional inequality of the European ETS-2. *Energy Policy*, 208. <https://doi.org/10.1016/j.enpol.2025.114891>
- Pereda, P. C., Lucchesi, A., Oliveira, T. D., & Wolf, R. (2025). Carbon tax in the shipping sector: Assessing economic and environmental impacts. *Energy Policy*, 204. <https://doi.org/10.1016/j.enpol.2025.114627>
- Pradhan, B. K., & Ghosh, J. (2021). COVID-19 and the Paris Agreement target: A CGE analysis of alternative economic recovery scenarios for India. *Energy Economics*, 103. <https://doi.org/10.1016/j.eneco.2021.105539>
- Rao, S., Blauert, M., Schlomann, B., Stede, J., & Schaper, J. (2024). Greening the drive: Unpacking the impact and equity aspects of Germany’s EV subsidy programme. *Eceee Summer Study Proceedings*, 719–728.
- Ravaioli, G., Lamperti, F., Roventini, A., & Domingos, T. (2025). Tackling emissions and inequality: Policy insights from an agent-based model. *Journal of Economic Behavior and Organization*, 237. <https://doi.org/10.1016/j.jebo.2025.107188>
- Rengs, B., Scholz-Wäckerle, M., & van den Bergh, J. (2020). Evolutionary macroeconomic assessment of employment and innovation impacts of climate policy packages. *Journal of Economic Behavior and Organization*, 169, 332–368. <https://doi.org/10.1016/j.jebo.2019.11.025>
- Rezaee, A., Chen, L.-W. A., Lin, G., Buttner, M. P., Gakh, M., & Bloomfield, E. F. (2022). Air Quality Health Benefits of the Nevada Renewable Portfolio Standard. *Atmosphere*, 13(9). <https://doi.org/10.3390/atmos13091387>



- Rizzati, M. C. P., Ciola, E., Turco, E., Bazzana, D., & Vergalli, S. (2025). Beyond Green Preferences: Demand-side and Supply-side Drivers in the Low-Carbon Transition. *Environmental and Resource Economics*, 88(5), 1239–1295. <https://doi.org/10.1007/s10640-025-00965-3>
- Rueb, D. (2026). Measuring the poverty effects of a carbon tax on mobility – But how? *Ecological Economics*, 239. <https://doi.org/10.1016/j.ecolecon.2025.108788>
- Schick, C., & Hufendiek, K. (2023). Assessment of the regulatory framework in view of effectiveness and distributional effects in the context of small-scale PV—The German experience. *Energy Policy*, 172. <https://doi.org/10.1016/j.enpol.2022.113310>
- Soubelet, A., Torné, A., Thalmann, P., & Trutnevyte, E. (2024). Distributional justice, effectiveness, and costs of current and alternative solar PV incentive schemes in Switzerland. *Environmental Research Letters*, 19(6). <https://doi.org/10.1088/1748-9326/ad4dba>
- Su, K., Li, Y., Chang, X., Fan, M., Zhang, Y., & Wang, T. (2024). Research on initial carbon quota allocation in China's power industry based on ZSG-DEA. 13090. <https://doi.org/10.1117/12.3025664>
- Teng, M., Ji, D., Han, C., & Liu, P. (2025). Optimizing the Allocation of CO2 Emission Rights in the Yangtze River Delta City Agglomeration Region of China Based on Equity, Efficiency and Sustainability. *International Journal of Environmental Research*, 19(1). <https://doi.org/10.1007/s41742-024-00693-4>
- Tiboldo, G., Boehm, R., Shah, F., Moro, D., & Castellari, E. (2022). Taxing the heat out of the U.S. food system. *Food Policy*, 110. <https://doi.org/10.1016/j.foodpol.2022.102266>
- Torné, A., & Trutnevyte, E. (2024). Banning fossil fuel cars and boilers in Switzerland: Mitigation potential, justice, and the social structure of the vulnerable. *Energy Research and Social Science*, 108. <https://doi.org/10.1016/j.erss.2023.103377>
