



Expanding Integrated Assessment Modelling:
Comprehensive and Comprehensible Science
for Sustainable, Co-Created Climate Action



Europe's path to decarbonisation: Net-zero emissions energy system

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1 Introduction

IAM COMPACT is a Horizon Europe research project, with the objective to support the assessment of global climate goals, the collective progress towards them, and the feasibility space in delivering on those goals. It aims to involve relevant stakeholders in the process to help promote acceptable, robust, sustainable transitions, as well as to enhance trust on both ends, yielding outputs intelligible in terms of real-world implications and actionable in terms of concrete policy recommendations.

Participatory approaches have been argued to bring a more diverse range of views into the IAM process, by building a better understanding of the social context and supporting more inclusive decision-making. In IAM COMPACT, we have designed a Policy Response Mechanism (PRM), a co-creation process that facilitates collaboration among modelling teams and with stakeholders. The PRM dynamically responds to changing policy priorities, aiming for policy relevance, knowledge exchange, and enhanced trust, by providing different layers of inputs and making modelling socially/politically realistic. Stakeholder engagement in IAM COMPACT is organised into themes (for stakeholders within the EU) and regions (for stakeholders outside the EU). The themes and regions were collaboratively determined within the project, with Bruegel coordinating the process. For the themes, the aim was to have a broad enough coverage to capture a range of issues, but also sufficiently selective to lead a clear research agenda later in the project. The conclusion of the first PRM cycle overlapped directly with the start of the second cycle, through another round of meetings with the Policy Steering Groups (PSGs) during June and July of 2024. Policymakers were asked what research questions not already discussed IAM COMPACT could explore in the second cycle, especially considering the new context of EU policy priorities—i.e., what is relevant from the perspective of the newly elected European Commission. Through this approach, the PSGs provided feedback on the first cycle research, proposed some refinements and developments for the second cycle, and offered new policy-relevant research questions.

Our project team received 46 research questions from the PSGs, which were then grouped into seven new modelling studies. After internal discussion among modelling teams, an initial scenario design for each study was agreed upon and presented to our Core Working Groups (CWGs) for discussion and co-design in three separate workshops. These proposals were in turn grouped into three overarching themes, "[*Modelling the Clean Industrial Deal*](#)", "[*EU Decarbonisation in the global economy*](#)", and "[*Citizens in the Transition*](#)", and discussed with the CWGs. In these final months of the project we are working to finalise the studies and present the results in the form of academic publications and policy briefs.

This policy brief is part of the theme "[*Modelling the Clean Industrial Deal*](#)", focusing on infrastructure investments towards a greener economy. During the workshop conducted under this theme, we met with stakeholders inter alia from ENTSO-E, IRENA, IEA, Ember, and CAN Europe, and sought their feedback on scenario design, inputs, and projections with regard to two proposed modelling studies. A key takeaway from the discussions was the need to better understand how various policy instruments can incentivise demand-side responses as well as the importance of reflecting evolving electricity market dynamics in modelling outcomes. The study presented here analyses how the updated National Energy and Climate Plans (NECPs) of EU Member States compare to a cost-optimal pathway for reaching EU-wide climate targets, considering grid infrastructure requirements and cross-border connections, offshore development, and electricity generation-storage-transmission cost balance.

2 Model ensemble & scenario co-design

Despite advancements in climate policy modelling, existing modelling tools often struggle to balance geographic detail with technical specificity, especially in the electricity sector. Operating mostly at regional or continental scales, Integrated Assessment Models (IAMs) obscure national differences in infrastructure, governance, and socioeconomic conditions, while national models provide detailed sectoral insights but lack the capacity to account for cross-border dynamics, limiting their usefulness in evaluating EU-wide policies like Fit-for-55 or the coherence of National Energy and Climate Plans (NECPs). This creates a gap in terms of capturing both national granularity and EU-level interdependencies. To bridge this gap, GCAM-Europe expands a well-established global IAM (GCAM) to include Member State-level disaggregation in its representation of the EU, thereby enabling more nuanced analysis of energy systems, emissions, and policy pathways at both scales. This improvement, notably in electricity load segmentation and spatial resolution, enhances the capacity to assess national energy transitions within the broader EU framework. To overcome limitations in capturing short-term variability in renewable generation within its five-year time, GCAM-Europe is coupled with a detailed electricity system model providing insights into capacity needs, grid constraints, and storage dynamics (EXPANSE), supporting a more robust analysis of the transition towards EU-wide targets and highlighting how national circumstances shape different pathways to net zero (for details on model linking see **Annex A**).

We explore three alternative climate policy scenarios alongside a benchmark baseline, each representing a distinct trajectory toward meeting the EU's emission reduction targets and broader climate objectives. These scenarios allow us to assess the implications of different policy designs. To isolate the relative price effects of climate policy, all scenarios incorporate existing country-specific energy taxes (on electricity, gas, and transport fuels) as of 2024 and hold them constant through 2030. Non-EU regions are assumed to follow NDCs and longer-term targets. Together, these scenarios (presented in **Table 1**) represent a range of plausible policy narratives that contrast prescriptive regulatory approaches with more flexible, least-cost mitigation strategies.

Table 1: Scenario protocol

Scenario	Description
NECP_POLICY	The scenario reflects a detailed representation of the existing Fit-For-55 policy portfolio, including EU-wide targets for the EU-ETS (1 and 2), vehicle emission standards, country-specific coal phase-out strategies, renewable energy as a % share of final energy and energy efficiency as a maximum to final energy use targets as defined in countries' NECPs.
NECP_FREE	In this scenario, Member States achieve the same level of CO ₂ emissions mitigation as in the NECP_POLICY scenario. However, in this case, emissions reductions are accomplished through emissions constraints without considering current climate policies, allowing the models to select the cost-optimal pathway for reducing emissions.
FF55_POLICY	This scenario is similar to the NECP_POLICY scenario, but instead of applying NECP-specific targets, EU-wide targets for 2030 in line with Fit-For-55 are applied for renewables (42.5% of final energy) and energy efficiency (11.7% reduction in final energy w.r.t. 2020), allowing the model to optimally allocate efforts for these targets over the different Member States.
FF55_FREE	In this scenario, the EU achieves the same level of CO ₂ emissions mitigation as in the FF55_POLICY scenario. However, in this case, EU emissions reductions are accomplished through emissions constraints without considering current climate policies, allowing the models to select the cost-optimal pathway for reducing emissions.

