IAM COMPACT

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

D4.5 - National, regional, global mitigation pathways

WP4 – Modelling – Quantitative evidence in support of post-2030 Paris-compliant climate action

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EC Summary Requirements

1. Changes with respect to the DoA

No changes with respect to the work described in the DoA. The report was originally submitted in line with the deadlines set out in the DoA—i.e., November 2023. However, it was updated and resubmitted in February 2024, upon finalisation of the mitigation analyses in the three non-EU regions (China, India, and the USA) as well as of the comparison among cost-optimal scenarios to achieve the EU emissions mitigation targets to EU-wide modelling of the Fit-for-55 policy package.

2. Dissemination and uptake

This report will be used internally by all consortium partners as a benchmark for forthcoming mitigation modelling work. It develops a set of stakeholder-driven global, regional, and national mitigation pathways and introduces the implementation of IAM COMPACT's "Broad Scenario Logic", described in detail in the Deliverable D4.3. The report will be shared with stakeholders outside the consortium to discuss how the credibility of results can be improved.

3. Short summary of results (<250 words)

The IAM COMPACT model ensemble was strategically selected to be flexible enough to allow for the assessment of emerging issues in response to urgent policy needs. An early modelling exercise aimed to provide quick insights into the energy supply crisis in Europe, by exploring the trade-offs among different approaches to replacing Russian gas in the bloc, aiming to understand and quantify their implications to energy sustainability, affordability, and emissions within the EU.

Emerging questions aside, the project builds on a detailed, multi-step policy response mechanism that co-defines the most pertinent policy questions with EC and national policymakers, groups these questions into Studies, co-designs a scenario framework and a series of critical aspects that the consortium is expected to explore, before carrying out modelling analyses aimed at addressing these questions, revisiting them, and co-creating policy prescriptions. As part of the first policy response mechanism cycle, seven such studies were put together, each documented in different deliverables; to address each, however, a common baseline must be defined, one that considers a reference scenario reflecting current policies, near-term pledges, and longer-term commitments. This deliverable thus documents this exercise, by analysing the trajectory of global CO_2 emissions considering current mitigation efforts, including updated policies, NDCs for 2030, and new long-term strategies that were put in place in the run-up to or after COP26.

The deliverable finally includes a set of mitigation scenarios for major emitting nations, namely India, China, and the USA, co-created with stakeholders as part of this first policy response mechanism cycle.

4. Evidence of accomplishment

This report.

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Preface

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 fully accounts for COVID-19 impacts and recovery strategies and aligns climate action with broader sustainability goals, while developing technical capacity and promoting ownership in non-high-income countries.

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Executive Summary

The "National, regional and global mitigation pathways" Work Package (WP4) of IAM COMPACT is designed to produce analysis of different low-carbon pathways for the world as well for EU and non-EU nations, using a range of global, multi-regional integrated assessment models (IAMs) and sectoral models.

IAM COMPACT's modelling ensemble was strategically selected to be flexible enough to allow for the assessment of emerging issues in response to the urgent policy and stakeholder needs. In this context, an early modelling exercise thus aimed to provide quick insights into the energy supply crisis that emerged in Europe at the time the project kicked off, fuelling a heated policy debate, by exploring the trade-offs among different approaches to replacing Russian gas in the bloc (replacing it with other gas imports, boosting domestic energy production, and accelerating energy efficiency) as well as understanding and quantifying their implications to energy sustainability, affordability, and emissions within the EU.

Emerging questions aside, the project builds on a detailed, multi-step policy response mechanism that co-defines the most pertinent policy questions with EC and national policymakers, groups these questions into Studies, co-designs a scenario framework and a series of critical aspects that the consortium is expected to explore, before carrying out modelling analyses aimed at addressing these questions, revisiting them, and co-creating policy prescriptions. As part of the first policy response mechanism cycle, seven such studies were put together, each documented in different thematic IAM COMPACT deliverables; to address each, however, a common baseline must be defined, one that takes into account a policy reference scenario reflecting current policies, near-term pledges, and longer-term commitments. This deliverable, therefore, continues with this exercise, by analysing the trajectory of global CO_2 emissions considering current mitigation efforts, including updated policies, Nationally Determined Contributions (NDCs) for 2030, and new long-term strategies (LTSs) for 2050, which were put in place in the run-up to, during, and after the COP26 conference.

The report also documents a set of mitigation scenarios for major emitting nations, namely India, China, and the USA, which were co-created with stakeholders as part of this first policy response mechanism cycle. Three regional studies were conducted based on the research priorities and questions emerged from the stakeholder interactions. During the US stakeholder meeting, for instance, deeper state-level analysis was deemed necessary, whereas stakeholders emphasised the importance of decarbonising the building sector in India.

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1. European energy crisis

Among others, the project's mission includes modelling analysis based on a large ensemble of simulation and optimisation tools, allowing to feed into the design of the next round of Nationally Determined Contributions (NDCs) and policy planning beyond 2030 for the European Union (EU), other major emitters, and non-high-income countries. The project's scope, however, is dynamic and its operational capacity flexible enough to assess emerging issues of importance to energy and climate policy. Among these issues has been Russia's invasion of Ukraine in February 2022. The first modelling exercise conducted within the project emerged considerably earlier than envisaged in the project's Description of Work and before the Policy Response Mechanism was established. Aiming to respond to a hot topic that troubled EU and global policymakers, it sought to understand the trade-offs among different approaches to living without Russian gas in Europe and their implications on EU's energy sustainability, affordability, and emissions.

The content of this section is published in Elsevier's *Energy* journal.

1.1 Introduction

Russia's war against Ukraine has exacerbated an ongoing energy and resource crisis [1], disproportionately affecting the European Union [2] (EU) and highlighting its considerable dependence on Russian natural gas. This has put energy sustainability and affordability at risk and reduced Europe's geopolitical room for manoeuvre [3,4]. Unless sufficiently resolved, these overlapping challenges [5] could eventually impact global financial markets [6] as well as possibly delay or reverse progress to climate goals [7], sustainable development [8], and future resilience [9]. On the climate front, despite the ever-closing window of delivering on the Paris Agreement temperature goals [10,11] and clear signs of insufficient acceleration of global mitigation efforts [12–14], the 27th UNFCCC Conference of Parties (COP27) was marked by lack of ambition to phase out fossil fuels; this was largely a continuation of the climate negotiation status-quo but also owing to the ongoing energy crisis [15].

In response, the EU released its REPowerEU strategy shortly after the invasion, aiming to rapidly attenuate its ties to Russian fossil fuels and become fully energy-independent from Russia by 2027 [16], along with a mandate on gas storage obligations [17] and efforts to accelerate the uptake of renewable energy and energy efficiency. Many EU countries also prioritised decoupling their economies from Russian fossil fuels at the national level, adopting a range of energy [18] and fiscal [19] measures towards mitigating the impact of higher costs on consumers and businesses, stabilising wholesale prices, and securing their energy supply. Although the coordinated European response entails measures to reduce energy vulnerability [20], entirely replacing Russian gas imports will be challenging in the near-term [21,22], with non-pipeline Russian gas still finding its way to Europe [23,24]. Ongoing and planned liquefied natural gas (LNG) infrastructures are projected to increase today's EU terminal capacity by 48% until 2030, with risks of possibly becoming stranded assets due to a mismatch with reductions in gas demand to meet climate objectives [25]. Meanwhile, Russia has continued to further reduce its gas supplies to the EU, essentially escalating its strategy of "weaponising" energy [26].

Pre-war Russian pipeline exports to the EU were 1,463 TWh in 2021, i.e., 41% of the bloc's total gas consumption (3,630 TWh). At the beginning of 2023, Russia still exported some 5 TWh per week via Turkstream and Ukraine (15% of pre-war volumes) as well as some 3.5 TWh as LNG—which would over the year sum up to around 440 TWh. Assuming that the EU eventually loses the entire amount of about 1,500 TWh of annual imports [22] relative to pre-war levels and that this reduction is permanent, the Union must seek ways in which it can optimally replace this loss. However, the impacts of gas market disruptions on the European energy system and overall economy and, in turn, the effects of EU responses on its transition pathway and 2030 climate targets remain uncertain [27–29].

A growing number of studies have set out to analyse the impacts and trade-offs of a temporary [30,31] and/or prolonged [21,32,33] Russian gas cut-off, with some discussing the evolution of the European gas market [20] and electricity system [34], assessing supply and demand policy options to mitigate adverse effects [18,35], or

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shedding light on potential spillover effects to biodiversity [35], climate risks [36], and stranded assets [37]. Owing to significant uncertainties as well as related resource requirements, modelling research has been sparing in assessing the implications of the Russia-Ukraine conflict and the impacts of a fast Russian gas phaseout in the EU [38]. Among the few studies available to date, all have been single-model efforts, while most have focussed on offering a very short-term outlook with limited possibilities of adjusting investment, production, and consumption patterns [32,34,39]. Few studies investigated longer-term impacts of a modelled European response to the conflict-fuelled energy crisis, including on emissions, by assuming different levels of and parties involved in an embargo [40–42], while aiming for the cost-optimal course of action. Building on but straying from these efforts, our research contributes to both literature and the heated policy discourse, by exploring *explicit directions* of how Russian gas could be phased out in the bloc as well as their implications *benchmarked against actual climate targets for 2030 and 2050*, enabling to identify insights into the trade-offs and synergies between the different considered approaches to replacing Russian gas. We also employ a *diverse ensemble of models* of different structure and theory, thereby enhancing the robustness of resulting policy prescriptions [43] and our understanding of the future uncertainty space [44] based on four established Integrated Assessment Models (IAMs), as well as allowing to extract finer sectoral insights via interlinkages with two sectoral modelling tools.

1.2 Methods

In this study we use an ensemble of four established integrated assessment models (IAMs), a dedicated electricity system optimisation model, and an Input-Output model to explore the energy-system implications—including macroeconomic impacts in the energy sector—of a complete and rapid phaseout of Russian gas imports in the EU by the end of 2023. We consider three 'corner' options for replacing Russian natural gas, representing entirely different directions and reflecting the core options embedded in the policy debate: (a) increasing natural gas imports from other regions to make up for the lost Russian supply ('*Gas Imports*'), (b) boosting energy production within the EU to make up for the lost gas imports ('*Domestic Production*'), and (c) accelerating the deployment of energy efficiency measures across sectors to reduce energy consumption accordingly ('*Energy Efficiency*')—see Section 2.2. Our modelling approach represents each 'corner' strategy as an individual scenario, benchmarked against a baseline that reflects mitigation efforts implied by Nationally Determined Contributions (NDC) for 2030 and long-term net-zero pledges for 2050 but disregards the energy-supply crisis ('*Baseline*'). Although our aim is not to calculate a cost-optimal course of action but rather to understand what each of these three markedly different directions could imply for the European energy system, we additionally calculate a '*Model-optimal*' scenario that does not prescribe a directed response but allows models to flexibly calculate their optimal pathways to the EU's 2030 and 2050 climate targets without Russian gas imports.

1.2.1 Scenario logic

The scenarios in the global modelling runs are designed to reflect different levels of compromised post-COP26 ambitions:

- **Current policies (CP):** level of short-term ambition that is likely to be materialised through actual policies or concrete policy targets
- **NDCs (NDC**): level of short-term ambition to which most countries are dedicated to through law or policy, but with risks of falling short if dedication is not high enough and/or changes occur in the political landscape.
- **Long-term targets (LTT):** level of longer-term ambition which many countries have stated to fulfil their part in mitigating climate change, but in most cases not backed with an actual policy agenda. These will come on top of pledged NDC targets, to create another increased level of proposed ambition. These pledges will be included for each separate model region as a linear pathway from the 2030 NDC target (NDC_LTT).

The first two levels of ambition are aiming on 2030, which is the common year for NDC targets and for many policy targets. To explore longer-term emission futures using current policies and NDCs, the Emissions Intensity

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(EI) method is applied after 2030 as a function of the ambition level up to 2030, by defining the rate of change in emissions intensity of GDP in each region from 2020 to 2030 and keeping the rate of change in emissions intensity of GDP constant after 2030. To increase the realism of how emissions reductions take place in all our scenarios, current policies are represented explicitly in both the CP and NDC scenarios, both before and after 2030. After 2030, current policies are assumed to remain in place as "constant" or "minimum" bounds on effort. The third level of action is aiming on incorporating long term pledges, predominantly net-zero emission pledges, to the modelled scenarios.

1.2.2 Model ensemble

GCAM [45] (Global Change Analysis Model) is a technology-rich, partial equilibrium IAM that represents the behaviour of, and interactions between five systems: the energy system, water, agriculture and land use, the economy, and the climate. The energy system is a detailed representation of the sources of energy supply, modes of energy transformation, and energy service demands such as passenger and freight transport, industrial energy use across subsectors, and residential and commercial energy service demands. The model achieves equilibrium between energy supply and demand in each represented sector, accounting for the changes in energy prices resulting from changes in fuels and technologies used to satisfy energy-service demands in these sectors. It operates on a 'recursive dynamic' cost-optimisation basis, meaning that decision-makers do not know the future when making a decision today, and solves for the least-cost energy system (constrained by observed technological preferences) in a given period before moving onto the next period and performing the same process. GCAM trades for natural gas trade in each region using an Armington approach, i.e., regions are allowed to choose between domestically produced products or globally traded products when making a consumption decision [46]. For the purposes of this study, we use a version of GCAM explicitly representing LNG and pipeline gas as separate trade pathways [47]. In particular, LNG is traded in a single, global market, following the Heckscher-Ohlin approach, while pipeline gas is traded in six regional pipeline networks (Europe, Russia+, Africa and Middle East, Asia-Pacific, North America, and Latin America). The pipeline networks that a given GCAM region may import from are dependent on historical country-level bilateral trade flows. It should be noted that the version of GCAM used in this analysis disaggregates EU regions as follows:

- EU_Central (Austria, Czech Republic, Hungary, Slovakia, Slovenia, Croatia, Poland)
- EU_Southwest (Italy, Malta, Portugal, Spain, Andorra, Gibraltar, San Marino, Vatican)
- EU_Southeast (Romania, Bulgaria, Cyprus, Greece)
- EU_Northwest (Belgium, Germany, France, Monaco, Netherlands, Luxembourg, Denmark)
- EU_Northeast (Finland, Sweden, Estonia, Latvia, Lithuania)
- EU_UK+ (United Kingdom, Ireland, Channel Island, Faroe Island, Guernsey, Greenland, Jersey, Saint Helena)

TIAM [48] (Times Integrated Assessment Model) is also a partial equilibrium, technology-rich IAM which covers the full energy chain from extraction of energy resources through conversion technologies, to the provision of energy service demands to end-users [49]. It achieves similar equilibrium between energy supply and demand in each sectoroperating on a 'perfect foresight' welfare cost-optimisation basis, whereby all consequences of technology deployments, fuel extraction, and energy price changes over the entire time horizon are considered when minimising the cost of the energy system to provide energy-service demands within specified emissions constraints. Exogenous inputs of GDP, population, household size and sectoral shares of the economy are combined to project future energy service demands across all sectors in each region. Energy system data (e.g., technology costs, resource supply curves and annual resource availability) are also input into the model. TIAM disaggregates the world into 15 different regions, which are interlinked by the trade of the main energy and material commodities [50].

MUSE [51] (ModUlar energy systems Simulation Environment) is an agent-based system model providing a detailed account of the energy sector to simulate GHG emissions reduction pathways—or the costs of alternative climate policies. It is bottom-up, in that it models the energy system from the interactions of networks of

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technologies. It models a microeconomic equilibrium on the energy system by iterating market clearance across all sector modules and interchanging price and quantity of each energy commodity within each region. Within the micro-economic framework, MUSE applies an agent-based structure, in that it characterises the behaviour of the major players in each sector thus providing an as-realistic-as-possible description of the investment and operational decision-making in each geographical region within a sector. LNG is traded via bilateral agreements, while pipeline gas is traded in pipeline networks (Europe, Russia+, Africa and Middle East, Asia-Pacific, North America, and Latin America). They are both based on historical patterns.

PROMETHEUS [52] is a global energy system model covering in detail the complex interactions between energy demand, supply, and energy prices at the regional and global level, allowing to assess mitigation pathways and low-emissions development strategies, analyse the energy system, economic, and emissions implications of a wide spectrum of policy instrument differentiated by region and sector, and explore the economics of fossil-fuel production to quantify the impacts of climate policies on the evolution of global energy prices. It notably features world supply/demand resolution for determining the prices of internationally traded fuels and technology dynamics mechanisms for simulating spill-over effects for technological improvements. Much like GCAM and MUSE, it operates 'myopically', meaning each time step is solved without full knowledge of the future.

All four IAMs differ in the way technologies are chosen across sectors: GCAM and PROMETHEUS employ a logit technology choice mechanism, which causes gradually decreasing returns as a technology is further diffused; TIAM uses a winner-takes-all optimisation mechanism, implying that the cheapest technology can dominate all new deployment; and MUSE follows an agent-based approach, where agent decision goals and strategies determine technology choices in each time step. Despite model harmonisation efforts, the four IAMs include different technological and sectoral granularity, which increases unwanted heterogeneity.