- Trotta, G., Hansen, A. R., & Sommer, S. (2022). The price elasticity of residential district heating demand: New evidence from a dynamic panel approach. *Energy Economics*, 112. <https://doi.org/10.1016/j.eneco.2022.106163>
- van der Wijst, K.-I., Hof, A., & van Vuuren, D. (2025). Equity principles, mitigation and climate impacts: Balancing welfare and costs. *Environmental Research Letters*, 20(9). <https://doi.org/10.1088/1748-9326/adeaa>
- Vandyck, T., Weitzel, M., Wojtowicz, K., Rey Los Santos, L., Maftai, A., & Riscado, S. (2021). Climate policy design, competitiveness and income distribution: A macro-micro assessment for 11 EU countries. *Energy Economics*, 103. <https://doi.org/10.1016/j.eneco.2021.105538>
- Vázquez-Serrano, J. I., Cárdenas-Barrón, L. E., Peimbert-García, R. E., Vicencio-Ortiz, J. C., Smith, N. R., Céspedes-Mota, A., & Koch-Schneider, A. (2026). Multi-crop production management for distributed and centralized scenarios under uncertainty with carbon tax assessment using a hybrid optimization simulation model. *Cleaner Logistics and Supply Chain*, 19. <https://doi.org/10.1016/j.clscn.2026.100328>
- Vogt-Schilb, A., Walsh, B., Feng, K., Di Capua, L., Liu, Y., Zuluaga, D., Robles, M., & Hubaceck, K. (2019). Cash transfers for pro-poor carbon taxes in Latin America and the Caribbean. *Nature Sustainability*, 2(10), 941–948. <https://doi.org/10.1038/s41893-019-0385-0>
- Wang, B., & You, F. (2025). Cropland enhanced weathering in low GDP regions for gigaton scale carbon removal with potential economic co-benefits. *Environmental Research Letters*, 20(12). <https://doi.org/10.1088/1748-9326/ae1cd4>
- Wang, Y., Zhang, R., Zhang, K., Chen, H., & Long, R. (2026). Carbon quota analysis of 284 cities in China under the carbon neutral goal based on the SBM dyadic modeling.



- Environment, Development and Sustainability. <https://doi.org/10.1007/s10668-025-07069-4>
- Wang, Y., Zhou, K., Wang, X., Yang, T., & Chen, H. (2024). Can carbon tax revenue recycling coordinate climate mitigation and energy poverty alleviation? *Energy*, 308. <https://doi.org/10.1016/j.energy.2024.132363>
- Wang, Z., & Zhong, M. (2024). An Equity-oriented Planning Method for Freight Carbon Tax Base on Integrated Modelling Framework. *Jiaotong Yunshu Xitong Gongcheng Yu Xinxi/Journal of Transportation Systems Engineering and Information Technology*, 24(4), 12–22. <https://doi.org/10.16097/j.cnki.1009-6744.2024.04.002>
- Wen, S., & Jia, Z. (2024). Call for multi-policy approach: Synergistic effects of emissions trading scheme and energy efficiency policies. *Journal of Environmental Management*, 360. <https://doi.org/10.1016/j.jenvman.2024.121186>
- Wu, H., Zhou, Y., Wang, X., Hu, X., Zhang, S., Ren, Y., Liu, J., Liu, Y., & Tao, S. (2024). The climate, health, and economic outcomes across different carbon pricing policies to achieve China's climate goals. *Applied Energy*, 368. <https://doi.org/10.1016/j.apenergy.2024.123498>
- Yan, S.-Y., Zhang, S.-X., Yuan, X.-C., & Jiang, H.-D. (2025). How can regional inequality caused by taxing non-CO2 greenhouse gases be mitigated? An economy-wide analysis. *Journal of Environmental Management*, 392. <https://doi.org/10.1016/j.jenvman.2025.126745>