While all scenarios are calibrated to achieve the same total reduction in CO₂ emissions at the EU level by 2030, they differ markedly in how mitigation responsibility is distributed across sectors and Member States. To ensure consistency with official projections, population and GDP assumptions are harmonised with the 2024 edition of

the EU Ageing Report reflecting expected demographic and economic trends across Member States.

At the EU level, climate policy instruments incorporated in the scenarios include:

- EU Emissions Trading System (ETS): This cap-and-trade mechanism covers power generation and large industrial emitters, setting a declining carbon cap to reduce emissions cost-effectively.
- ETS2: A new emissions trading system for buildings and road transport, assumed to introduce a carbon price of €45/tCO₂ (in 2020 prices) by 2030.
- Vehicle emissions standards: These are modelled to tighten gradually over time, culminating in near-zero emissions from new vehicles by 2035, in line with EU regulation phasing out the sale of internal combustion engine (ICE) vehicles.

Country-specific policies reflect national contributions under the NECPs and include:

- Energy Efficiency Directive targets, requiring a reduction of final energy consumption to 764 million tonnes of oil equivalent (Mtoe) by 2030 at the EU level.
- Renewable Energy Directive objectives, mandating that 42.5% of final energy consumption be met through renewable sources by 2030.
- National coal phase-out plans, which specify timelines for retiring coal-based electricity generation.
- After 2030, we assume the absolute targets of policies remain constant, and use economy-wide carbon price towards net-zero in 2050 (or earlier for specific countries)

These differentiated policy frameworks allow for a comparative analysis of the trade-offs between coordination, flexibility, and equity in the pursuit of the EU's climate goals.

3 Model insights

3.1 Changes in the energy system

Current EU and national climate policies, represented by the *NECP_POLICY* and *FF55_POLICY* scenarios, are projected to significantly reduce CO₂ emissions by 2030 (**Figure 1**). GCAM-Europe results show that fossil CO₂ emissions across the EU-27 decline steeply from 2015 to 2030 in all policy and cost-optimal pathways, with the electricity sector delivering the largest share of reductions, followed by significant decreases in buildings and transport. All four scenarios achieve emissions reductions of more than 1 Gt CO₂ by 2030 compared to 2015 levels and reach the Fit for 55 emission target of 55% reduction compared to 1990, with only minor differences between the policy-driven and free variants. The *POLICY* scenarios reflect additional constraints, such as minimum renewable shares, efficiency measures, and carbon pricing, which lead to slightly different sectoral contributions compared to the *FREE* scenarios, mainly higher emission cuts in electricity rather than transport. By 2050, emissions in all scenarios are reduced by ~94% compared to 1990; the electricity sector approaches carbon neutrality, having the highest share of emission cuts from 2030 onwards in cost-optimal scenarios. Industrial emissions in the EU are projected to fall by over 130% in 2050, requiring deep transformation of industrial processes and widespread deployment of carbon capture and storage (CCS). The right panel highlights how reductions are shared across Member States: big emitters (Germany, France) drive the bulk of absolute emissions declines, while smaller economies (Portugal, Greece) lead in "percentage terms," showing ambitious transformations relative to their baseline. Overall, the results illustrate that the EU's Fit-for-55 and updated NECP targets are broadly consistent with cost-optimal decarbonisation, while revealing regional and sectoral diversity in how these reductions are achieved.

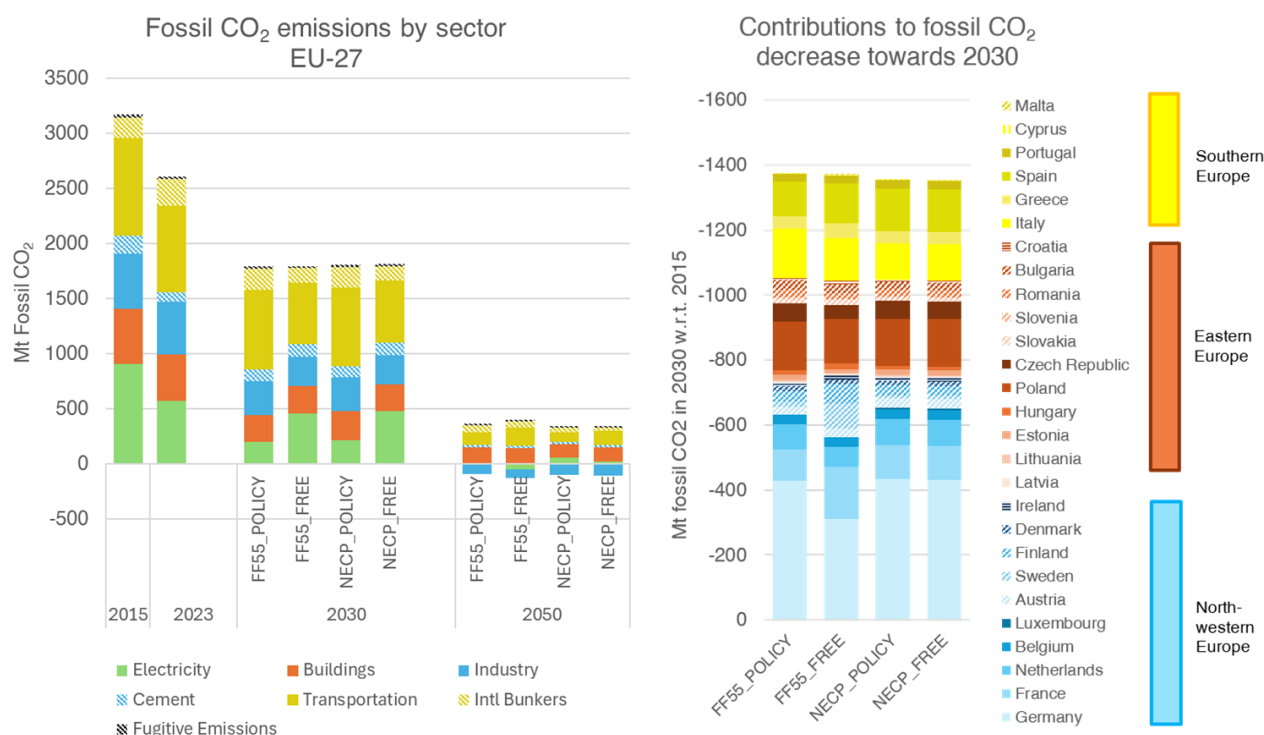


Figure 1: CO₂ emissions by period, region, and scenario (MTCO₂). The left panel shows the emissions at the EU level by sector and scenario, while the right panel shows emission reduction in 2030 with regards to 2015 and latest historical data (Eurostat, 2023)) by EU Member States and scenario.