Furthermore, these global IAMs are then interlinked with two sectoral models, to provide additional insights with regard to electricity (EXPANSE) and employment (MARIO) impacts of the modelled pathways per model and scenario.

EXPANSE [53] is a spatially explicit, bottom-up, technology-rich, single-year optimisation model of the European electricity system that covers 33 countries (EU minus Cyprus and Malta, and plus Albania, Bosnia and Herzegovina, Montenegro, North Macedonia, Norway, Serbia, Switzerland, and the UK). The model accounts for operation and capacity planning of electricity generation, storage, and transmission until 2035. The model represents electricity generation at the level of 296 NUTS-2 regions and electricity demand, storage, and transmission at the level of 128 transmission grid nodes, ensuring that electricity generation, storage, and transmission balance inelastic electricity demand at each transmission grid node and time step.

MARIO [54] (Multi-functional Analysis of Regions through Input-Output) is an open suite for input-output analysis based on the DynERIO [55] (Dynamic Extraction and Recycling Input-Output) framework, a comparative-static simulation model able to assess the impacts of implemented macroscopic trends and scenarios from an economic and environmental perspective—here with respect employment implications of the IAM-modelled pathways. With respect to typical input-output models, DynERIO allows to quantitatively assess the extraction of raw materials for selected technologies driven by regional production of commodities provided by the Leontief Production Model.

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Table 1 : Key characteristics of all six models, including references to detailed online documentation.

Model Name	Model Type	Solution Horizon	Tech choice	Detailed documentation in I^2AM PARIS
GCAM	Partial equilibrium	Recursive dynamic (myopic)	Logit choice	https://www.i2am-paris.eu/detailed_model_doc/gcamv2022
PROMETHEUS	Partial equilibrium	Recursive dynamic (myopic)	Logit choice	https://www.i2am-paris.eu/detailed_model_doc/prometheus
TIAM	Partial equilibrium	Intertemporal optimisation (perfect foresight)	Winner takes all	https://www.i2am-paris.eu/detailed_model_doc/tiam
MUSE	Partial equilibrium – Agent based	Recursive dynamic (myopic)	Agent decision goals and strategies	https://www.i2am-paris.eu/detailed_model_doc/muse
EXPANSE	Electricity system	Intertemporal optimisation (perfect foresight)	Winner takes all	https://www.i2am-paris.eu/detailed_model_doc/expanse
MARIO	Input – Output	Comparative-static simulation	Input from IAMs	https://www.i2am-paris.eu/detailed_model_doc/dynerio

Gas prices, electricity demand, power-sector CO_2 emissions, and gas availability from the four IAMs are then used as inputs into EXPANSE, which also uses GDP growth as a proxy of households' consumption growth, regionally adjusted according to population growth projections.

MARIO, on the other hand, requires gas import patterns that are implemented into the Exiobase database as an economic perturbation, electricity production mixes that are used to model the gradual regional shifts from fossil to renewable power generation, and industrial electrification rates (fraction of electricity over total energy consumed).

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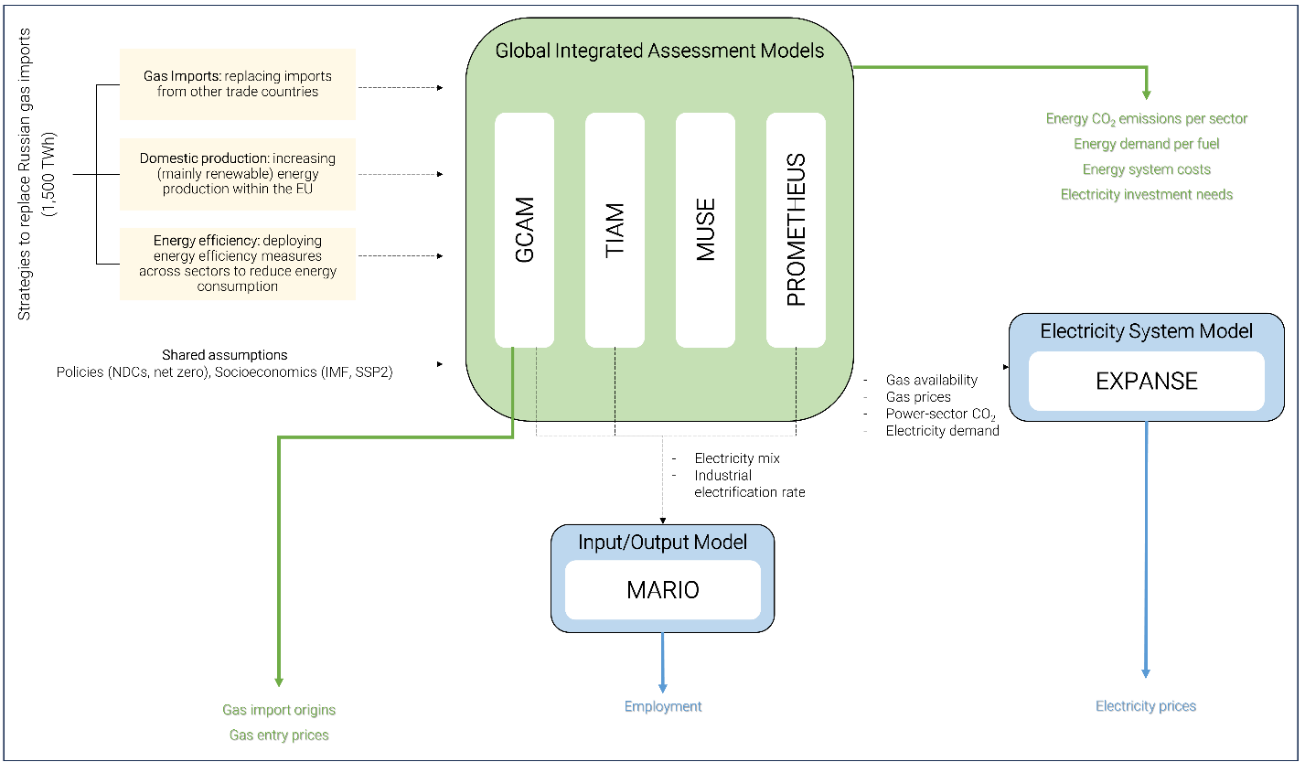

Figure 1: Methodological framework and information flow, including scenario design, model ensemble, and inputs and outputs of each model.

1.2.3 Scenario Design

We consider three strategies (scenarios) prescribing different 'corner' options for replacing the lost Russian gas. As the goal is to understand the implications of these three strategies in Europe (EU27 + UK), not only from an energy security and socioeconomic perspective in the near term, but also from a climate policy perspective in the longer term, we use 2050 as our time horizon, with the aim to comprehend any impacts on the EU's path to net zero.

The *Baseline* scenario, against which all other scenarios are benchmarked, reflects mitigation efforts implied by NDCs and long-term strategies on top of current policies. It is assumed to describe the climate policy context before Russia's invasion of Ukraine: we draw from the current climate targets and NDCs of all regions until 2030, and LTSs post-2030 and until 2050 (see [11] for more details). All pledges announced until COP26 in Glasgow are considered, including the revised NDC target of the EU, for which the *Baseline* scenario assumes that the bloc achieves its NDC target of at least 55% GHG emission reductions in 2030, relative to 1990 levels, as well as climate neutrality by 2050. Socioeconomic assumptions for GDP and population are drawn from October's 2022 short-term socioeconomic outlook of the IMF until 2027 [56] (extrapolated to 2050 according to the commonly used SSP2 socioeconomic pathway reflecting historic trends, see [57]) to account for the recent implications of the COVID-19 shock and recovery as well as the onset of the energy crisis—i.e., without reflecting Russia's invasion of Ukraine and associated policy responses. All scenarios prescribing ways to replace the lost Russian gas are benchmarked on top of this *Baseline* scenario.

The *Model-optimal* scenario allows the four IAMs to identify their own cost-optimal way of replacing these gas imports while still meeting the EU's climate targets for 2030 and 2050. To implement this scenario, Russian pipeline gas into Europe is completely switched off in 2023, but current policies, NDC targets for 2030, and net-zero targets for 2050 are retained.

The *Gas Imports* scenario assumes that the EU replaces Russian gas imports with energy—and primarily gas (both pipelines and LNG)—imports from other trading partners.This scenario explores the expectedly increasing

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pressure emerging in LNG and pipeline gas markets, to cover for the loss of Russian gas. Policy decisions to encourage this strategy include gas infrastructure developments and gas supply deals. It is noteworthy that many European countries have taken both approaches since the beginning of the energy crisis.

The *Domestic Production* scenario assumes that the EU replaces Russian gas imports with increased domestic energy production—notably via accelerated electrification, increased gas/hydrogen production, new infrastructure in domestic renewable/nuclear power options, etc.—without increasing imports from non-EU regions. Energy trade from other regions is assumed identical to *Baseline*. The EU could encourage this approach by providing additional funding for clean electricity and electrification of heat, transport, and industry, or through establishing higher and legally binding renewable energy targets—the European Parliament, European Commission and European member states reached a political agreement on 30 March 2023 on a target of 42.5% of the share of renewable energy in the EU's overall energy consumption by 2030.

The *Energy Efficiency* scenario assumes that the EU replaces Russian gas imports, essentially reducing gas demand with enhanced energy efficiency—including renovation, limited relocation of emissions-intensive trade-exposed (EITE) industries outside the EU, demand-side response, and behavioural changes. Stronger energy efficiency targets, improved building standards, and funding for retrofitting could spur energy efficiency improvements, for example.

A detailed summary of the protocol, based on which the scenarios are implemented across the four IAMs, is presented in the below **Table 2.**

Table 2: Scenario implementation across the four global IAMs

Scenario Name	Description	GCAM	TIAM	MUSE	PROMETHEUS
'Baseline'	No constraint on EU imports, situation as before the Russian invasion to Ukraine. Emissions are constrained by NDCs to 2030 and net zero to 2050.	See scenario protocol in van de Ven et al. (2023)[1], which is implemented across all four models.			
'Model-optimal'	No Russian gas imports from 2023 onwards. Models choose their "optimal" way to replace these gas imports. Emissions are constrained by NDCs to 2030 and NZ to 2050.	Russian pipeline gas into Europe is switched off completely in as early as 2023 without any constraint on the global LNG trade, but current policies, NDC targets for 2030, and net zero targets for 2050 are retained across all four models.			
'Gas Imports'	Lost Russian gas is replaced with imports from other sources/regions (pipelines and LNG). Emissions are	Immediate ban on Russian pipeline gas and flexibility to replace	Immediate ban on Russian pipeline gas imports and flexibility to	Immediate ban on Russian pipeline gas imports and flexibility to	Immediate ban on Russian gas pipeline imports and increased gas supply contracts from

[1] https://www.nature.com/articles/s41558-023-01661-0

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	constrained by NDCs to 2030 and NZ to 2050.	with imports from other trading partners, forcing increase in LNG and other regions' pipelines.	replace with imports from other trading partners (as domestic supply is not allowed to grow)	replace with imports from other trading partners (as domestic supply is not allowed to grow).	other regions (primarily LNG, and pipelines from N. Africa).
'Domestic Production'	Lost Russian gas is replaced with increased domestic energy production. Energy trade from other regions remains at 'Model-optimal' levels. Emissions are constrained by NDCs to 2030 and NZ to 2050.	Immediate ban on Russian pipeline gas imports, while fixing gas imports from other regions (and trade infrastructure) to '*Baseline*' levels and allowing to increase the production of gas or other sources (e.g., RES) within the EU, as well as to reduce demand.	Immediate ban on Russian pipeline gas imports, while fixing gas imports from other regions (and trade infrastructure) to '*Baseline*' levels and allowing to increase the production of gas or other sources (e.g., RES) within the EU, as well as to reduce demand.	Immediate ban on Russian pipeline gas imports, while fixing gas imports from other regions (and trade infrastructure) to '*Baseline*' levels and allowing to increase domestic supply within the EU.	Immediate ban on Russian pipeline gas imports, while fixing gas imports from other regions to '*Baseline*' levels and supporting electrification of end-uses via subsidies and higher uptake of electric vehicles, heat pumps, etc. powered primarily with RES electricity.
'Energy Efficiency'	Replace lost Russian gas with enhanced energy efficiency. Emissions are constrained by NDCs to 2030 and NZ to 2050.	Immediate ban on Russian pipeline gas imports, while fixing gas imports from other regions (and trade infrastructure) '*Baseline*' levels, while allowing more flexibility in building shell efficiency and setting a	Immediate ban on Russian pipeline gas imports, while fixing gas imports from other regions (and trade infrastructure) '*Baseline*' levels, while allowing more flexibility in building shell efficiency and setting a	N/A *(MUSE cannot implement the 'Energy Efficiency' scenario protocol, as final energy consumption cannot be constrained in the model.)*	Immediate ban on Russian pipeline gas imports, while fixing gas imports from other regions to '*Baseline*' levels and supporting energy efficiency in all end-use sectors with stringent building standards, funds for building retrofitting, support for

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		target on final energy demand equal to the amount of final energy in *'Baseline'* but subtracting the part that comes from Russian pipeline in that scenario.	target on final energy demand equal to the amount of final energy in *'Baseline'* but subtracting the part that comes from Russian pipeline in that scenario. Limited relocation outside the EU applies for EITE industries (% reduction in EU industrial production relative to GCAM's *'Baseline'*)		energy efficient technologies, behavioural changes. Limited relocation outside the EU applies for EITE industries (% reduction in EU industrial production relative to GCAM's *'Baseline'*)

1.3 Results

This section presents and discusses the resulting changes in energy supply and demand, including critical trade-offs, energy system costs, and diversification of import sources, documented in the modelling suite upon running each of the scenarios described in **Section 1.2.2**.

1.4 Clear trade-offs between supply- and demand-side energy CO_2 emissions

Overall EU fossil energy CO2 emissions do not vary across scenarios (1.4 to 2.3 $GtCO_2$ in 2030 and -0.4 to -0.03 $GtCO_2$ in 2050—i.e., an average decline of 8% per year over 2020-2050), since aggregated emissions in the EU are largely driven by the 2030 (-55%) and 2050 (net zero) targets rather than impacted by any response to the energy crisis. There are, however, observed differences in emissions in different sectors, most notably between residential/commercial and industry sectors, depending on how Russian gas is substituted in each strategy (**Figure 2a**).