- Ying, J., Jiang, J., Wang, H., Liu, Y., Gong, W., Liu, B., & Han, G. (2023). Analysis of the Income Enhancement Potential of the Terrestrial Carbon Sink in China Based on Remotely Sensed Data. *Remote Sensing*, 15(15). <https://doi.org/10.3390/rs15153849>
- You, K., Qian, Q. K., Cai, W., Wang, X., & Visscher, H. (2024). Subsidy allocation for residential building energy retrofit: A perspective of families' incomes. *Sustainable Cities and Society*, 104. <https://doi.org/10.1016/j.scs.2024.105317>
- Young-Brun, M., Dennig, F., Errickson, F., Feindt, S., Méjean, A., & Zuber, S. (2025). Within-country inequality and the shaping of a just global climate policy. *Proceedings of the National Academy of Sciences of the United States of America*, 122(39). <https://doi.org/10.1073/pnas.2505239122>
- Yu, X., Fan, Y., & Xiao, B. (2026). Global carbon pricing under financing inequality. *Energy Economics*, 157. <https://doi.org/10.1016/j.eneco.2026.109273>
- Yu, Z., Geng, Y., Calzadilla, A., & Bleischwitz, R. (2023). Assessing distributional impacts of synergetic air pollution reductions under different power system decarbonisation policies in China. *Environmental Impact Assessment Review*, 102. <https://doi.org/10.1016/j.eiar.2023.107215>
- Yuan, M., Barron, A. R., Selin, N. E., Picciano, P. D., Metz, L. E., Reilly, J. M., & Jacoby, H. D. (2022). Meeting U.S. greenhouse gas emissions goals with the international air pollution provision of the clean air act. *Environmental Research Letters*, 17(5). <https://doi.org/10.1088/1748-9326/ac6227>
- Zhang, J. (2026). Carbon tax revenue recycling impact on tourism: A comparative assessment of policy design options in China. *Tourism Management*, 117. <https://doi.org/10.1016/j.tourman.2026.105453>
- Zhang, S., Wang, Y., Hao, Y., & Liu, Z. (2021). Shooting two hawks with one arrow: Could China's emission trading scheme promote green development efficiency and regional carbon equality? *Energy Economics*, 101. <https://doi.org/10.1016/j.eneco.2021.105412>
- Zhang, Y., Jiang, S., Lin, X., Qi, L., & Sharp, B. (2023). Income distribution effect of carbon pricing mechanism under China's carbon peak target: CGE-based assessments.



- Environmental Impact Assessment Review, 101.
<https://doi.org/10.1016/j.eiar.2023.107149>
- Zhao, S., Fujimori, S., Hasegawa, T., Oshiro, K., & Sasaki, K. (2022). Poverty and inequality implications of carbon pricing under the long-term climate target. *Sustainability Science*, 17(6), 2513–2528. <https://doi.org/10.1007/s11625-022-01206-y>
- Zhao, X., Li, X., Wu, Y., Qiao, L., & Zhang, C. (2025). Assessment of the effects of China's new energy vehicle industry policies: From the perspective of moderating effect of consumer characteristics. *Environment, Development and Sustainability*, 27(2), 4319–4340. <https://doi.org/10.1007/s10668-023-04078-z>
- Zhao, Y., Wang, C., & Cai, W. (2022). Carbon pricing policy, revenue recycling schemes, and income inequality: A multi-regional dynamic CGE assessment for China. *Resources, Conservation and Recycling*, 181. <https://doi.org/10.1016/j.resconrec.2022.106246>
- Zhaohua, W., Jingyun, L., Bin, L., Bo, W., Bin, Z., Kaining, S., & Mao, F. (2023). Effectiveness and risk of initial carbon quota allocation principle under the uncertainty of the Chinese electricity market. *China Economic Review*, 77. <https://doi.org/10.1016/j.chieco.2022.101892>