All policy scenarios lead to a marked decline in final energy consumption by 2030, primarily through reduced use of fossil fuels (**Figure 2**). The *POLICY* scenarios, driven by the EU's binding 11.7% energy efficiency target, achieve the lowest energy demand, with Germany, France, and Italy again contributing the most to the savings;

they do not however reach the 763 Mtoe target, but at best reduce demand at 830 Mtoe in the *NECP_POLICY*. Cost-optimal scenarios *NECP_FREE* and *FF55_FREE*, result in almost double the efficiency gain compared to *POLICY* ones, hinting that planned policies are pushing beyond what is least-cost from a model perspective, especially in more ambitious countries. While these scenarios achieve very similar levels of sectoral mitigation in the EU, their contributions by Member State differs. In the *FF55_FREE* scenario the model redistributes mitigation efforts to where they are least costly from a system perspective, and thus efforts are shifted toward high-potential, low-cost regions (Nordics and France) while reducing pressure on higher-cost regions (like Germany). Overall, policy-driven (*POLICY*) scenarios lead to a broader distribution of energy efficiency gains across Member States, extending well beyond the largest economies. In contrast, cost-optimal (*FREE*) scenarios concentrate reductions in a few major emitters. This highlights that efficiency improvements are primarily the result of targeted policy intervention rather than a naturally cost-optimal outcome.

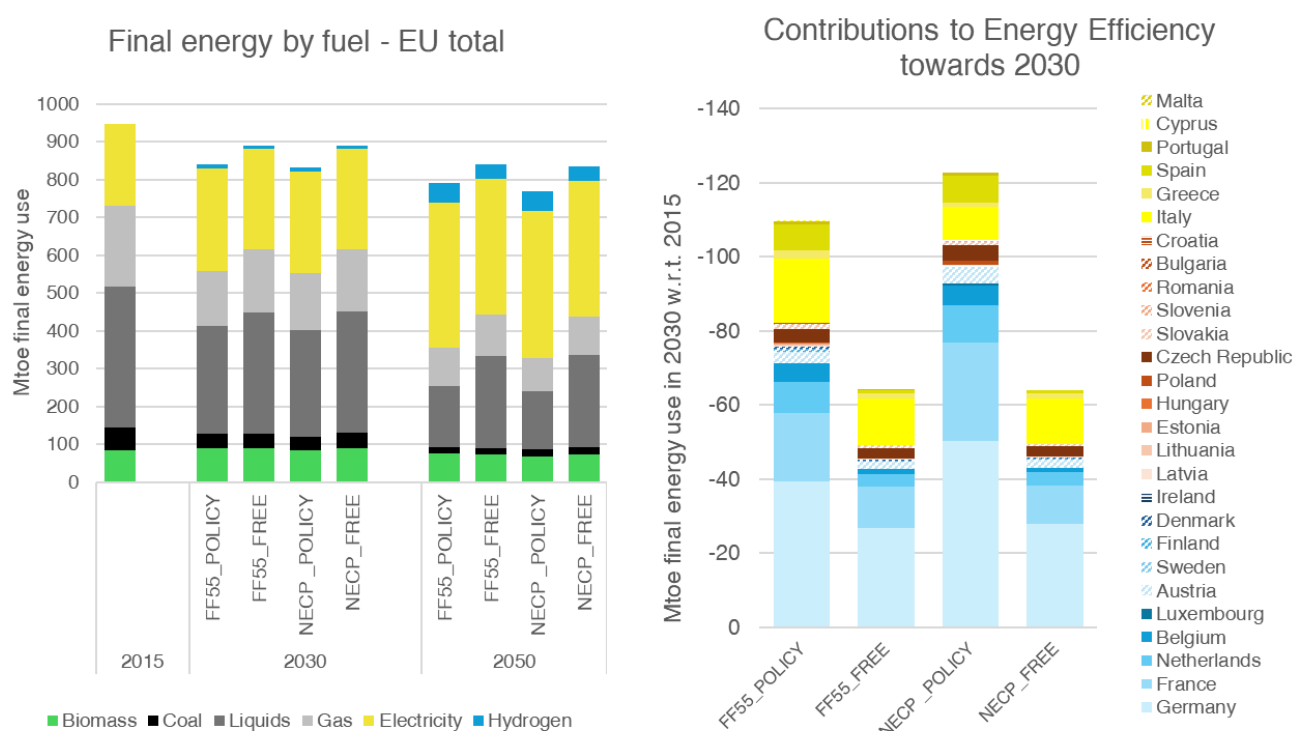


Figure 2: Final energy by fuel at the EU level in 2015, 2030, and 2050 (left) and final energy use by Member State in 2030 for all scenarios

Renewable energy use across the EU nearly doubles by 2030 under all scenarios, with electricity and biofuels leading the growth (**Figure 3**). The *FF55_POLICY* scenario nearly meets the 42.5% renewable share target, and even cost-optimal variants approach similar levels (~40%), demonstrating that renewable energy targets are consistent with cost-effective pathways. Germany and France are the largest contributors to this expansion, supported by strong uptake in countries like Spain, the Netherlands, Sweden, Greece, and Poland. These results confirm that both EU and national policies are effectively accelerating the transition to renewables, while allowing flexibility for countries to leverage their unique domestic resources and cost advantages. While all scenarios nearly double renewable energy use by 2030, the underlying fuel mix differs: *POLICY* scenarios frontload electrification and heat pump uptake, while *FREE* scenarios rely relatively more on biofuels.