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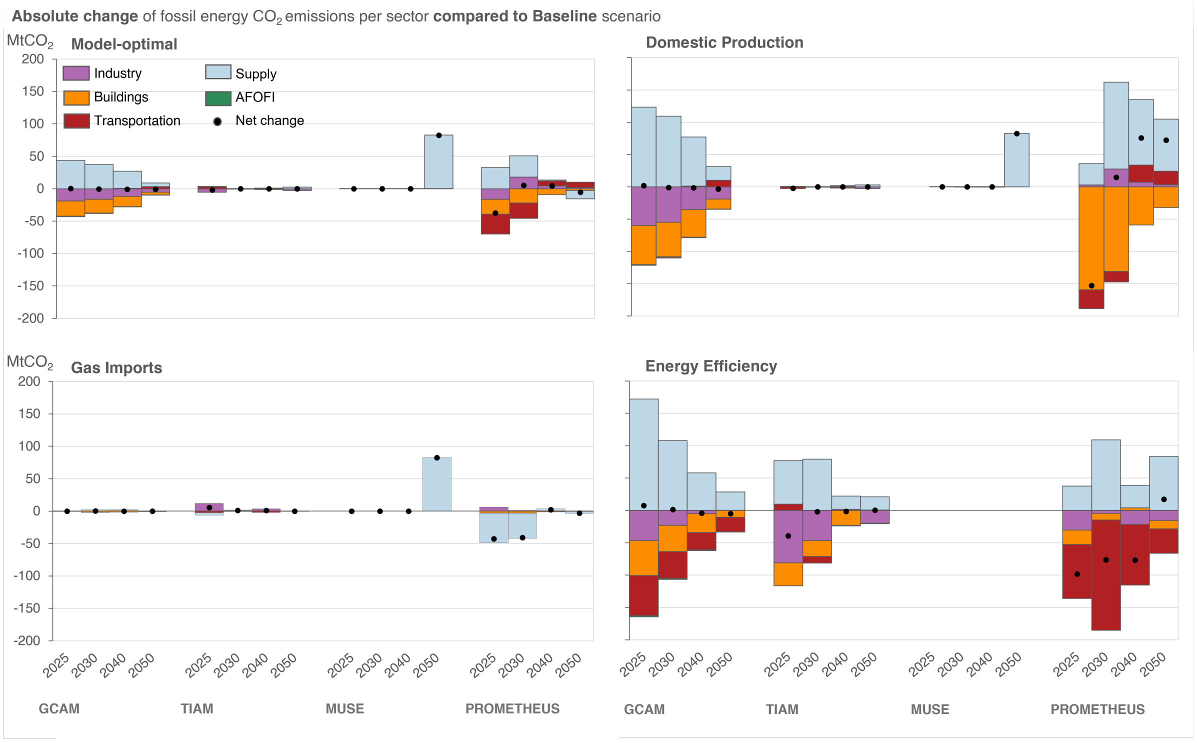
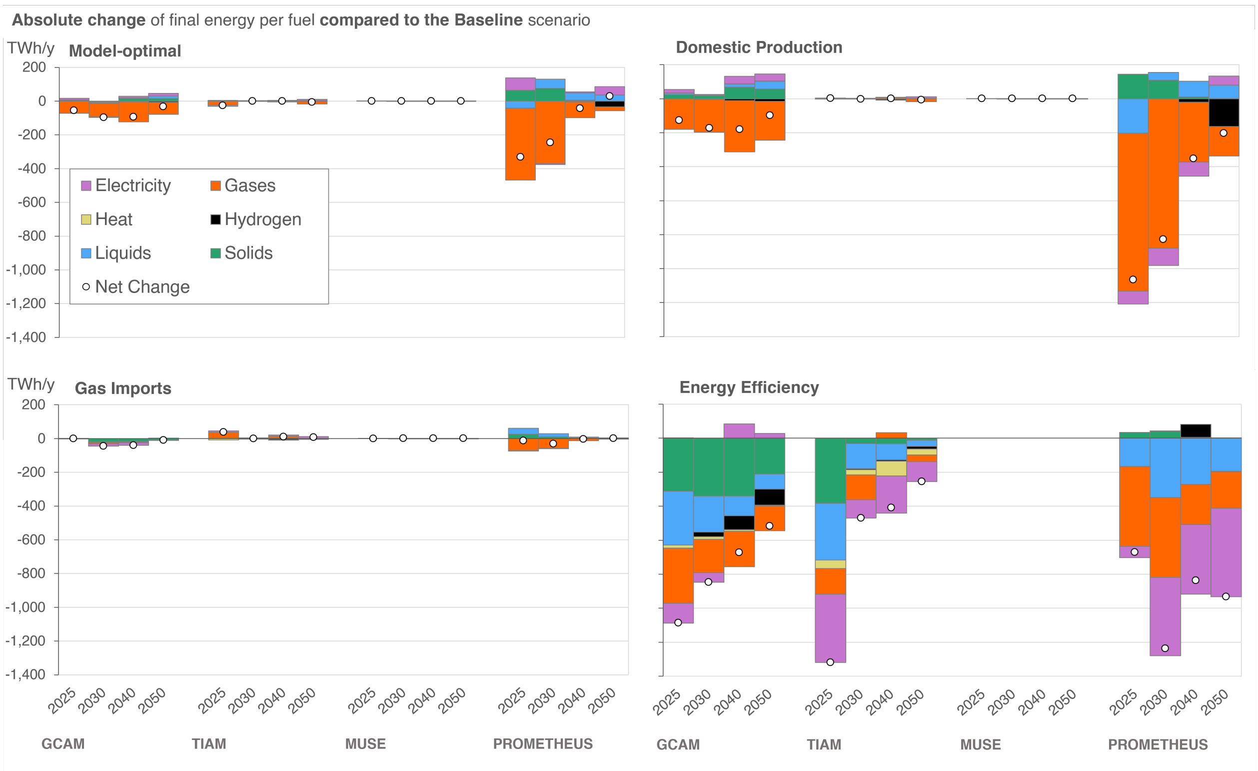


(a)



(b)

Figure 2: Absolute changes across the four IAMs and across scenarios compared to Baseline (2025-2050), in terms of (a) fossil energy CO_2 emissions, and (b) final energy per fuel. AFOFI includes emissions from fossil fuel combustion in the agriculture, fisheries, and forestry sectors. MUSE cannot implement the 'Energy Efficiency' scenario protocol, as final energy consumption cannot be constrained in the model.

Results show greatest emissions cuts in the Energy Efficiency scenario on top of the Baseline in all energy end-

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use sectors, due to reduced overall energy use with energy savings and efficiency measures deployed sooner and deeper, alongside relocation of EITE industries outside the EU. Moderate emissions cuts are also observed in the Domestic Production scenario, where GCAM & PROMETHEUS agree that these cuts mainly happen in the residential and commercial sectors, critically as in this scenario gas is being displaced by electricity (which can be easier produced within the EU). The building sector is the most sensitive to such a switch, as enhanced competitiveness of heat pumps notably enables their increased uptake. In contrast, the Gas Imports strategy would achieve negligible emissions deviations from the Baseline—from very low emissions cuts to increases even, across model range—as Russian gas would be substituted by other forms and sources of imported pipeline or liquefied gas, at best slightly changing demand levels caused by higher gas import costs. In this case, a small uptick in industrial emissions can be expected as coal and/or oil would replace part of the more expensive gas.

Overall, across most IAMs and strategies, there is consensus that supply-side energy-related CO_2 emissions would increase within any response to the energy supply crisis, as the EU is poised to enable all readily available fossil-fuel levers (e.g., decommissioned coal plants) to make up for the critical amounts of gas that was until recently imported from Russia; that contrasts with projected CO_2 emissions reductions in the end-use sectors, where residential and commercial emissions would drop due to the gas-to-electrification shift, especially since coal and oil use in the EU are in long-term decline in these sectors and there exist limited prospects for EU consumers to return to coal and oil use in buildings. This observed trade-off between demand- and supply-side CO_2 emissions when substituting Russian gas, to be in line with the 2030 and 2050 targets, hints at the need to reconsider the EU's sectoral pathways to carbon neutrality in the light of the Russia-Ukraine conflict.

Model variance points to the diverse representation of certain technologies in each model. Technology-richer models cover a wider set of energy efficiency measures and technologies, thereby better exploring the potential of energy efficiency in the building and industrial sectors; notably, in PROMETHEUS, emissions cuts are projected to continue until 2050 since technology push is assumed to continue post-2030, reducing total gas consumption and the need for gas imports in the EU.

Little variations on the model outputs are obtained with the MUSE model compared to other models. In MUSE, changes of the energy system in the EU are driven by the imposed emission trajectory, which is common across the scenarios. Gas supply strategies, which differ across the scenarios, induce smaller price-induced effects compared to the carbon price set through the emission strategy. The gas supply strategies induce different consequences on prices on the basis of techno-economic assumptions about domestic supply and import technologies, which were not harmonised across the models.

1.5 Consistently decreased energy demand in any response to the Russian gas import ban

Energy demand reduction requirements are primarily subject to the 2018 recast of the Energy Efficiency Directive, which entails a target of 846 Mtoe of final energy demand across the EU-27 by 2030 [58]. Critically, though, demand reduction played a critical role as a first-level response to the energy crisis [38]: the European Council introduced a voluntary 15% gas demand reduction target (compared to the average of the previous five years) in August 2022, which was extended in March 2023 to last for an additional year [59]. An emergency regulation was also introduced in October 2022 that inter alia set electricity demand reduction targets between December 2022 and March 2023 [60].

In our study, the calculated 2025-2050 final energy evolution varies, but we mostly project a decrease in final energy demand compared to the *Baseline* scenario (**Figure 2b**). The highest demand reductions are observed in the *Energy Efficiency* scenario, ranging in 2030 from -11% to -4% and in 2050 from -5% to -2% compared to the *Baseline*, mainly driven by reductions of demand for electricity, gases, and liquids.

To a lesser extent, this is also the case for the *Domestic Production* scenario, where reductions range from -5% to -1% in 2030, and from -2% to -1% in 2050, compared to the *Baseline* scenario. Finally, the *Gas Imports* scenario overall displays only a minor effect in end-use demand, as Russian gas is almost entirely substituted by

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liquefied and pipeline gas from trade partners outside Russia; nonetheless, even in this case, the technology-richer PROMETHEUS model foresees demand cuts due to slight increases in gas import costs, implying there exists high potential for demand-side reductions as well as potential benefits through learning-by-doing and learning-by-research, which is only endogenously available in this model among the ensemble.

1.5.1 Higher energy-system costs, unevenly distributed electricity price changes across the EU, but positive implications for electricity-sector employment

When it comes to energy-system costs, which can only be directly extracted from two models in the ensemble, expectedly the *Model-optimal* pathway is cheaper than all other 'corner' options, as it is by definition calculated to minimise system costs (**Figure 3a**). We also see that the costs of the *Domestic Production* pathway are consistently moderate; in TIAM costs are higher in the *Energy Efficiency* scenario in the short term but become the lowest in the long run, while in PROMETHEUS costs are consistently higher in the *Gas Imports* scenario due to higher cost of imported fuels from regions outside Russia. This traces to model dynamics and the role that the two models envisage for natural gas in their *Baseline* scenarios: in TIAM, gas would more radically phase out post-2030, meaning there is considerable need to invest in energy efficient technologies to offset the loss of Russian gas imports until then. Nonetheless, both IAMs agree that the *Energy Efficiency* strategy eventually becomes the cheapest among the three 'corner' options after 2030, while also pushing carbon prices lower in both models.

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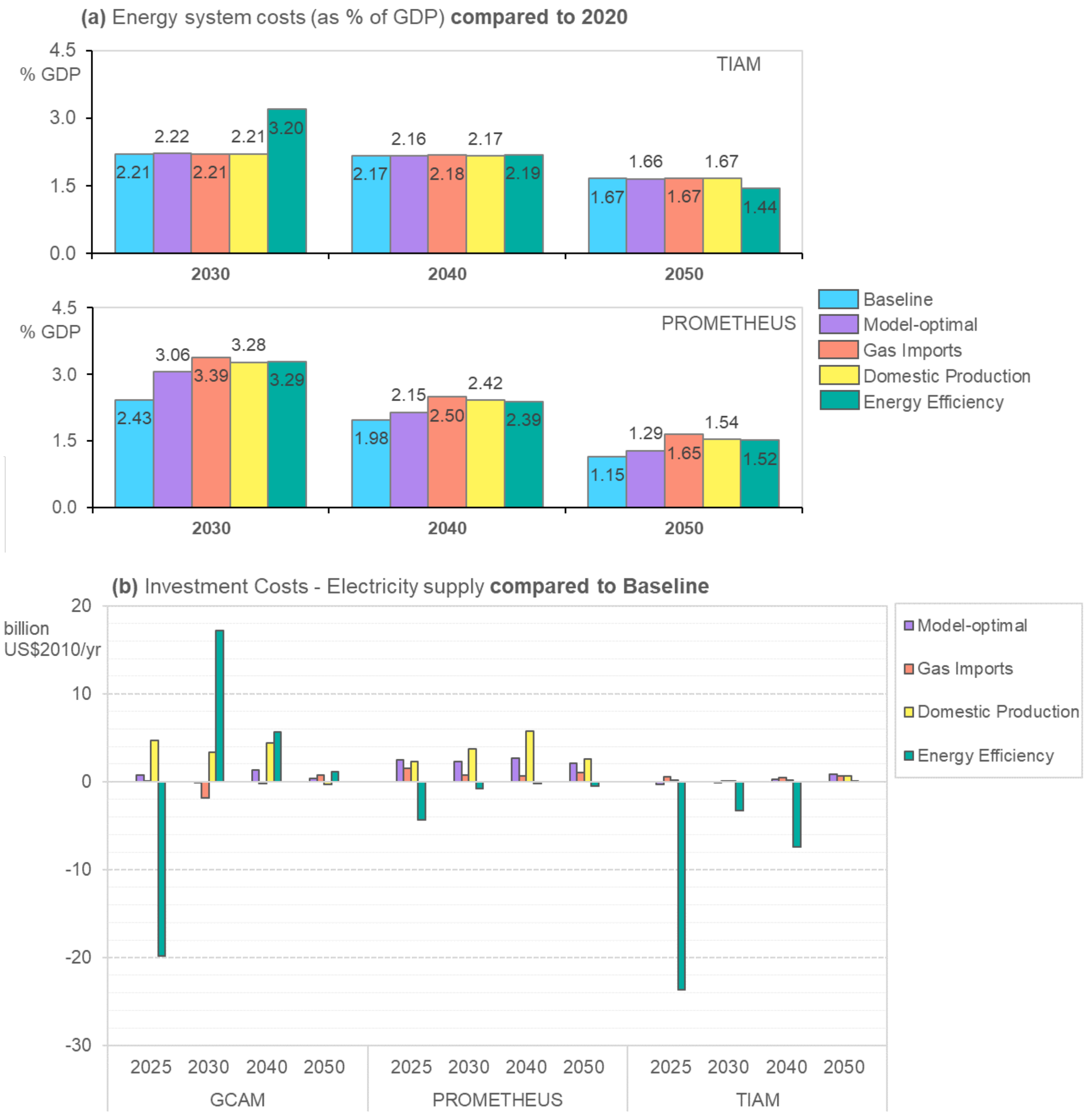

Figure 3: Energy system and electricity investment costs. (a) Energy system costs (as % of EU GDP), as a % change compared to 2020 in TIAM and PROMETHEUS (data not available for GCAM and MUSE). (b) EU electricity supply annual investment costs (in billion US$/2010) compared to Baseline (2025 – 2050) in GCAM, PROMETHEUS, and TIAM (data not available from MUSE).

As industry, transport, and heating are increasingly electrified, the electricity system will become the backbone of Europe's decarbonised energy system. The electricity-sector investments necessary (**Figure 3b**) to simultaneously decarbonise and meet increasing electricity demand are thus considerable, while renewable energy capacity and the associated clean technology infrastructure needed to complement it must be deployed at significant scale. Our analysis consistently points to high annual investment costs for electricity supply in the *Domestic Production* case, due to the investments required for ramping up domestic energy supply to make up for lost Russian pipeline gas (e.g., renewable electricity used for heat pumps and electric vehicles accompanied by storage)—although this effect is less pronounced in TIAM. It also points to lower investments in electricity supply in the *Energy Efficiency* strategy, due to overall decreased demands, although one model (GCAM) projects

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a trend reversal towards the end of this decade, owing to increased electrification to satisfy end-use demands with reduced energy quantity; in particular, GCAM reduces electricity supply in 2025 because the large final energy demand constraint-related "shock" causes a strong decline in final demand for energy services (similar to TIAM's response) that also comes down to less electricity use but, in subsequent periods, the persistent constraint to final energy supply stimulates electrification of final demand sectors, increasing electricity demand to above baseline levels. These increased costs could potentially be lowered, by improving sector coupling and integration [61], for example with the use of district energy that could considerably boost energy efficiency in the European energy system [62].

These investment cost changes are also reflected in the projected electricity prices (**Figure 4** for 2035), obtained from the EXPANSE electricity system model, soft-linked with the scenario results of the four IAMs (see **Section 1.2.1**). Average electricity prices in the middle of the next decade are projected to be lowest in the *Energy Efficiency* scenario, as improving efficiency leads to the lowest electricity demand, investment costs, and hence electricity prices (as low as 20-30 EUR/MWh in Scandinavian countries and Ireland). Conversely, increasing domestic production and importing gas from elsewhere can both lead to high electricity prices (as high as 60-120 EUR/MWh in the east, in 2035). Again, GCAM shows opposite, albeit more moderate, trends due to increased electricity demand.