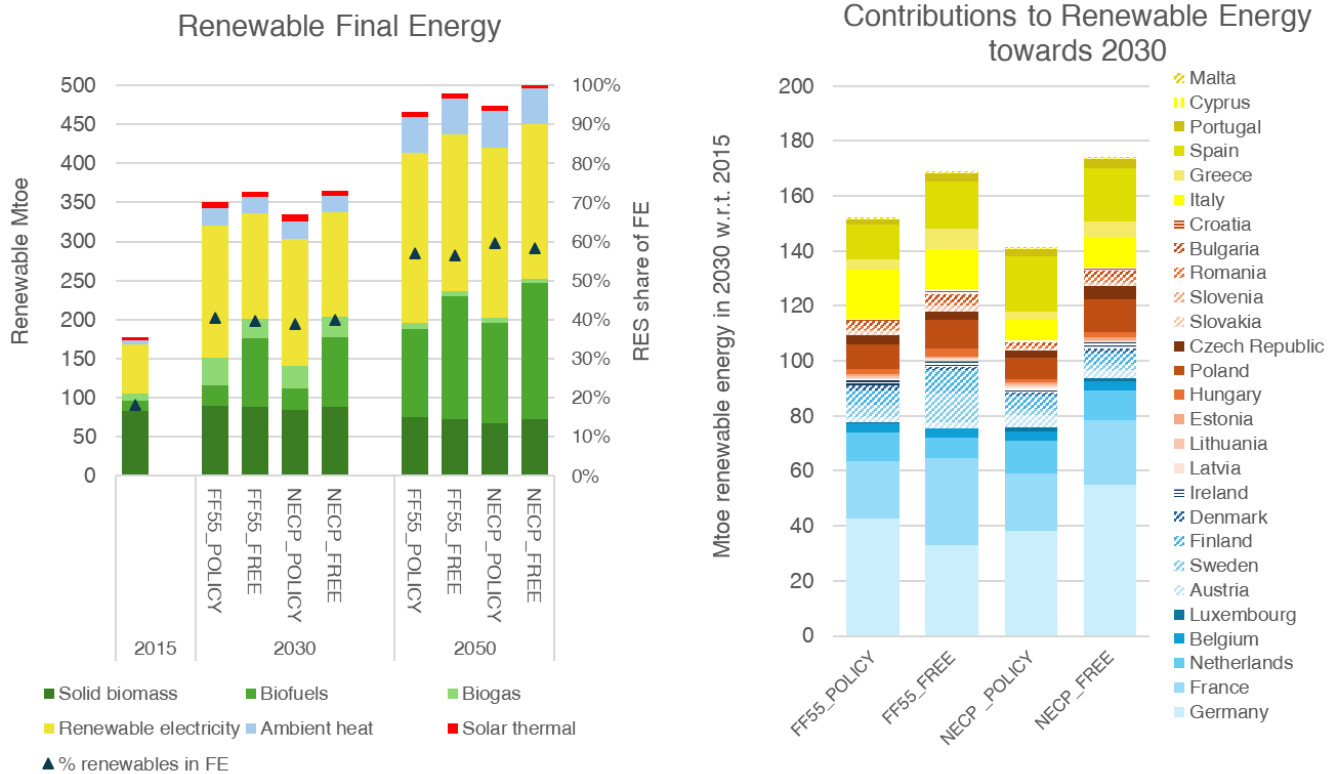


Figure 3: Renewable energy use in Mtoe and as a share of final energy in 2015, 2030, and 2050 at the EU level (left) and renewable energy use in 2030 with regards to 2015 in all Member States (right) for all scenarios

3.1.1 Highlights

- Current EU and national policies, as represented by the Fit-for-55 and updated NECP scenarios, can achieve deep, cost-efficient emission reductions by 2030, particularly in the power sector, placing the EU broadly on track toward its legally binding climate targets.
- The 11.7% EU efficiency target drives major energy savings, especially in Germany, France, and Italy.
- Renewable energy use nearly doubles by 2030, nearing the 42.5% target, with strong growth across most regions.

3.2 Changes in the electricity system

By 2035, Europe's electricity system would need to undergo a major transformation in response to climate policy goals, with new capacity additions dominated by wind power (onshore and offshore) and solar PV (**Figure 4**). These technologies are concentrated in regions with the highest renewable potential, offshore wind in the North Sea, solar in Southern Europe, and onshore wind across Central and Eastern Europe. The deployment of battery storage and hydrogen for electricity storage is particularly evident in western and northern countries. High-voltage transmission infrastructure is critical for connecting renewable-rich regions to demand centres, underscoring the need for coordinated planning between generation and grid expansion to support system flexibility and integration.

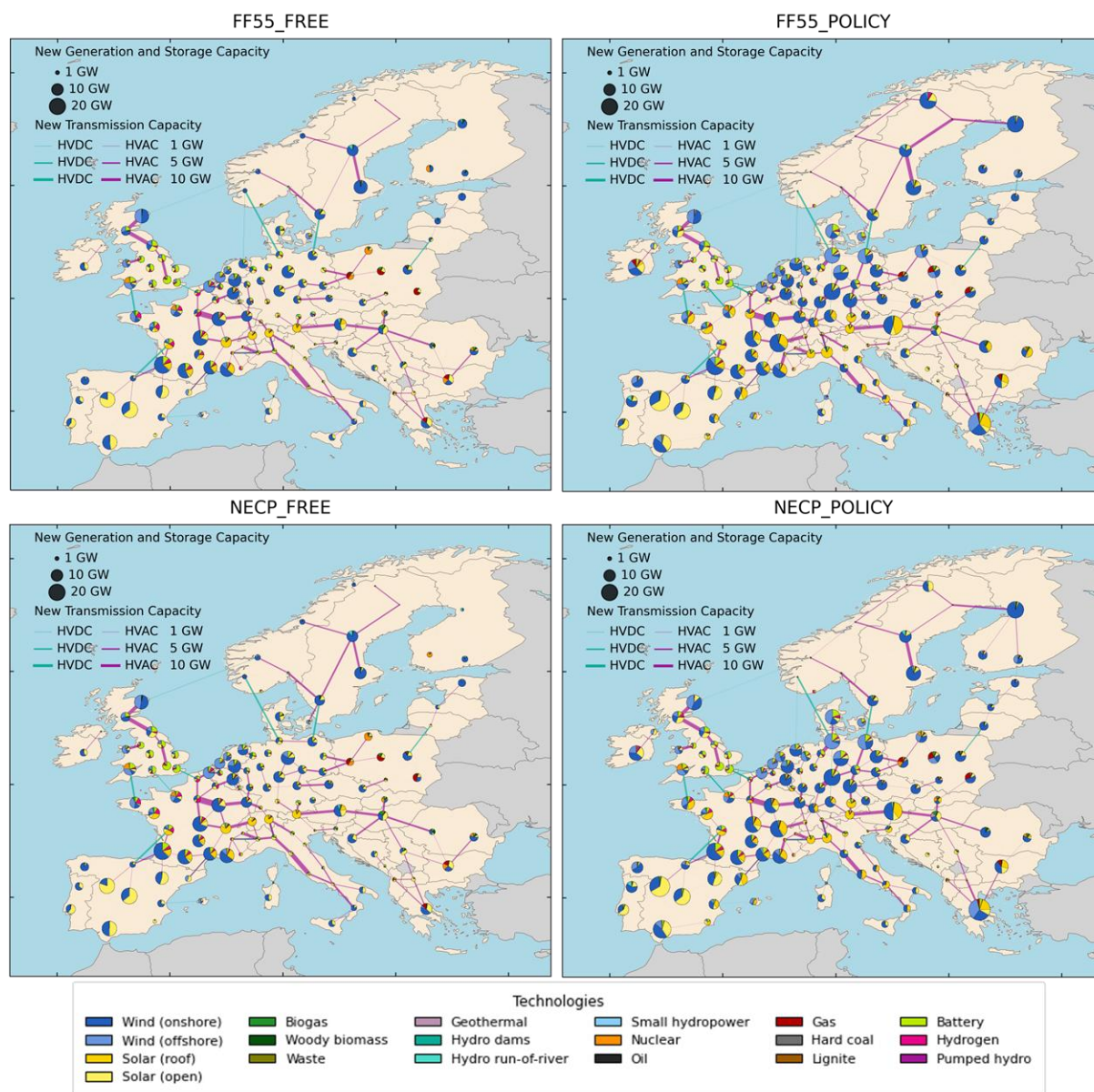


Figure 4: New installed capacities in 2035 as a difference from 2018

Investment needs in power system technologies vary significantly across scenarios (**Figure 5**). The FF55_POLICY scenario shows the highest investment requirements due to stringent EU-wide carbon pricing and renewable targets, which promote capital-intensive deployment of new generation capacity. The NECP_POLICY scenario follows, with slightly lower but still substantial investment driven by national-level constraints. In contrast, the cost-optimised FREE scenarios reach similar emissions reductions with far lower investments, as they avoid prescriptive efficiency and renewable targets, allowing generation and infrastructure deployment where it is most

cost-effective. These differences illustrate the financial implications of policy stringency and the trade-offs between economic efficiency, national sovereignty, and equitable distribution of investments.