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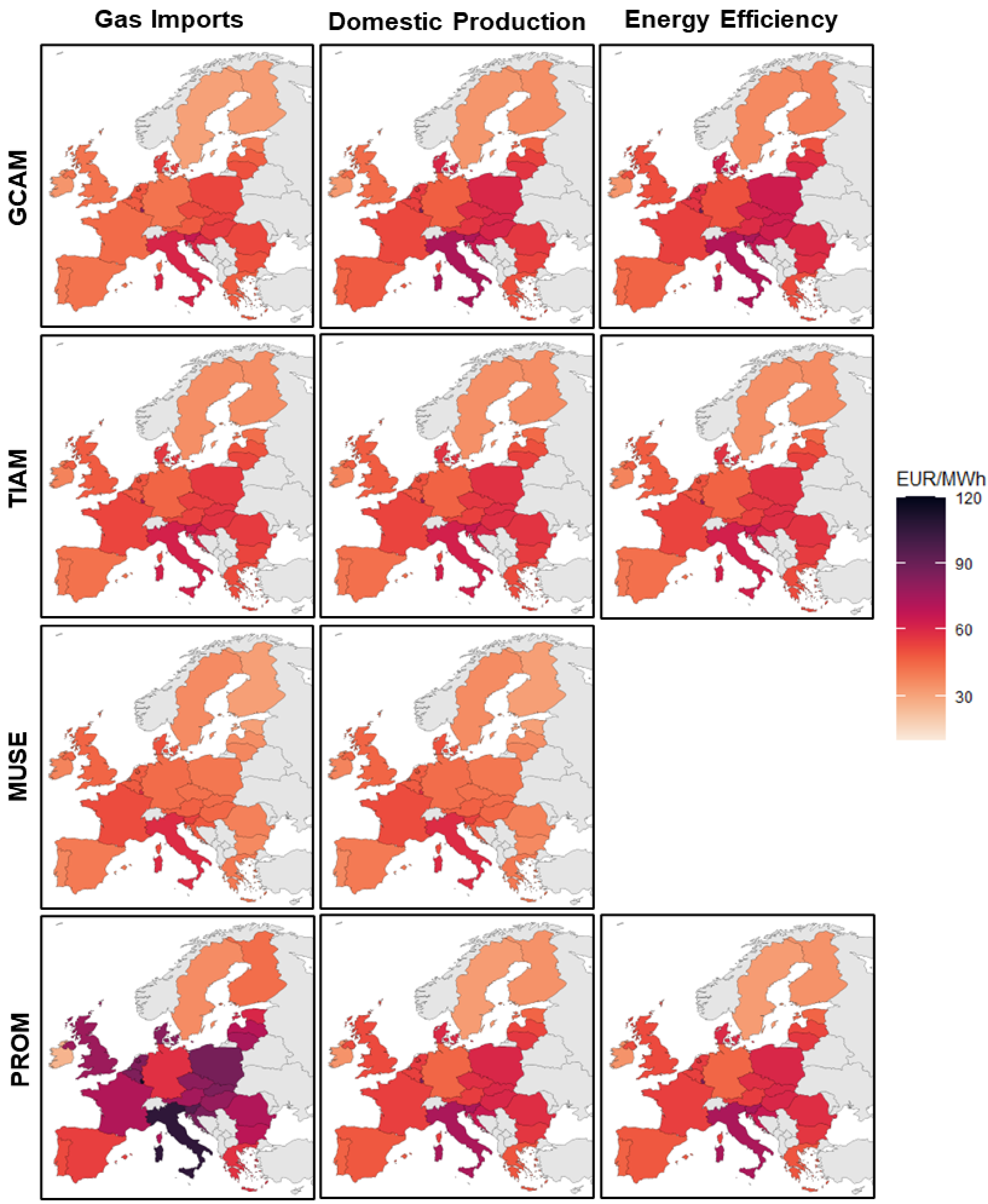

Figure 4: Average electricity prices across European countries, across scenarios, and across IAMs, for the year 2035. Source: EXPANSE, using inputs from the global IAMs. MUSE cannot implement the 'Energy Efficiency' scenario protocol, as final energy consumption cannot be constrained in the model.

Critically, southern Europe seems to be the most vulnerable to electricity price spikes: Italy appears to be the country facing the highest electricity price spikes, due to its relatively higher reliance on gas imports, followed by eastern countries.

We also perform a deeper dive into the electricity system across our model ensemble. A snapshot for the same year (2035), illustrated in **Figure 5**, shows that PROMETHEUS sees highest renewable electricity generation in the *Gas Imports* scenario, along with increased (hydrogen) storage capacity, grid expansion, intermittent

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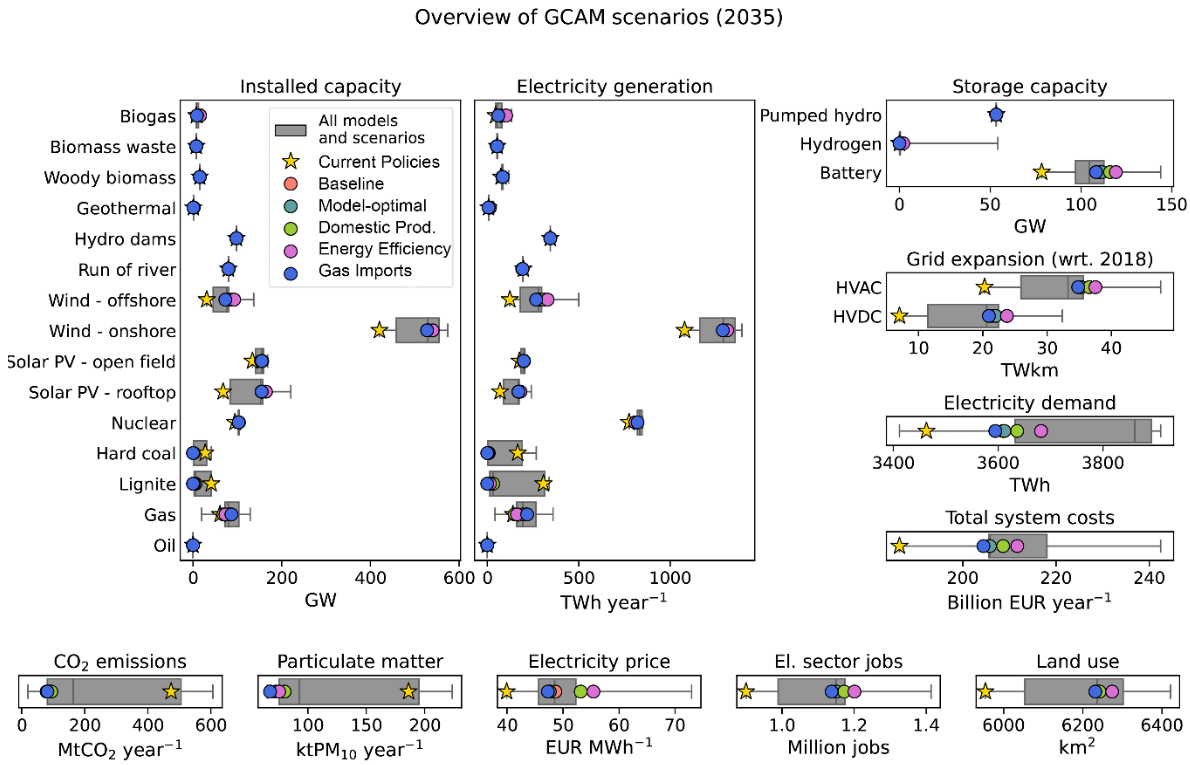
renewable energy capacity, and prices in that scenario (as opposed to *Energy Efficiency*). Conversely, GCAM sees maximum RES electricity generation, grid expansion, and battery storage capacity in the *Energy Efficiency* Scenario. In TIAM & MUSE there is less variation in electricity-system configuration across scenarios, with TIAM however projecting the highest (battery) storage capacity, grid expansion, and RES capacity in the *Domestic Production* strategy. These trends are also evident in electricity-system costs since, in the case Russian gas is substituted by gas imports from other sources, the low electricity demand in TIAM and PROMETHEUS also implies less capital and operational expenditure compared to a strategy promoting energy efficiency uptake—as opposed to GCAM that shows reverse cost trends, with the *Energy Efficiency* strategy requiring the highest capital electricity system costs.



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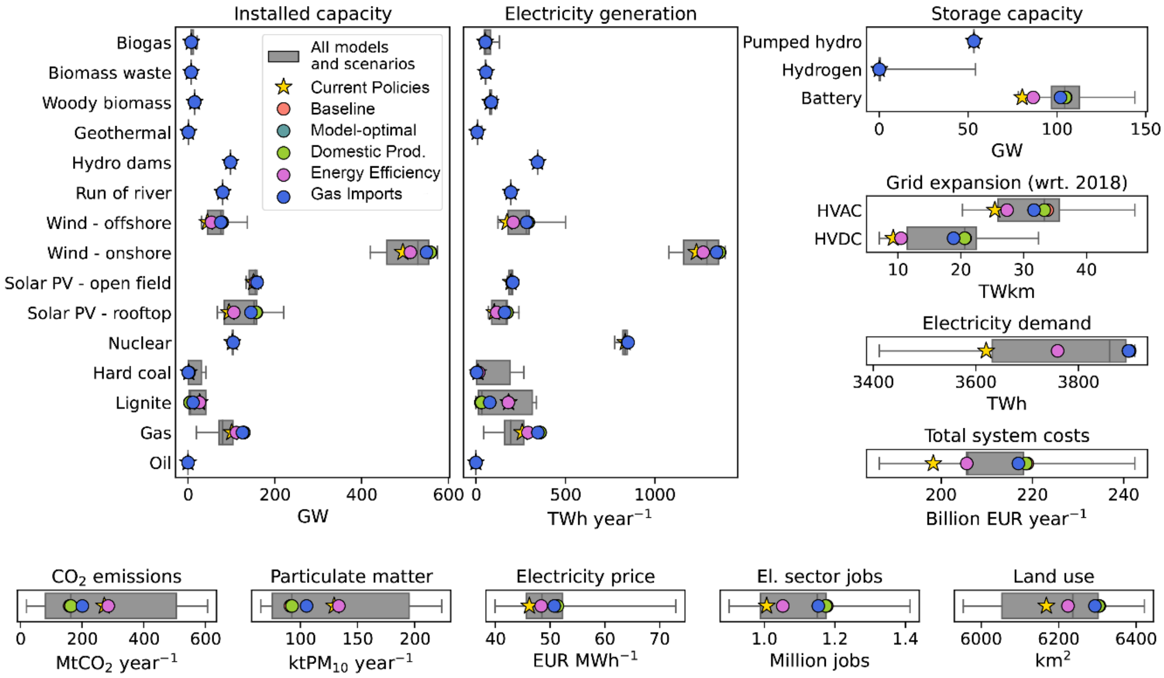
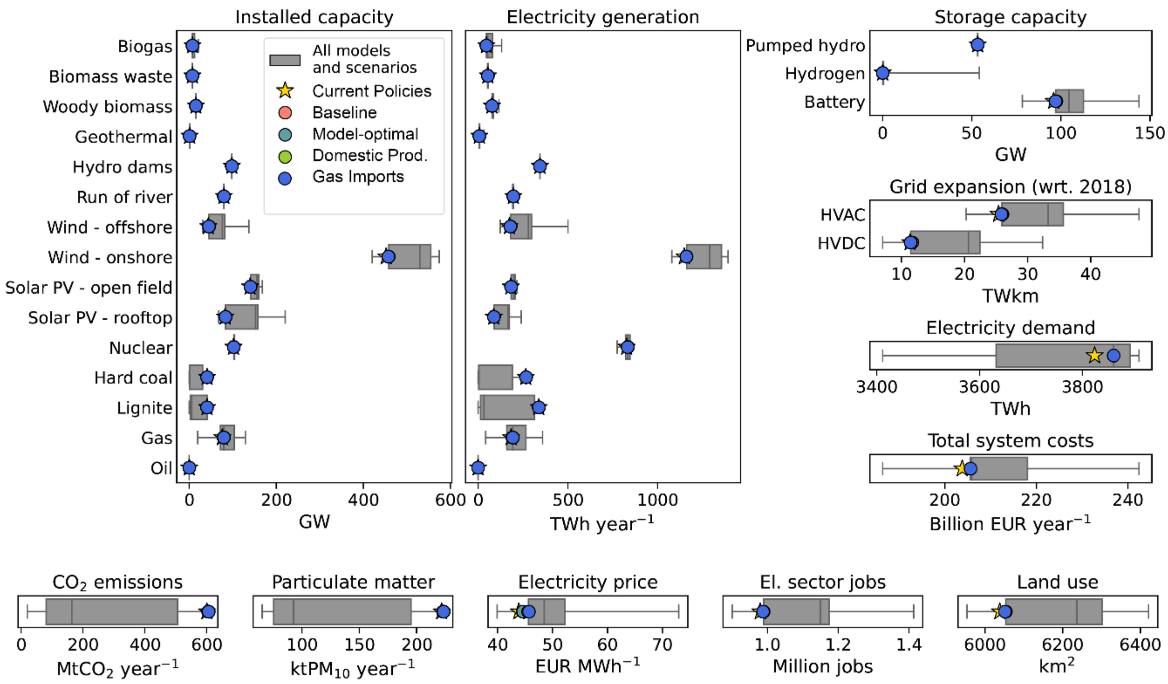
Overview of TIAM scenarios (2035)



Overview of MUSE scenarios (2035)



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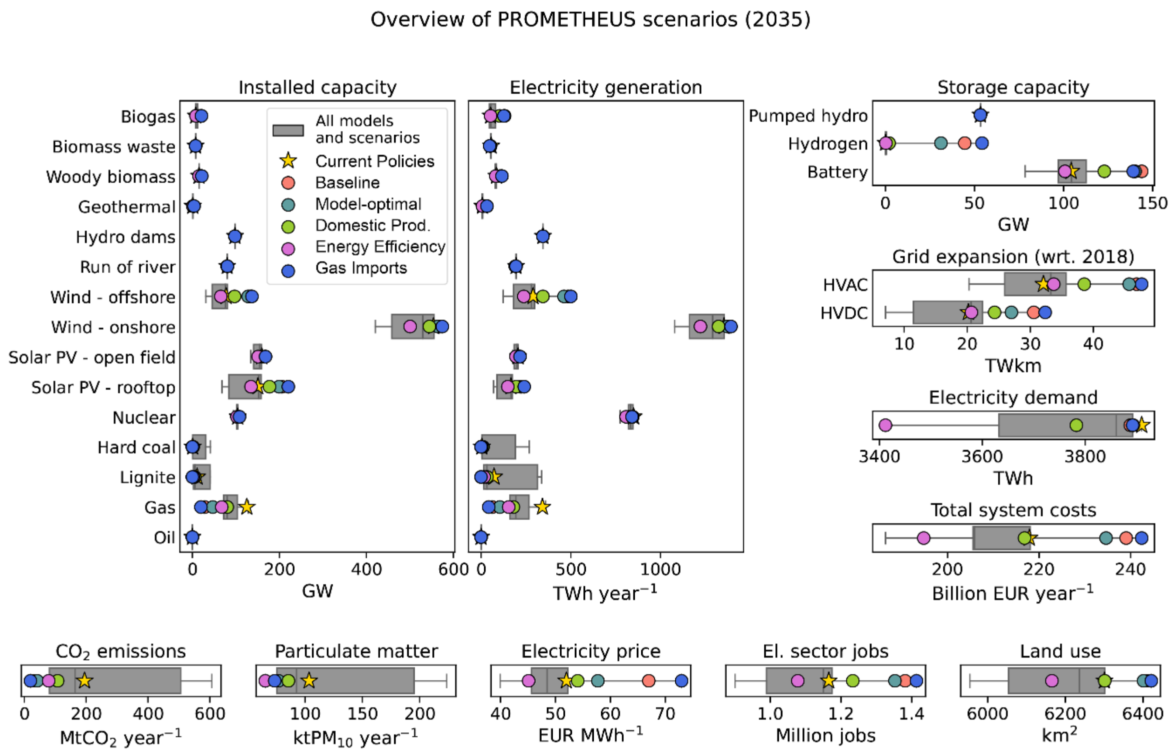

Figure 5: Overview of EXPANSE model results (2035) based on results of the four global IAMs; these include installed capacity, electricity generation, storage capacity, grid expansion, electricity demand, total system costs, CO_2 and PM emissions, electricity price, power-sector jobs, and land use changes.

We finally provide insights into employment impacts by sector, using MARIO (**Figure 6**), soft-linked with the scenario results of the four IAMs (see **Section 1.2.1**). Mining and quarrying essentially constitute the only sector experiencing employment losses—naturally as they encompass fossil fuel extraction activities. The electricity-sector structural differences lead to diverging insights into power-sector employment between GCAM on the one hand and TIAM and PROMETHEUS on the other, driven also by different labour intensity for each technology. Power-sector employment shows more than a 1.5-fold increase in the *Energy Efficiency* scenario by 2050 in GCAM, while PROMETHEUS and TIAM showcase a mid-term employment decrease across all scenarios, in fact with a steeper decline (followed by a post-2040 increase) in the *Energy Efficiency* scenario owing to the high decrease in investments in the sector as a short-term response. Nonetheless, we project an overall positive impact on electricity-sector employment in the long term, also considering the decrease in fossil-dominated sectors and the relative higher labour intensity of renewable energy technologies compared to fossil fuels [63–65]. It should be noted that sectors outside power are not considered in this analysis, despite expected implications (e.g., in the construction sector).