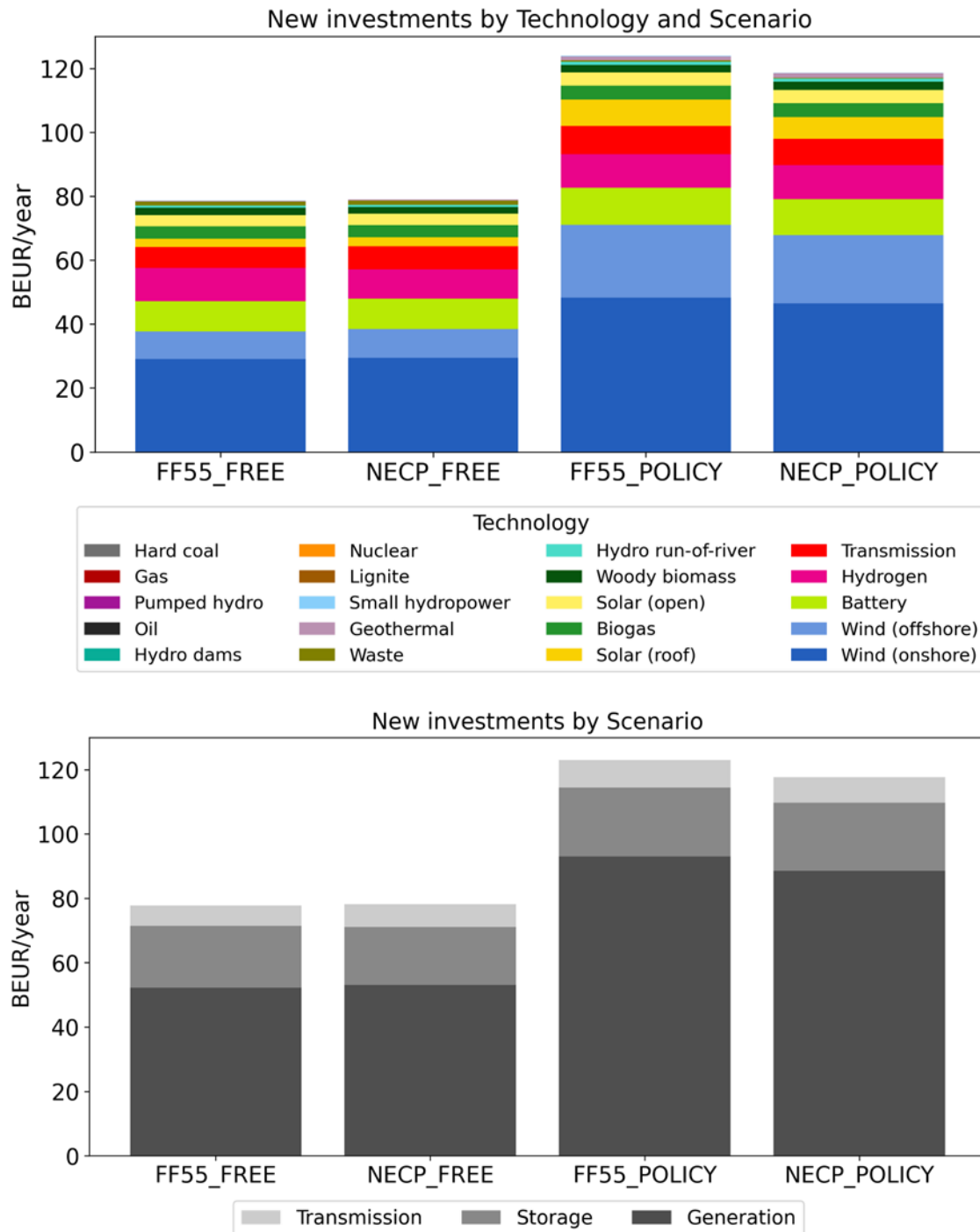


Figure 5: New power system investments in 2035 by technology (top) and by generation, transmission or storage (bottom) in all scenarios

Electricity price dynamics, represented by Locational Marginal Prices (LMPs), further reflect these trade-offs (**Figure 6**). The POLICY scenarios result in higher and more spatially varied LMPs, especially in Central and Southern Europe, due to high CO₂ prices that are part of the marginal cost of dispatchable fossil fuel-based generation, the reliance on this generation during low renewable output periods, and the merit-order effect. In contrast, the FREE scenarios produce lower and more uniform LMPs, particularly in Northern and Eastern Europe, where the of CO₂ prices, abundant renewables, and fewer constraints reduce marginal generation costs. These

results highlight the importance of flexibility, interconnection, and targeted investment to manage electricity affordability and system reliability in a decarbonised power sector.

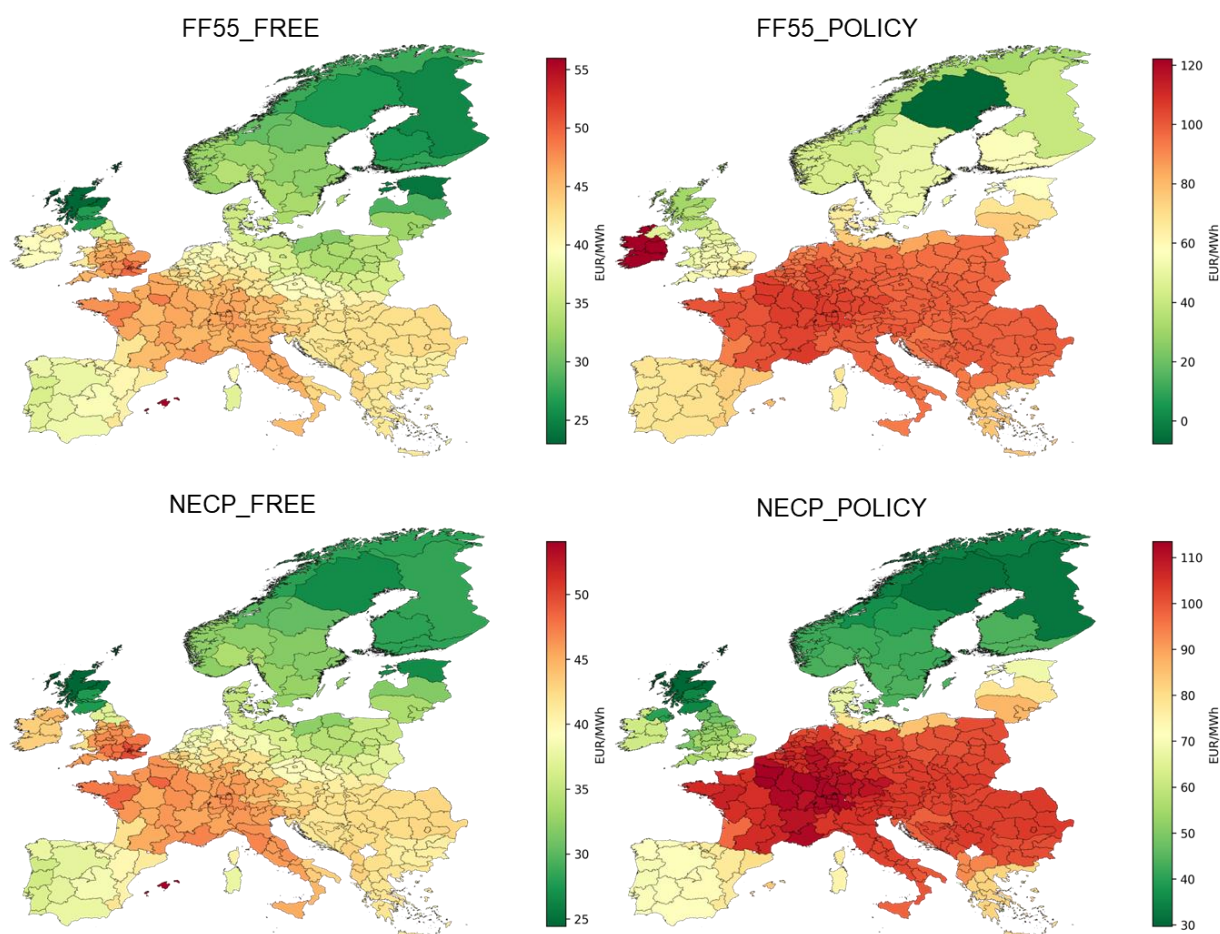


Figure 6: Average wholesale locational marginal price (LMP)

3.2.1 Highlights

- Wind and solar dominate new capacity by 2035, with strong regional focus: offshore wind in the North Sea, solar in Southern Europe, and onshore wind in Central and Eastern Europe.
- Battery storage, hydrogen, and transmission expansion are essential for integrating renewables and balancing supply and demand.
- Fit-for-55 and NECP (POLICY) scenarios require up to 50% more investment in electricity infrastructure by 2035 compared to cost-optimised alternatives; the largest difference is observed in generation, followed by transmission and storage.
- Cost-optimal (FREE) scenarios cut emissions at lower costs, by avoiding rigid efficiency and RES mandates, and concentrating investment where it is most efficient.
- Electricity prices are higher in POLICY scenarios, primarily driven by adding CO₂ pricing rather than markedly different flexibility or infrastructure needs.