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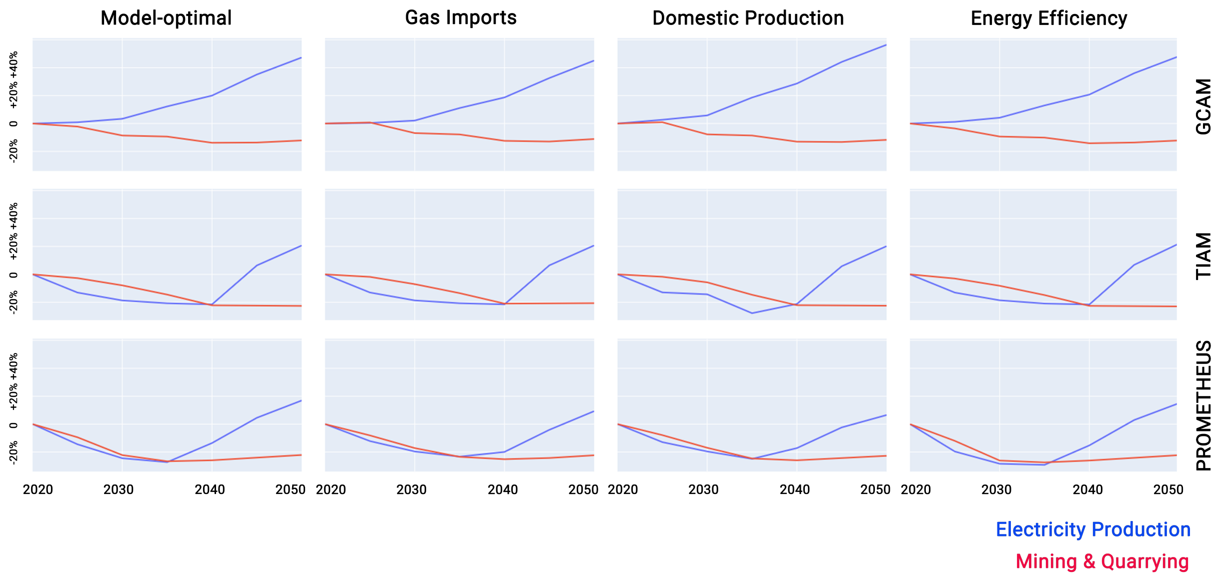

Figure 6: Employment by sector and region (variation from Baseline). Employed population in electricity production and mining & quarrying sectors compared to Baseline in the EU (2020 – 2050) in GCAM, TIAM, and PROMETHEUS. Source: MARIO, using inputs from the global IAMs.

1.5.2 Diversifying import sources reduces gas prices but fosters a new gas trade landscape in Europe

The envisaged role of gas in Europe's energy system in the transition to net zero has been fundamentally changed in response to the recent energy crisis. Here, we focus on the *Gas Imports* scenario and the GCAM model, as it features increased granularity for the bloc's gas pipelines and routes (see **Section 1.2.1** for regional disaggregation). Despite direct substitution of gas from other sources, the EU is on track to reducing its net gas imports by almost 40% in 2030, compared to 2020. In most regions, the remaining gas imports may be provided either by European pipeline gas (predominantly from Norway) or LNG, up by 28.5% and 33.3% EU-wide in 2030 compared to 2020, respectively. An exception here would be southwestern Europe, where pipeline gas from Africa (Algeria and Libya) covers 30% of gas imports, resulting in EU-wide imports from those regions doubling by 2030. Demand for LNG would also increase in all regions, with considerably higher imports in the central and eastern member states (see **Figure 7**).

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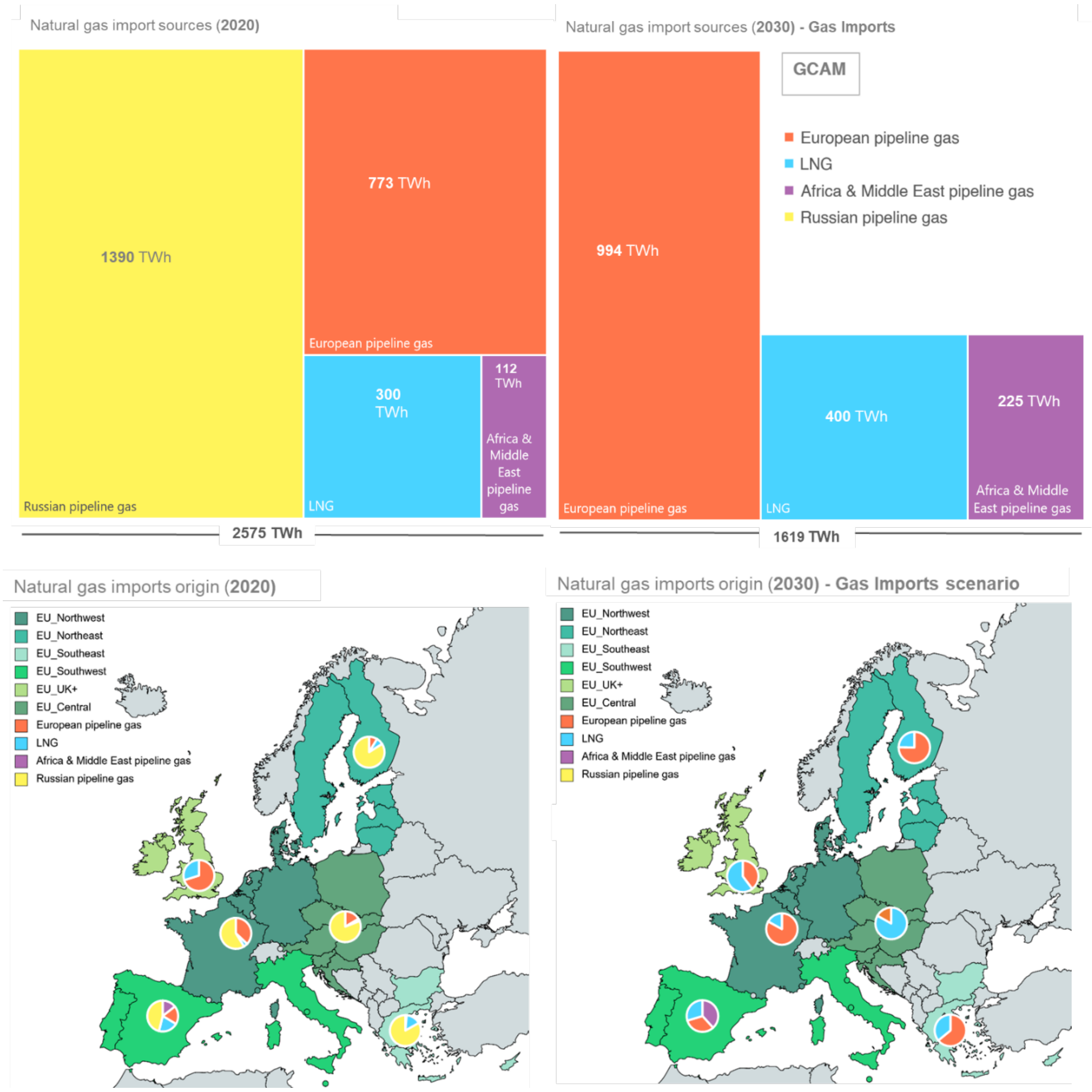

Figure 7: Natural gas imports in 2020/2030 for the Gas Imports scenario. Gas import sources are displayed on top, while the regional disaggregation is displayed on the bottom. Only GCAM results are available. See Section 1.2.1 for regional disaggregation in the GCAM model.

Average natural gas (entry) prices across scenarios are shown in **Figure 8**, alongside the % change compared to the *Baseline*: the *Domestic Production* strategy would lead to the highest gas prices until 2050, owing to reduced supply based on the cap on imports and reflecting the stronger burden to replace Russian gas with domestic energy production; the *Model-optimal* and *Energy Efficiency* scenarios would arrive at similar mid-range prices; whereas the *Gas Imports* scenario would instead lead to the lowest prices, even lower than the *Baseline,* through diversification of import sources. The regional disaggregation of price difference for the mid-range *Model-optimal* scenario is also shown in **Figure 8**: in general, regions with the highest Russian gas imports in 2020/2021, low LNG capacity, and insufficient storage capacity are the most vulnerable to higher gas price spikes [66]. Modelling results suggest that the highest gas price differences in 2030 compared to the *Baseline* are observed in Finland, Sweden, and Baltic countries, followed by Central Europe, Poland, then Northwest and Southeast EU, and finally Southwest EU.

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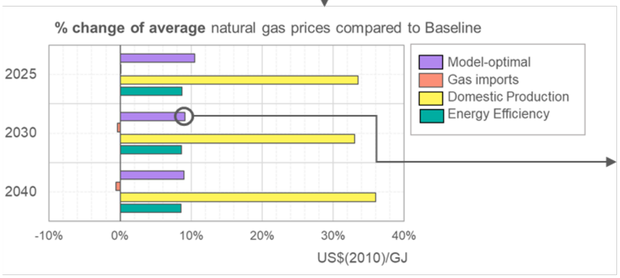
Scenarios	Average natural gas price (US$(2010)/GJ)			
	2020	2025	2030	2040
Baseline	6.13	5.90	5.72	5.57
Model-optimal	6.13	6.51	6.24	6.07
Gas Imports	6.13	5.90	5.69	5.54
Domestic Production	6.13	7.87	7.61	7.58
Energy Efficiency	6.13	6.41	6.21	6.05



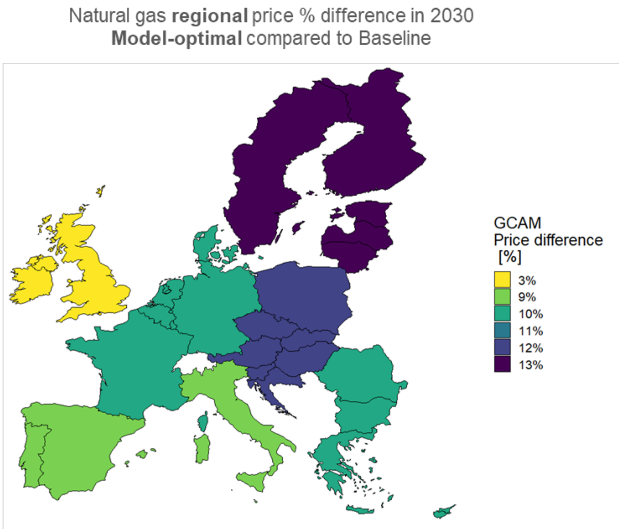


Figure 8: Natural gas prices. Average natural gas entry price (USD2010/GJ) in the years 2020, 2025, 2030, and 2040, across all scenarios (top left), as well as % change of average gas prices compared to Baseline (bottom left); regional price increase in the Model-optimal scenario for 2030 (right). Only GCAM results are available. See Section 1.2.1 for regional disaggregation in the GCAM model.

1.6 Discussion and Conclusions

Our results suggest that entirely replacing Russian pipeline gas with gas imports from other sources, such as LNG from the USA or pipeline gas from North Africa and Norway, misses an opportunity to accelerate decarbonisation of the European economy, especially in energy end-use sectors. In contrast, increasing the use of domestic resources (outside gas) and—especially—investing in energy efficiency would mitigate demand and enable reinforcing emissions reductions in certain sectors. Unlike other studies [41], the projected overall EU's emissions pathway is mainly driven by 2030 and 2050 climate targets and thus relatively unimpacted by any response [42]. Positive environmental implications of any of the three 'corner' options would thus be observed on the demand side, as low-carbon energy outcompetes fossil fuels in end-use sectors, with supply-side energy-related CO_2 emissions instead growing to make up for the lost Russia-imported supply. This diversity in sectoral emissions responses is partly reflected in the different ways member states addressed the energy supply crisis in the short term. For example, much like the EU overall [67], Germany and Poland both saw lower GHG emissions in 2022, with Germany achieving greater industrial and household energy demand cuts than coal use spikes and Poland boosting renewable power generation to a record while cutting both gas and coal consumption; Spain, on the other hand, saw its gas and coal use for electricity radically increase, leading to a ~7% increase in GHG emissions compared to 2021 [68]. As a long-term strategy, substituting Russian gas by gas of different origin ('Gas Imports') critically risks locking Europe into fossil-fuel dependency and carbon-intensive infrastructure (e.g., LNG import terminals), when alternative approaches are feasible. It would also see minimal reductions in demand for energy carriers, compared to all other options.

The challenge of balancing the need to resolve the short-term energy supply-demand mismatch with the long-term aims of a cost-optimal and just energy transition are highlighted in our results, which point to similar-to-higher energy-system costs should Russian gas imports be replaced by gas trade with other countries. Insistence on gas, alongside higher costs of imported fuels as well as reduced security of supply—and increased vulnerability to international price changes—could also plausibly affect electricity-system costs and, correspondingly, prices for end-users. Given these potentially higher system costs, also driven by short-term fossil-fuel infrastructure needs [21], there is evident conflict with the long-term goals of decarbonisation and energy security, risking creating sizeable, stranded assets in the fossil-fuel sector—e.g., in LNG infrastructure, as much as half of which may be obsolete by the end of this decade [25]. Nonetheless, it would also entail the lowest gas price uptick in the near term among all 'corner' options, due to the relatively increased availability of gas, making it perhaps an attractive

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proposition from a political perspective as end-use heating costs for consumers might be lower; besides, along the transition by 2050, gas prices may affect not only heating costs for end users but also the overall evolution of the heating sector [69]. On the other hand, despite displaying moderate energy-system costs, increasing energy production within the EU using all domestically available levers to make up for the 1,500 TWh of lost Russian gas, is projected to require the costliest investments (especially in electricity supply and storage) and thus feature high annual costs for power supply, in turn pushing electricity prices up, as the costs of meeting the higher demand for electricity must be ultimately recovered from consumers. Our results imply that whichever approach Europe takes to respond to the crisis may mostly not (according to TIAM), or even negatively (according to PROMETHEUS), impact total energy-system costs: results from the model showing the most pronounced effects (PROMETHEUS) suggest an increase in costs of 26-40% in 2030 and 12-32% in 2050, across scenarios. A study by Pedersen et al. [40] showed similar findings in the near-term and more pronounced impacts by mid-century: about +30% and +5% in 2030 and 2050, respectively, for a 2°C-aligned pathway, whereas zero impacts in a 1.5°C-consistent trajectory. It should be noted, however, that our pathways are calculated on top of actual policies and pledges rather than regional carbon budgets consistent with global temperature goals. Increased sector-coupling—including electricity for heating in district energy and thermal storage—could help mitigate these effects of increased system costs by providing alternatives to expensive electricity supply and storage. We acknowledge that such opportunities are not considered in detail in our study, although we note that European energy system transition pathways considering extensive sector coupling and synergetic effects across energy grids have been explored in the recent literature (e.g., [61]). Responding to a structural loss in gas supply by reducing demand for energy would yield the highest cuts in energy use and emissions on top of the *Baseline* (notably among the technology-richer models with a diverse range of energy efficiency options) and the lowest energy-system costs in the long term. The International Energy Agency had, early in the crisis, released a report outlining several such instruments that could enable such a strategy [70], featuring both technological solutions and lifestyle changes. Consistently across all models, this strategy would also see the lowest electricity-sector investment costs, on the order of tens of millions of euros per year, as well as the lowest electricity price spikes in the long term in most models, emphasising that policy measures incentivising energy efficiency can mitigate the costs of the energy transition, increase EU system resilience and security of energy supply, and enable positive impacts on overall energy-sector employment. Despite its numerous advantages, however, this 'corner' option also comes with notable risks. For example, emissions reductions in the models were achieved in part through the relocation of energy-intensive industries, which is of paramount concern to European policymakers. There is also the issue of potential rebound effects in the longer run, in relation to both emissions and investment needs [71]. As energy efficiency measures are deployed and delivering the same energy services with less energy becomes possible, the demand for those services may increase, wiping out the gains from efficiency and in fact negating the return on associated investments.

Focussing on the bloc's most pressing concern [72] of addressing gas price spikes and reducing natural gas demand, a strategy replacing lost Russian gas with domestic, predominantly renewable energy resources would lead to the fastest decline of natural gas in the European economy, while even diversifying gas import sources is in line with a 40% reduction of gas imports by 2030. In the latter case, although LNG demand would increase across the EU, the bloc would benefit more from additional European pipeline gas (primarily from Norway, acknowledging however the challenges Norway faced in ramping up production to make up for lost Russian gas in 2022) as well as pipeline imports from North Africa and Turkey, than it would from additional LNG imports (a moderate +100 TWh by the end of the decade); this is in complementary to other studies suggesting higher LNG needs [22,70], of which the focus has been on mitigating gas shortage in the short term while leveraging all possible options rather than 'corner' long-term (equilibrium) solutions. In 2021, EU's natural gas import dependency rate was 83% (estimated as the ratio of imported natural gas to gas primary energy); in 2030 and across scenarios, this rate is projected to decrease to 58-69% (averaged values across models), compared to 73% in the *Baseline* scenario[2]. Our study also suggests that gas consumption is bound to decrease overall (up to

[2] Gas import (and price) deviations from the baseline are affected by technoeconomic assumptions on costs and resource availability (partly harmonised across models), as opposed to increasing imports. However, some overall trends can be extracted across IAMs, while a reduction in natural gas imports over time can be observed as an effect of the fossil fuel phase-out, justified by decarbonisation efforts.

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-11% in 2030) compared to the *Baseline*, although this effect is not as pronounced as a previous study—comparing against a similar baseline, albeit based on a single model of different economic theory—where gas consumption could drop by up to 25% [42]. As far as natural gas prices are concerned, we find notable discrepancies across the EU and critically across scenarios, with the highest prices observed for a strategy prioritising domestic energy production to replace the lost gas rather than trading with other countries. Even the models' cost-optimal approach—i.e., without prescribing a 'corner' response to the crisis—finds such regional discrepancies, with the southern and Atlantic regions seeing lower gas prices than the northern regions by 2030, as countries previously dependent on Russian gas imports but with low LNG capacity are susceptible to gas price volatility going forward. Understanding such distributional effects of the new energy landscape in Europe is critical if EU energy and climate policymaking is to obtain sufficient buy-in from member states to achieve the Union's decarbonisation ambitions together with enhanced energy security and resilience.

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2. First policy response mechanism

A principal component of IAM COMPACT is to enable stakeholders to co-define policy questions and other parts of the scientific course within its modelling process. The core component of the stakeholder engagement strategy revolves around the policy response mechanism (PRM), a structured format for engagement between project partners and stakeholders to ensure policy relevance, share knowledge and enhance trust between modellers and stakeholders, as well as provide direct inputs to IAM COMPACT and co-create the research process, incorporating political and societal realities into our modelling[3].

IAM COMPACT uses the broad definition of a stakeholder from the Intergovernmental Panel on Climate Change (IPCC): "a person or an organisation that has a legitimate interest in a project or entity or would be affected by a particular action or policy" [73].

2.1 Stakeholders' engagement mechanism

Stakeholders in IAM COMPACT are aggregated into separate groups.

- *Policy steering groups.* These groups are made up of 3-5 policymakers. Within the EU, each *policy steering group* focuses on specific themes (e.g., industrial relocation, electricity system, hydrogen). The list of themes is discussed and agreed upon within the consortium before the selection of stakeholders. A key responsibility of the *policy steering groups* is to guide the initial scoping of the policy questions.
- *Core working groups (CWG)*. These groups comprise 10-20 stakeholders from policy, industry, academia, and civil society; these will also be country-specific when operating outside of the EU and theme-specific within the EU. There will be one *core working group* per *policy steering group*. The stakeholders for the *CWGs* will be selected by the consortium to represent a diverse set of relevant views from the EU and non-EU countries (especially our pilot countries), as well as represent relevant industrial sectors and civil society groups. The *CWGs* will co-create, with the modelling teams, the research process throughout the project. They will be involved in refining and adding to the initial policy questions, co-creating the scenario logic, and discussing the modelling results.

A set of themes within the EU and the regions outside the EU were agreed upon within the consortium before stakeholders were identified. The regions encompassed our pilot countries as well as major emitters, namely Ukraine, India & Sri Lanka, Kenya & Ethiopia, USA, and Mainland China. Regarding themes, the aim was to have a broad coverage and capture a range of issues, but also remain sufficiently selective to lead a clear research agenda later in the project. Thus, the selected themes were: "European industry", "Electrification", "Global green investment", and "Behavioural change". After a set of meetings with Policy Steering Groups, policy-relevant questions were identified and combined into seven modelling studies. These studies were then presented and discussed within four CWGs, under the overarching themes of" Global effects", "Industry and innovation", "Optimal transition", and "Behavioural change".

A step-by-step example of the PRM is below:

1. A policy steering group is selected and made aware of the general model capabilities at our disposal.
2. Starting with an initial policy question co-created with a *policy steering group*, Bruegel moderates a discussion within the consortium on which teams would be best suited to fully or partially provide insight into the proposed question.
3. Models are then matched to the appropriate *core working group* (corresponding to the theme or region of the *policy steering* group) and enter a moderated discussion on how to make the best use of the model capabilities to address various aspects of the policy research question.

[3] D2.1 Stakeholder Engagement Plan

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4. Once the policy question has been refined, we then proceed to co-created scenario building (if necessary for the model and question) in collaboration with modellers and stakeholders.

5. The modelling teams then carry out their first modelling iteration.

6. After the first modelling iteration, engagement with the core working groups will allow to further refine the research questions, modelling parameters, assumptions, etc.

7. The second modelling iteration then takes place, based on input from stakeholders regarding the results of the first modelling iteration and their policy priorities at the time.

8. The final model results will then be communicated to the stakeholders, with the opportunity for feedback and input to the policy recommendations stemming from the analysis.

9. The final step is the publication of a policy brief summarising the model results and their relevance for policy.

2.2 Stakeholders' feedback

In each co-creative cycle, there will be 2 rounds of stakeholder engagement and modelling. Initial policy-relevant research questions will be co-created with stakeholders in the *policy steering groups* before each cycle begins. Each PRM, is organised as follows:

- An initial set of discussions is held between the consortium and the stakeholders in the policy steering groups to co-create policy-relevant questions that are within the scope of the project. An indicative framework that encapsulates the most pressing climate and energy policy questions is developed for each theme and each region.
- Scenario building, a key element of modelling, is the next step in each PRM cycle. Modellers and stakeholders in the core working groups co-create scenarios, considering both realistic input assumptions and desired outputs. Stakeholder involvement at this step should enhance the legitimacy of the modelling exercises later in the project.
- Post-modelling, the modelling teams report to the *core working groups* with the model results. After discussions of the first iteration results, research questions or assumptions may be revisited, leading to a second modelling iteration.
- The second co-creative cycle will incorporate a new set of scenarios and research questions.

From the first iteration, twenty-two questions were collected from the dialogue with the stakeholders:

1. How does the implementation of the updated draft National Energy and Climate Plans compare to the cost optimal EU approach?
2. Can models indicators for energy security be developed?
3. How do supply-chain constraint the potential ramp-up of clean technologies?
4. Are there certain future system configurations that are more susceptible to disruption from geopolitical events?
5. How resilient are transition pathways if certain technologies are unavailable?
6. Will falling cost per MWh of renewables translate into lower customer bills? (e.g. will the energy system cost decrease through decarbonisation)
7. Will electrification drive up energy costs for consumers due to capital costs of switching to electrified heating and transport?
8. Which technologies are best placed to provide flexibility in a low-carbon system?
9. What would be the benefits (cost reduction, emissions) of better (industrial) demand-side response?
10. What is the impact of smart grids, interconnection, and flexibility solutions on capacity needs?
11. How does the share of generation vs. transmission & distribution change in the total cost of a decarbonised power system compared to our existing system?
12. How do scenarios of European industry (e.g., in terms of production, location, energy-intensiveness, and

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input costs) compare regarding cost, resilience to shocks, sustainability and labour market outcomes?
13. What are the energy, climate, labour and cost implications of reshoring critical industries?
14. What will be the available supply and cost of hydrogen in Europe? (both produced domestically and imported)
15. Which manufacturing sectors are likely to use hydrogen?
16. What are the impacts of a decoupling/multipolar world on clean energy technology supply chains?
17. Which sectors require innovation to decarbonise?
18. How necessary is carbon capture and storage (CCS) to decarbonise industry and power?
19. What are the most economic forms of long-duration energy storage? (will hydrogen be competitive?)
20. How will shifts in interest rates affect decarbonisation pathways?
21. What are the economic impacts (rather than the cost or effectiveness of policy implementation) of a given behavioural change?
22. How do heterogenous discount rates across consumer categories affect the adoption rates of clean technologies?

These questions were further combined into seven modelling studies:

- Study 1: How does the implementation of the updated draft National Energy and Climate Plans compare to the cost optimal EU approach? – Led by BC3
- Study 2: What are the different cost, energy security and resilience metrics and how do they compare for different scenarios? – Led by AAU
- Study 3: How could geopolitics affect decarbonisation pathways? - Led by E3M
- Study 4: What are the implications of EU industry decarbonisation, considering possible off / re-shoring scenarios? – Led by WI
- Study 5: What is the contribution of earlier stage technologies if they undergo rapid cost reductions? [how much time will this take?] – Led by Imperial
- Study 6: How do interest rates influence decarbonisation pathways? – Led by NTUA
- Study 7: What are the economic impacts (rather than the cost or effectiveness of policy implementation) of a given behavioural change? – Led by UVa

In the first global modelling iteration of IAM COMPACT, global IAMs are used to answer those policy-relevant questions, and explore where emissions are heading, considering pre-COP26 2030 NDCs and current policies, and resulting warming pathways as well as what has changed after COP26, taking into account countries' net-zero aspirations, and any updates to their 2030 pledges.

2.3 Methodology

To address these questions, global IAM models GCAM, PROMETHEUS and TIAM-Grantham (see section 1.2.1 for model description) are first used to assess the national commitments and targets, aiming to create a realistic baseline scenario that will be used across all seven Studies. An extensive harmonisation process has been implemented in preparation for the global modelling runs. By harmonisation we refer to the process of aligning the inputs of the different models for producing the model inter-comparison study to restrict model response heterogeneity mostly to the differences behind each model structure and theory. Socioeconomic parameters, techno-economic assumptions, policies and historical emissions are harmonised in this study. The details of the parameters are mentioned in Table 3.

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Table 3: Overview of the parameters harmonised in this study

Topic	Variable	Context	Recommended data
Socioeconomics	**Population**	EU27+Norway[4]	Population data from Eurostat: Historical statistics through 2018 [74]; EUROPOP2019 projections from 2019 through 2100 [75,76] [6]
		OECD+[5] except EU27/Norway	Population data from OECD Economic Outlook 109 Long-term baseline projections (available for 1990 through 2060), to ensure consistency with GDP projections [77]. Extend with growth rates from UN WPP2022 after 2060 if necessary (see below).
		Rest of World	UN World Population Prospects 2022 [78] figures for all years (available from 1960 through 2100, with historical data until 2022)
	GDP	All regions, through 2028	GDP from IMF World Economic Outlook April 2023 [79,80][8], in constant 2017 international dollars unless otherwise indicated by the research question
		EU27+Norway, from 2029	Extend IMF forecast with linearly interpolated real GDP growth rates from the 2021 Ageing Report [81,82]
		OECD+ except EU27/Norway, from 2029	Extend IMF forecast with real GDP growth rates from the OECD Economic Outlook 109 long-term baseline
		Rest of World	Extend IMF forecast with GDP growth rates *per working age capita* from SSP2 (must be calculated using the projected population figures) multiplied by population growth rate from the harmonised population time series
Techno-economics	**Technology costs (for reference scenarios)[6]**	EU27 and comparable countries[7]	Should be decided case-by-case, but most suitable option is likely to be technology costs from the EU Reference Scenario 2020[83,84].
		Other regions, power-sector technologies	No firm recommendation at this point. Most suitable option is likely to be cost assumptions from IEA's World Energy Outlook 2022 [85]. Alternatives include technology costs from TIAM database as used in PARIS REINFORCE [86], or using the

[4] EUROPOP2019 also includes population projections for the United Kingdom (EU28) as well as the EFTA member countries Iceland, Liechtenstein, Norway and Switzerland. However, in the 2021 Ageing Report, GDP and other data are only provided for EU27 and Norway. To ensure consistency between population and GDP numbers, only the EU27 and Norway are therefore included here.
[5] OECD member countries, Argentina, Brazil, China, India, Indonesia, Russia, Saudi Arabia, South Africa.
[6] The appropriate choice of technology costs will often depend strongly on the research question. It can potentially also vary by model for models that employ learning curves, and resulting differences in technology costs could be a desired part of model diversity. The tentative recommendations here only apply to cases where the research question does not prescribe any particular assumptions about energy technology costs, but where a "neutral" technology scenario with harmonised energy costs is desired.
[7] "Comparable countries" here refers to non-EU European countries that are similar enough in terms of energy and trade policies and other economic and technological factors that one can assume the same technology cost levels as in the EU, in the context of a given scenario and research question. Whether using EU cost levels is appropriate for a given country must be decided by research question leaders on a case-by-case basis.

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			costs from the EU Reference Scenario 2020 in regions where this is appropriate, possibly adapting the costs levels if feasible.
		Other regions, non-power technologies	No firm recommendations at this point. Options include the TIAM database (see above) or adapting costs from the EUR Reference Scenario 2020.
	Fossil fuel prices	Historical prices	Regional prices from IEA datasets [87]. If participating modellers do not have access to proprietary IEA data, data for some years and regions can be extracted from the freely available World Energy Outlook 2022 report [85], or if global benchmarks are sufficient, some of these are available for free from the World Bank "pink sheet" [88]
		Price projections	Regional price forecasts from the World Energy Outlook 2022 extended dataset[80], requires subscription. Participating modellers who do not have a license can extract some prices visually from charts in the World Energy Outlook 2022 report [85]. For long-term EU-specific exercises that do not need short-term trends, price projections from the EU Reference Scenario 2020 may be used [84].
Energy	**Energy production and consumption**	Historical data[11]	IEA World Energy Balances (International Energy Agency, 2023e)
Emissions	**Energy-related[8] CO_2, CH_4, N_2O**	Historical data	IEA Greenhouse Gas Emissions from Energy dataset [89], if modellers have or can acquire access. Alternatively use EDGAR v7.0 [90] which is consistent with IEA but with less detailed breakdowns. Emissions can also be calculated from energy consumption data using default Tier 1 emission factors from the 2006 IPCC guidelines for GHG inventories, which are consistent with IEA emission factors.
	IPPU CO_2 from cement	Historical data	Production data and emission factors from [91]. Updated data available on Zenodo [92].
	F-gases and non-energy CO_2, CH_4, N_2O	Historical data	EDGAR v7.0 [90]
	Other emissions	Historical data	CEDS [93]

[8] NB! The recommended datasets use the 1996 IPCC Guidelines for GHG inventories to define the boundary between energy-sector and industrial-process and product-use (IPPU) emissions, not the newer 2006 guidelines. The IEA also provides a dataset where emissions are categorised in accordance with the 2006 guidelines, but with less granular breakdowns of energy types and sectors. EDGAR does not provide any data using the 2006 sector boundaries.

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	Land-use change emissions	Historical data	No firm recommendation on harmonised data but should check that used or generated data falls within or close to range spanned by 3 bookkeeping models in the Global Carbon Budget 2022 [94]. Use an average of the three models if a single harmonised dataset is required and no other constraints are implied by the research question.
	All emissions	Infilling of historical and future emissions	Use Silicone software package to infill missing emission components, if required by the modelling exercise (e.g., for climate impact assessment) [95–97]

In the next step, a current policies database is created for each country and/or region. The combined policy database included 280 national policies such as such as the European cap and trade system for CO_2 emissions, the share of renewables, or carbon tax, efficiency standard, capacity deployment target. The models differ in the level of policy implementation due to technological and sectoral granularity, which differs across the models used.

NDC targets are based on a direct interpretation of countries' *unconditional* Paris Agreement pledges, or the less ambitious range for pledges where NDC targets are given in ranges. Annex Table 1 provides the details of NDC target announced by different nations. Some countries announced their NDC target in terms of % reduction from its baseline emission and others in terms of % reduction from the reference year.

Long term targets announced by the countries as part of their long-term low-emission development strategies implementation. Most of long terms targets included net-zero and carbon neutrality pledges (see Annex table 2) considered in the study are either put in law or in policy document. Some long-term pledges may not yet be made official are also considered to have a complete stock of post-Glasgow climate action.

The rest of this section describes the scenario logic and the protocol for implementing the four reference scenarios explored in the realistic current policy trajectories.

2.3.1 Scenario protocol

After harmonisation of different parameters in the above sections, three scenarios are implemented to assess the gap between the national commitment and Paris climate stabilisation target.

CP_EI: The first scenario is based on the current portfolio of actual emissions reduction policies as well as credible policy targets until 2030 in G20 countries including the entire EU. Post-2030 action is then modelled by measuring the average rate of change in emissions intensity of GDP from 2020 to 2030 in each region and assuming emissions-intensity reduction rates will remain the same after 2030. The applied policy targets until 2030 (for example, renewable energy mix targets, vehicle fuel standards) are maintained as minimum levels beyond 2030 to avoid backtracking of achieved policies.

NDC_EI: The second scenario is based on stated 2030 emission targets pledged in NDCs submitted or announced by June 2023, capturing all mitigation ambition updates during and after the COP26 in Glasgow (Table 4). These NDC targets are applied on top of current policies (CP) modelled in the previous scenario; in model regions where current policies overachieve the mitigation targets of NDCs, no additional emission constraints are applied. Emissions reductions in NDC scenarios are therefore never less ambitious than what CP implies. The same EI method is applied for post-2030 action as in CP_EI.

NDC_LTT: The third and most ambitious scenario is built on the NDC_EI until 2030 but, for regions that expressed an LTT, such as net-zero commitments or other targets for 2050 or later (either in law, policy documents or only

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announced) (Table 5), emission constraints are applied that linearly decline from 2030 emissions as in the NDC_EI scenario towards said long-term target. For regions without LTTs, post-2030 emissions follow an identical path as in the NDC_EI scenario.