4 Policy Implications

Our modelling analysis highlights that current EU and national climate policies are broadly on track to achieve 2030 emissions targets; however, doing so under Fit-for-55 and NECP pathways comes with significantly higher investment needs in the electricity system, especially in renewable generation, storage, and high-voltage transmission infrastructure. These policies enforce minimum renewable shares and carbon pricing, which drive investment but also result in higher electricity prices in Central and Southern Europe due to system constraints and reliance on expensive dispatchable generation. In contrast, cost-optimising (model-optimal) scenarios achieve the same emissions reductions with less investment and lower electricity prices, by concentrating generation in resource-rich regions and avoiding rigid national targets. However, such flexibility may undermine equity and political feasibility. The results underscore that reaching EU targets requires not just more renewables, but stronger coordination on cross-border infrastructure and targeted support for Member States with higher decarbonisation costs. Grid planning, flexibility mechanisms, and long-term funding instruments must be scaled up to ensure secure, affordable, and equitable transitions. Future policy design must consider these spatial and temporal dynamics, reinforcing the value of coupling long-term system planning with short-term flexibility and targeted national support. Although cost-optimal scenarios can, in principle, achieve comparable decarbonisation outcomes at lower system costs and electricity prices, real-world energy transitions rarely align with idealised optimisation outcomes due to political, institutional, and socioeconomic constraints. Therefore, current policies may require recalibration or complementary instruments to steer investment effectively, despite the associated political and regulatory complexity.

Key takeaways

- Current EU and national policies can deliver 2030 targets, but sustaining momentum to 2050 requires stronger support for industrial transformation and CCS deployment.
- Cost-optimal scenarios can, in principle, achieve comparable decarbonisation outcomes at lower system costs and electricity prices, but real-world energy transitions rarely align with idealised optimisation outcomes due to political, institutional, and socioeconomic constraints.
- Energy efficiency gains are not cost-optimal but policy-driven; binding measures and funding instruments are essential to lock in demand reductions.
- Wind, solar, and storage must scale rapidly; EU-level planning should balance concentrated vs. distributed investments across Member States.
- Grid congestion and underinvestment could undermine decarbonisation; fast-tracking permitting, financing, and EU-level coordination of transmission projects is crucial to meet 2030 and 2050 goals.
- ETS auction revenues for bill rebates or green investments could be used in high-price regions

Annex A: Model linking

For each modelled scenario, we run GCAM-Europe in 5-year intervals from 2015 to 2050, generating outputs such as country-level electricity demand, required emission reductions, and renewable electricity shares consistent with EU or national targets. These results are used as (maximum or minimum) constraints for the EXPANSE model, which we use to analyse the EU electricity system in 2035, specifically generation, storage, and transmission capacity needs, associated investments, and electricity prices. Carbon prices are taken from GCAM-Europe and used as fuel tax. EXPANSE is an optimisation model that solves for least-cost pathways, and in certain cases diverges from GCAM-Europe constraints, sometimes even pursuing more ambitious outcomes, when these are found to be more cost-efficient. EXPANSE does not include negative emission technologies, contrary to GCAM-Europe; thus, meeting EU targets would require the electricity system configuration described by EXPANSE, plus the level of CCS provided by GCAM-Europe. EXPANSE assumes frozen nuclear capacity everywhere except for a complete phaseout in Belgium and Germany, at least partial phaseout in Switzerland, and possible expansion of nuclear (by order from most to least) in Poland, the UK, Finland, Bulgaria, France, Slovakia, and Romania. Inputs, outputs, and linkages between GCAM-Europe and EXPANSE are shown in **Figure A1**.