2.4 Results

2.4.1 Emissions

Current policy constrained scenarios reach levels of emissions from fossil energy between 30-37 $GtCO_2$ in 2030 and 22-32$GtCO_2$ in 2050 (Figure 9) and NDC constrained scenarios reach levels of emissions between 27-33 $GtCO_2$ in 2030 and 17-23 $GtCO_2$ in 2050 (Figure 10). In the NDC_LTT scenario, 2050 emissions from fossil energy are in the range of 9-9.3-11 $GtCO_2$. The difference between current policies and NDC constrained scenarios arise because not all regions are on track to meet their NDC targets. Figure 10 shows the temperature outcomes across the three models and three scenarios considered in this study. For the Prometheus model, the emission trajectories were extended beyond 2050 using the emission infilling tool Silicone. As all models don't report all the GHG emissions, unreported emissions were also calculated using the infilling tool. These emissions trajectories were then fed into the simple climate Model FAIR for the probabilistic temperature assessment. The results show that in the NDC scenario, where the ambitious NDC pledges made by the countries are considered, the temperature is expected to rise to 1.8-2.1 ºC . CHowever if the countries comply with their long term climate commitments considered in the NDC_LTT scenario,then the temperature rise will be limited to 1.6-1.7 ºC where there is convergence between the models. Depiste this,the emissions are still higher than to reach the 1.5 ºC target with 50% certainty. This implies that governments need to strengthen their targets to reach the 1.5 ºC climate target.

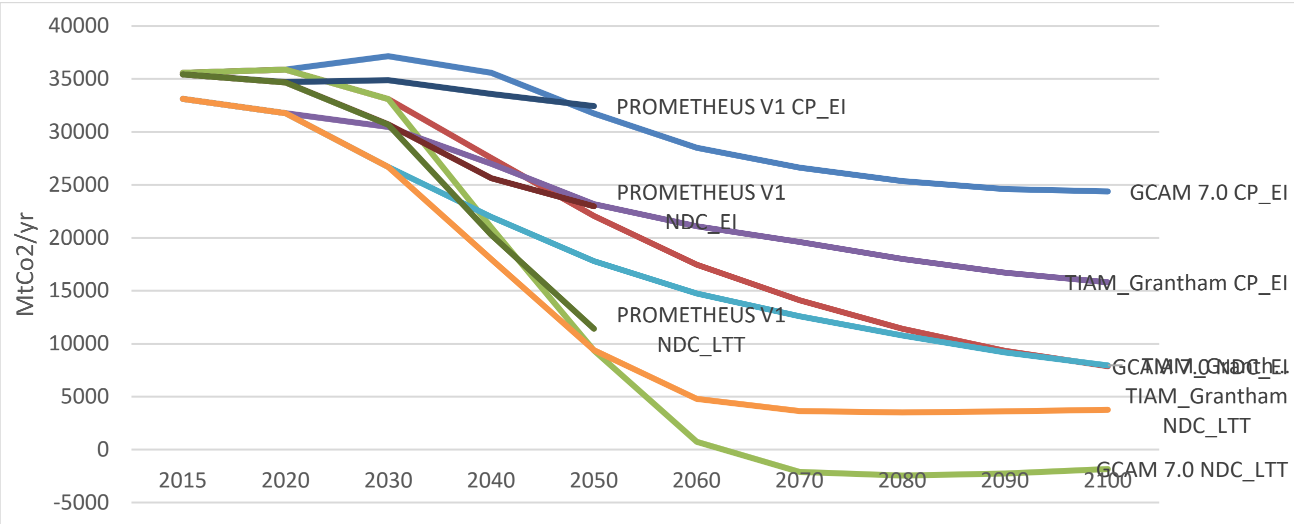

Figure 9: Emissions pathways in different scenarios

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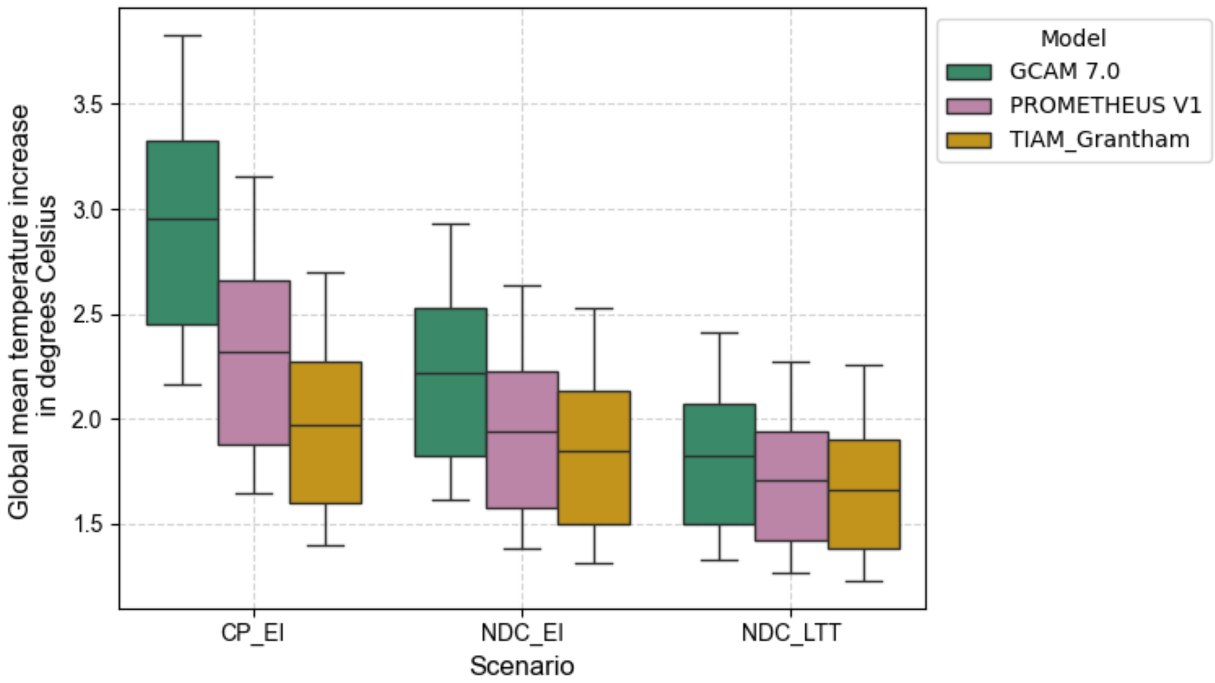

Figure 10: Temperature assessment.

2.4.2 Energy system transformation

In the TIAM model, the final energy demand in 2050 is lower compared to the GCAM and PROMETHUS model due to the lower energy service demandin the NDC_LTT scenario (Figure 12). This is one of the reasons why the CO_2 emissions in TIAM model are lower compared to GCAM and PROMETHUS in NDC_EI & CP_EI scenarios in 2030. All three models show that global final energy demand can be reduced with steeper emission reductions. In all three models, the total global final energy demand is lower in the NDC_LTT scenario compared to CP_EI and NDC_EI scenarios in 2050, mainly due to increased efficiency and electrification of end uses.

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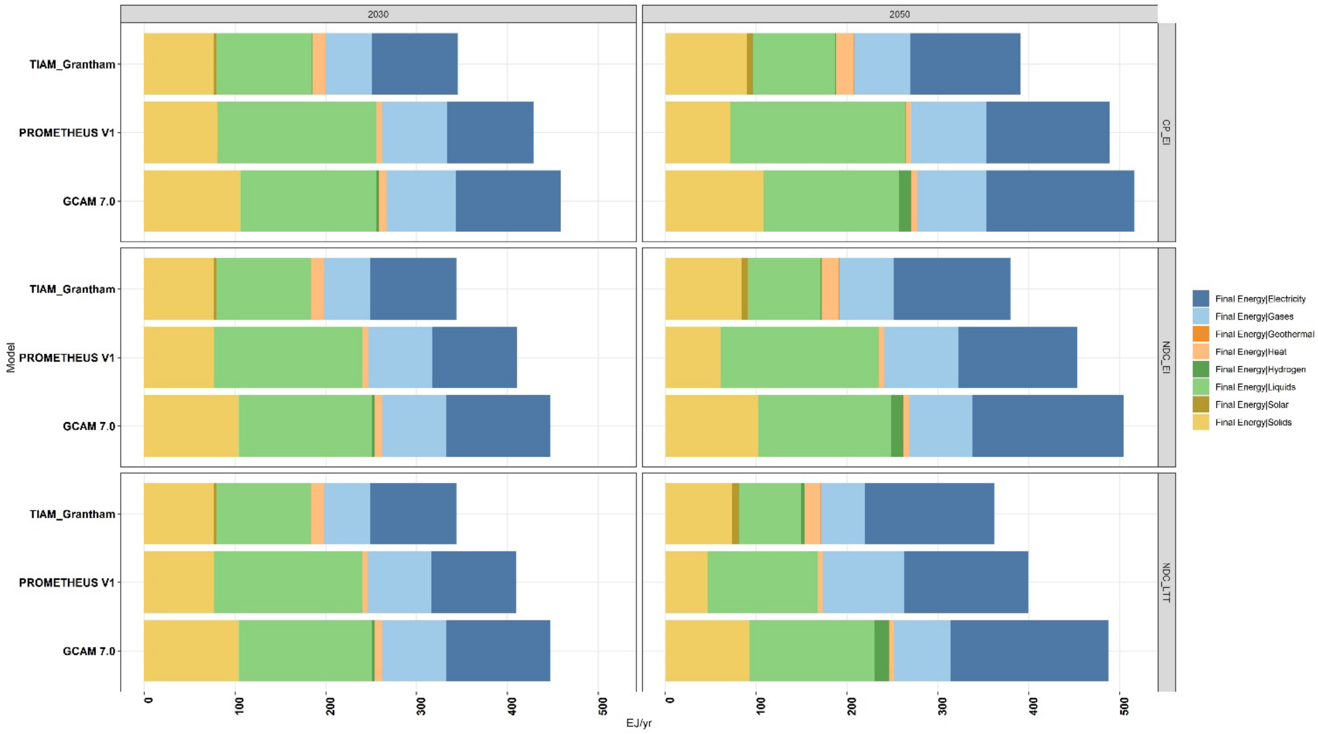

Figure 11: Global final energy by fuels in 2050

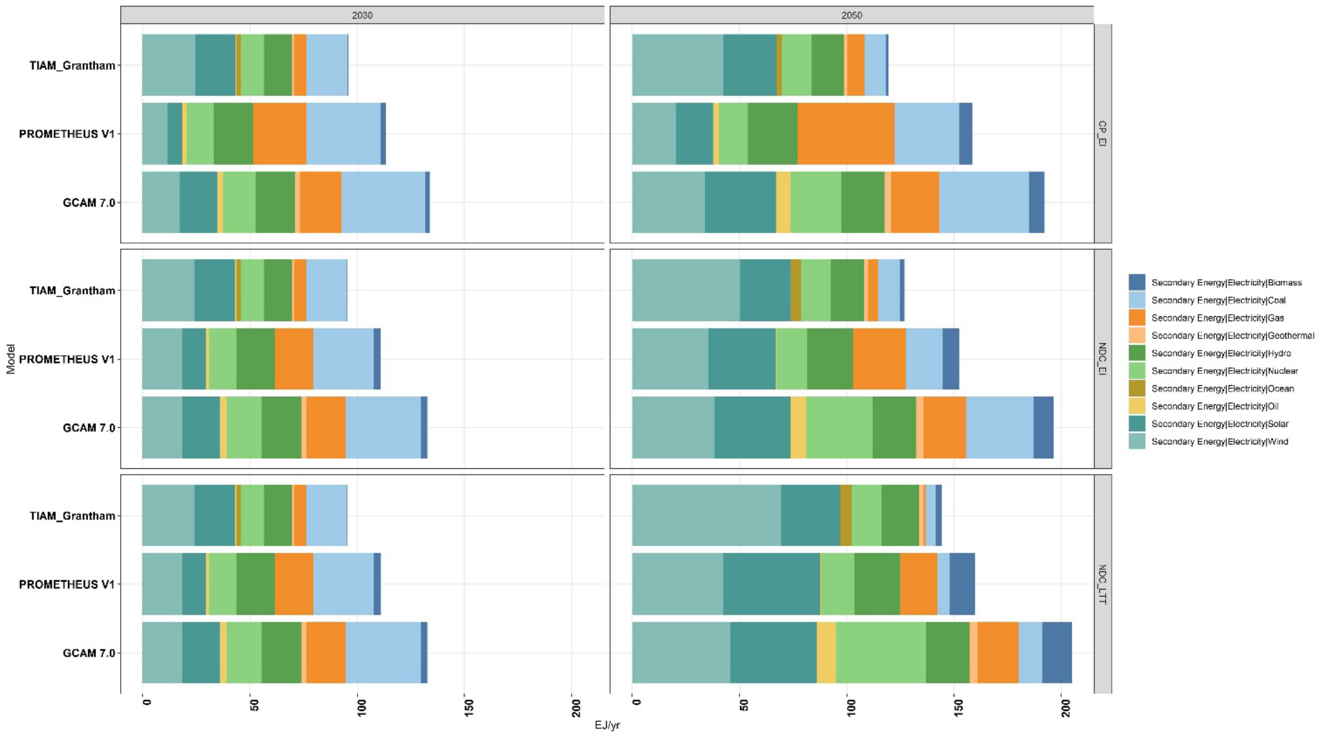

Figure 12: Electricity generation by fuel in 2050

In the NDC_LTT scenario, all three models show an increase in electricity demand in 2050 due to the electrification of the end-use sector (Figure 13). Furthermore, the share of non-fossil-based electricity also increases in all

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models in this scenario. However, there is a difference in the share of different non fossil fuel-based electricity generation between the models: nuclear energy has a higher share in the GCAM model compared to other two models, while wind power has a higher share in the TIAM model and solar power has a higher share PROMETHEUS. This highlights the differences in the models' approaches to achieving low carbon transformation, with the selection of different low carbon technologies.

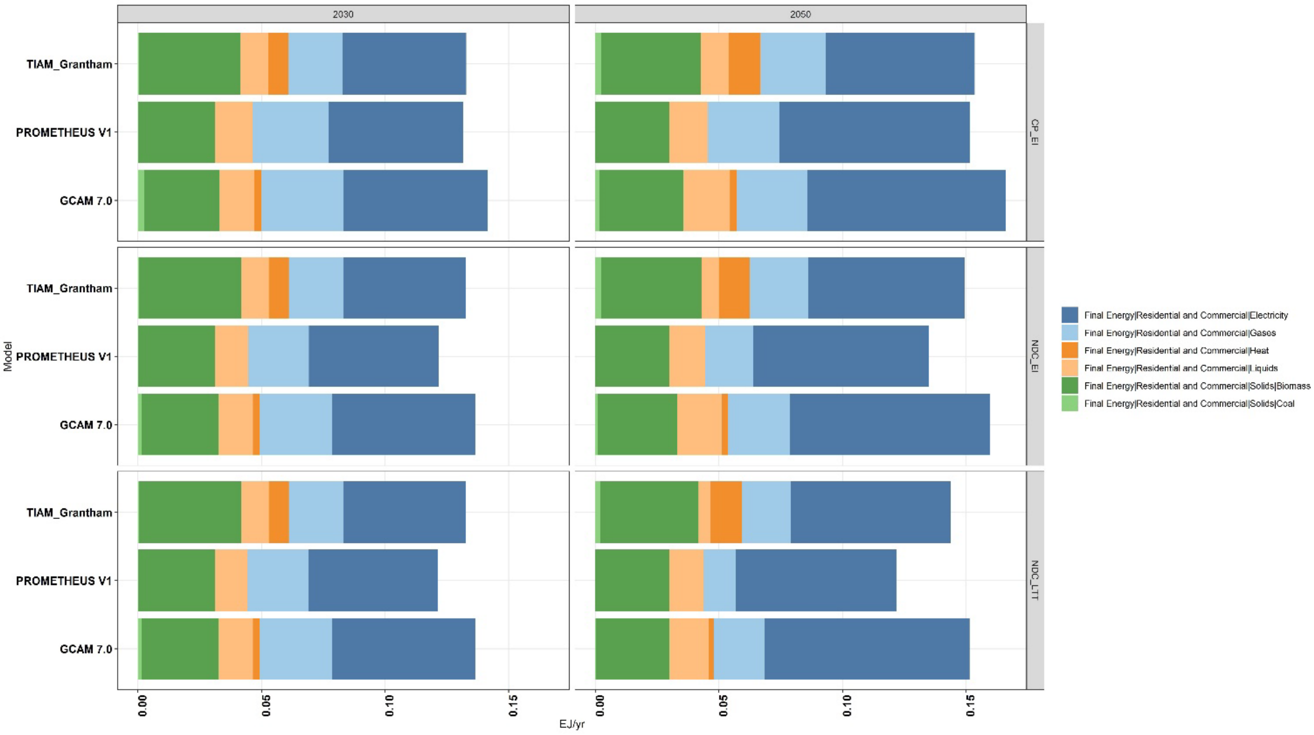

Figure 13: Final energy consumption by fuel in the building sector in 2050

In the building sector, the final energy consumption is reduced in NDC_LTT scenarios in allmodels when compared to CP_EI and NDC_EI scenarios but the reduction is significant in PROMETHUS model compared to other models due to better representation of energy efficiency improvement measures in the model (Figure 14). Moreover, there is an increase in the share of electricity in the building energy mix in 2050. The share of liquid fuel is relatively higher in GCAM as compared to other two models and it remains constant across all scenarios.