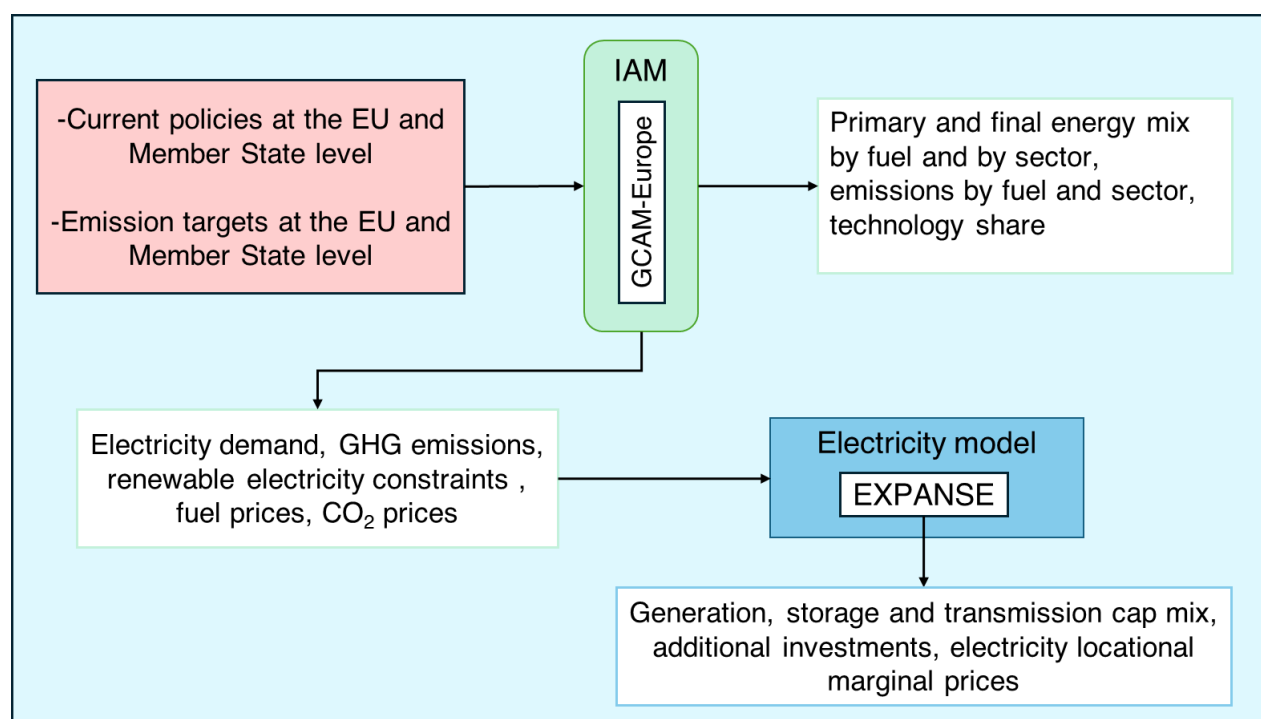


Figure A1: Inputs, outputs, and model connections

Annex B: Model intercomparison

This section summarises key findings of a relevant study from the 1st Policy Response Mechanism of the project, which focused on the comparison of a model-driven cost-optimal scenario (EU_Optimal) and a modelled Fit-for-55 policy scenario (NDC_LTT) for reaching the EU climate targets, before the final NECPs became available. The study used three global IAMs (GCAM, IAM-Grantham, and PROMETHEUS) and focused only on two scenarios:

- NDC_LTT: Representation of all current policies (including FF55 policy pillars), 2030 NDC, and long-term net-zero emission targets.
- EU-Optimal: Emission targets in the EU achieved through an economy-wide emissions cap and not any other (sectoral) policy.

The analysis had revealed a clear divergence between cost-optimal mitigation scenarios and the policy-driven FF55 framework, particularly in terms of final energy demand (**Figure B1**). Cost-optimal pathways generally exhibited higher energy consumption by 2030 and 2050, as they prioritised least-cost supply-side decarbonisation and often relied heavily on Negative Emission Technologies (NETs) like BECCS and DACCS. In contrast, by imposing stricter targets on final energy use through instruments like the Energy Efficiency Directive, the FF55 package resulted in deeper reductions, especially in buildings and transport. This discrepancy suggested that models may underrepresent feasible demand-side and behavioural options, treating energy demand reduction as a last resort. Additionally, many models still relied on NETs that are technically uncertain and unsupported by current policy frameworks. Strong FF55 emphasis on reducing energy use in households and mobility highlighted the importance of distributional instruments, like the Social Climate Fund, to ensure fairness and affordability in the transition, particularly for low-income groups who may bear a disproportionate share of the burden.

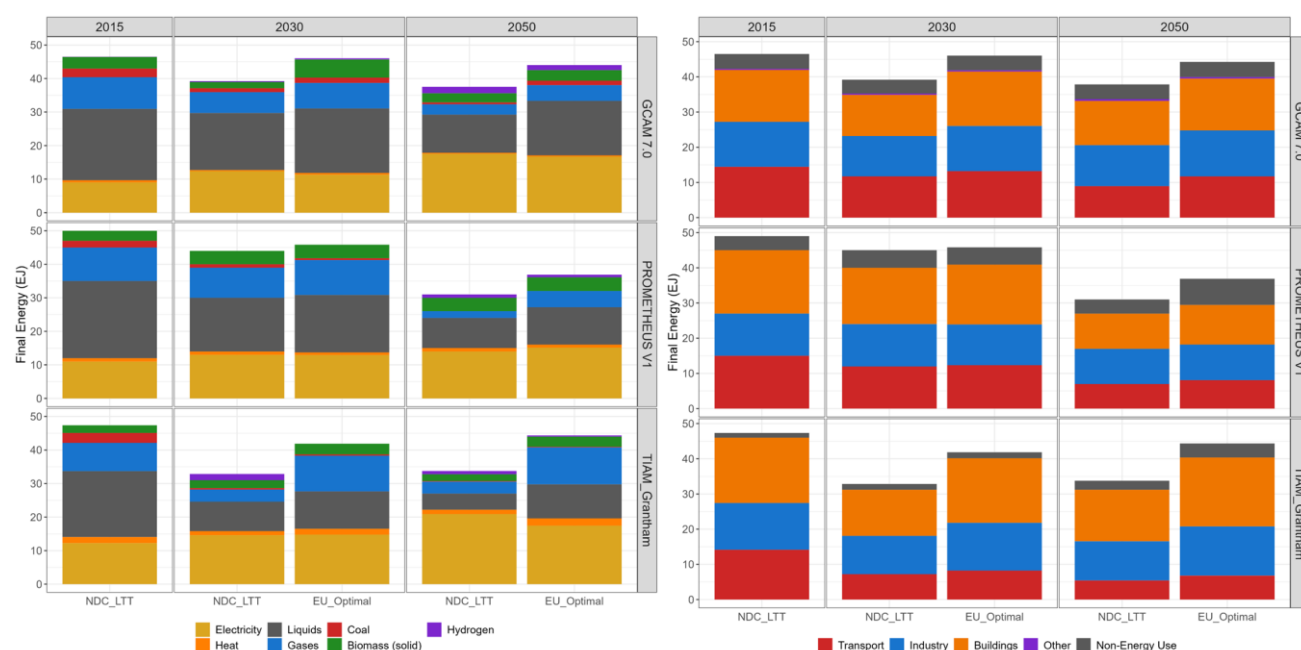


Figure B1: Final energy demand by model, scenario, and energy carrier (left) and model, scenario, and sector (right)

Policy Brief

Europe's path to decarbonisation: Net-zero emissions energy system



In a nutshell

IAM COMPACT supports the assessment of global climate goals, progress, and feasibility space, and the design of the next round of Nationally Determined Contributions (NDCs) and policy planning beyond 2030 for major emitters and non-high-income countries. It uses a diverse ensemble of models, tools, and insights from social and political sciences and operations research, integrating bodies of knowledge to co-create the research process and enhance transparency, robustness, and policy relevance. It explores the role of structural changes in major emitting sectors and of political, behaviour, and social aspects in mitigation, quantifies factors promoting or hindering climate neutrality, and accounts for extreme scenarios, to deliver a range of global and national pathways that are environmentally effective, viable, feasible, and desirable. In doing so, it aligns climate action with broader sustainability goals, while developing technical capacity and promoting ownership in non-high-income countries.

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