In the industrial sector, the final energy demand in GCAM is significantly higher compared to the TIAM and PROMETHUS models, resulting in higher industrial emissions, mostly due to the increased share of solid fuels in all scenarios in 2050 (Figure 15). The consumption of solid fuel in 2050 is around 60 EJ in GCAM compared to 30EJ in TIAM and 16EJ in PROMETHUS model. Electricity climbs to 50% of industrial energy use by 2050 in the NDC_LTT scenario of TIAM, while remaining constant around 30% among scenarios in GCAM and PROMETHUS models.

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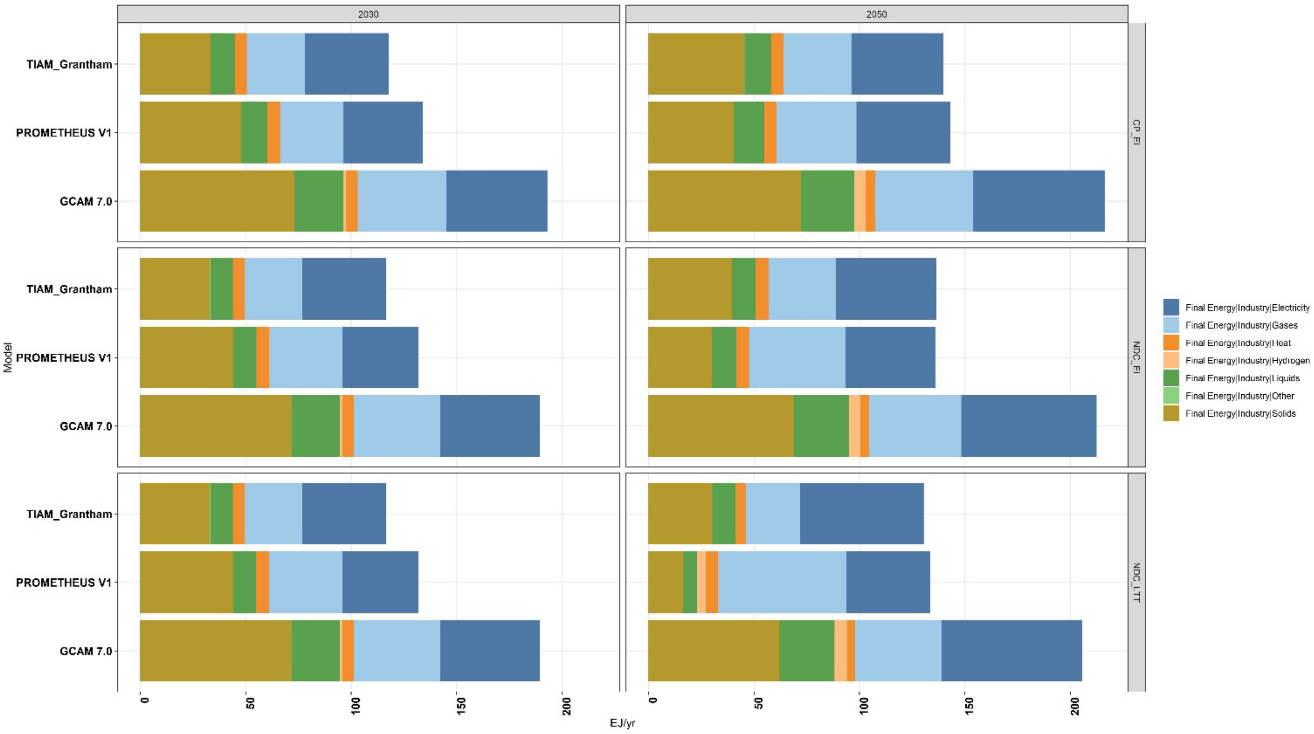

Figure 14: Final energy consumption by fuel in industry in 2050

2.5 Conclusions

To assess how far we are from reaching the temperature targets set by the Paris Agreement, global scenarios simulating policy packages under IAM COMPACT's scenario logic (D4.3) have been developed. These scenarios first predict the impact of current policies and nationally determined contributions (NDCs) on global emissions. The results indicate that in NDC_LTT scenario where we assume countries comply with long term commitments and net zero target will help to achieve the Paris Agreement's goal of limiting global warming to "well below 2°C". but this most optimistic scenario falls short of goal of reaching 1.5°C. Achieving this goal will require stronger global mitigation efforts and concrete policies to back up new commitments. Policymakers need to know where emissions are headed to determine how much ambition must be raised to meet climate targets.

In recent years, many countries have updated their mitigation pledges and submitted long-term development strategies to the United Nations Framework Convention on Climate Change (UNFCCC), including net-zero pledges for 2050-2070. These pledges have helped to reduce the gap between current commitments and the Paris target. While different models prefer different technologies to achieve mitigation, the tendency towards renewable energy sources, such as biomass and non-biomass renewables, and away from fossil fuels, particularly coal, is evident in all models. This shift towards higher electrification and lower final energy consumption is visible in all models.

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3. Comparison of Fit-for-55 Policy and Cost Optimal Scenarios for the European Union

This modelling exercise was carried out to directly answer the stakeholder question "*How does the implementation of the updated draft National Energy and Climate Plans compare to the cost optimal EU approach?*" mentioned in the section 2. However, due to delays in the release of the National Energy and Climate Plans by EU member states and model limitations in representing granular national policies, cost-optimal model scenarios to achieve the EU emissions mitigation targets are compared here to EU-wide modelling of the Fit-for-55 policy package. While this may not capture all national idiosyncrasies, it captures a number of key EU-level targets for mitigation pathways that differ from the cost optimal outcomes in IAMs. The Fit-for-55 package includes policies limiting energy sector and industrial emissions, promoting renewable deployment, and limiting energy demand in order to reach the EU goal of 55% emissions reduction in 2030, compared to 1990. Below we elaborate on the models included in this analysis and the Fit-for-55 components included in the study.

3.2 Methodology

In this study, three models were included to compare Fit-for-55 to cost optimal scenarios: two global IAMs, GCAM and TIAM-Grantham, and one global energy model PROMETHEUS (see section 1.2.1 for model descriptions). Within each global model, there is an EU region, although with some slight variations. In the version of GCAM used here, the 27 EU member states are split into two regions, combined in all results presented in this analysis; results for TIAM-Grantham combine a Western Europe and Eastern Europe region, which includes the EU member states as well as the UK, Switzerland, Iceland, Norway, Albania, Bosnia-Herzegovina, Czech Republic, Macedonia, Serbia, and Montenegro; PROMETHEUS results include all EU member states plus the UK.

The Fit-for-55 package and other major EU climate policies are included in the current policies modelled under the NDC_LTT scenario (section 2.3.2). Below (Table 4) we outline the major EU policies that are modelled in the NDC_LTT scenario:

Table 4: EU Fit-for-55 climate policies modelled in the NDC_LTT scenario

Policy	Variable	Target
Renewable energy directive	Share of renewables in final energy	40 % in 2030 (target was increased to 42.5% after study began, not captured in these scenarios)
Renewable energy directive	Share of advanced renewables in energy use in rail and road transport	5.5% in 2030
Emissions trading system	ETS sector (electricity generation, industry) emissions reduction	62% reduction in 2030 from 2005 level
Energy efficiency directive	Energy consumption - maximum final energy	763 Mtoe
CO_2 vehicle emission standards	Light-duty Vehicle emissions intensity	0 g CO2/km for vehicles sold from 2035 onwards
Strategy on offshore renewable energy	Installed capacity - offshore wind energy	60 GW in 2030; 300 GW in 2050
REPowerEU plan	Installed capacity – solar energy	320 GW in 2025; 592 GW in 2030
European wind power action plan	Installed capacity – wind energy	in 2030

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4.2.1 Scenario protocol

The scenarios are designed to specifically compare the difference in the EU when achieving emissions targets for the NDC and long-term target between a pathway including current climate policies and a cost-optimal pathway in the models:

- **NDC_LTT**: Identical to the scenario described in section 2.3.2, this ambitious global scenario includes current policies, NDC targets, and long-term targets in all global regions.
- **EU_Optimal**: In this scenario, the EU achieves the same level of mitigation of GHG emissions or CO_2 Fossil Fuel and Industrial (CO_2 FFI) emissions from 2030 to 2050 as in NDC_LTT. GCAM measures all GHG emissions while TIAM-Grantham and PROMETHEUS only track CO_2. However, here EU emissions reductions are achieved with emissions constraints, and no inclusion of the current climate policies, allowing the models to choose the cost-optimal pathway to reduce emissions. For other global regions, the same scenario protocol from the NDC_LTT is modelled, including both current climate policies and emissions targets.

3.3 Results

3.3.1 Emissions

CO_2 FFI emissions in the EU decrease substantially from 2015 across all scenarios (Figure 1), achieving 2030 emissions reductions between 1,509 MtCO_2 to 1,545 MtCO_2 in GCAM and PROMETHEUS and 2,493 MtCO_2 in TIAM. 2030 net CO_2 FFI emissions are identical in both TIAM scenarios, but for GCAM and PROMETHEUS vary slightly, with NDC_LTT emissions 23 MtCO_2 and 16 MtCO_2 greater than in EU_Optimal, respectively. Across all models 2050 FFI emissions approach or reach net zero, with the sole exception of NDC_LTT in PROMETHEUS with a remaining 63 MtCO_2 of FFI emissions, compared to -17 MtCO_2emissions in the EU_Optimal scenario. TIAM FFI emissions reach exactly 0 MtCO_2 in both scenarios, while GCAM goes farther net negative, achieving -465 Mt$CO_2$and -430 MtCO_2 in the NDC_LTT and EU_Optimal scenarios, respectively.

Across all models and in both 2030 and 2050, the EU_Optimal achieves greater mitigation in the Supply sector, composed of emissions from energy production via electricity, hydrogen, heat, liquids, and gas production. Averaged across all three models, 2030 FFI emissions from energy supply are 513 MtCO_2 in NDC_LTT vs 217 MtCO_2 in EU_Optimal. This gap widens further in 2050, with average emissions of -585 MtCO_2 in NDC_LTT compared to -959 MtCO2 in EU_Optimal. This means that the EU_Optimal scenario goes beyond the energy supply emissions reductions required by the Emissions Trading System in NDC_LTT.

Conversely, the NDC_LTT scenario relies more on emissions reductions from end-use demand sectors. FFI emissions from all three end-use sectors, buildings, transport, and industry, are lower in the NDC_LTT scenario. Average emissions in 2030 are lower in NDC_LTT by 134 MtCO_2 in buildings, 103 MtCO_2 in transport, and 88 MtCO_2 in industry. The difference in 2050 is quite similar with emissions lower in NDC_LTT by 176 MtCO_2 in buildings, 124 MtCO_2 in transport, and 62 MtCO_2 in industry. These differences are likely driven primarily by the Energy Efficiency Directive, which decreases final energy consumed by demand sectors in NDC_LTT. In the NDC_LTT scenarios, the lower energy demand leads to greater reduction of emissions by demand sectors and relieves some pressure from the energy supply sector.

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Figure 15: CO2 emissions from fossil fuels and industry in the EU, by model and year

3.3.2 Energy system transformation:

In line with the lower end-use sector emissions in NDC_LTT, final energy consumption is also lower in 2030 and 2050 in all models in NDC_LTT (Figure 16 and Figure 17). Compared to 2015, 2030 final energy demand in NDC_LTT decreases by 7.3 EJ, 6.0 EJ, and 14.5 EJ in GCAM, PROMETHEUS, and TIAM, respectively. In the EU_Optimal scenario the drop in energy consumption from 2015 to 2030 is smaller, with decreases of 0.4 EJ, 4.2 EJ, and 5.5 EJ in GCAM, PROMETHEUS, and TIAM, respectively. The gap in final energy consumption between the two scenarios increases in the models, from an average of 5.9 EJ more consumption in EU_Optimal in 2030 to an average of 7.7 EJ more energy consumption in 2050.

The lower end-use energy demand in NDC_LTT primarily comes from lower consumption of liquid and gaseous fuels, as well as solid biomass in GCAM (Figure 16). 2030 consumption of liquids is an average of 1.9 EJ higher in the EU_Optimal, while consumption of gas is an average of 3.7 EJ higher than in NDC_LTT. These differences expand to 4.1 EJ more liquid fuels and 4.0 EJ more gaseous fuels in EU_Optimal in 2050.

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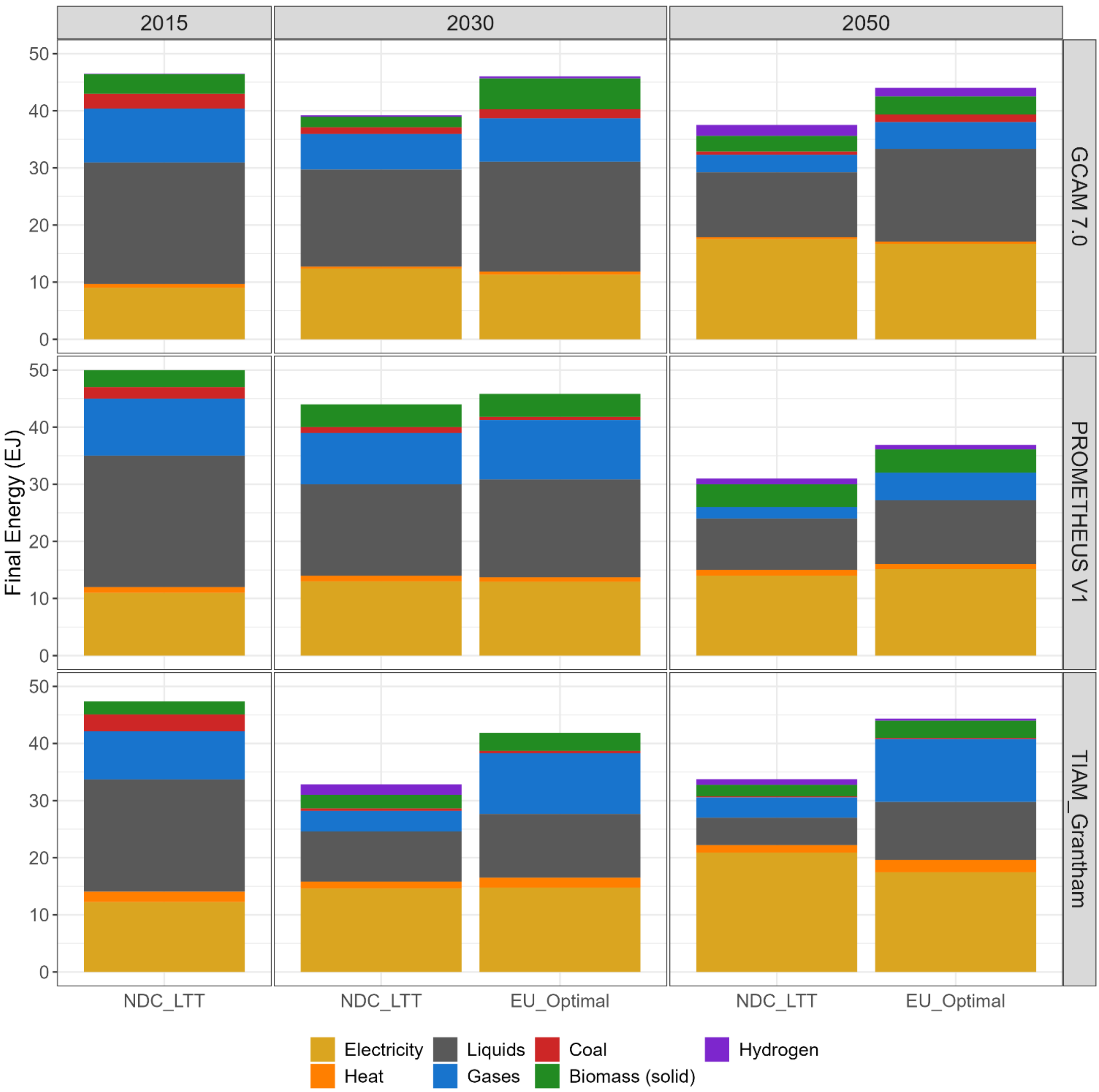

Figure 16: Final energy consumption by fuel in the EU, by model and year

When looking at the final energy demand by sector (Figure 3), all models agree that in 2030 the largest difference between the scenarios comes from the buildings sector, with an average of 3.4 EJ less energy consumed in NDC_LTT compared to EU_Optimal. This is nearly three times more than the gap between the scenarios in average transport consumption, 0.9 EJ, and industrial consumption, 1.2 EJ. In 2050, there is more disagreement, with GCAM having the largest difference between the two scenarios in transport energy, while buildings remain the biggest difference in PROMETHEUS and TIMES. Averaging over the models, 2050 energy consumption is greater in the EU_Optimal scenario by 2.8 EJ in buildings, 1.8 EJ in transport, and 1.5 EJ in industry.

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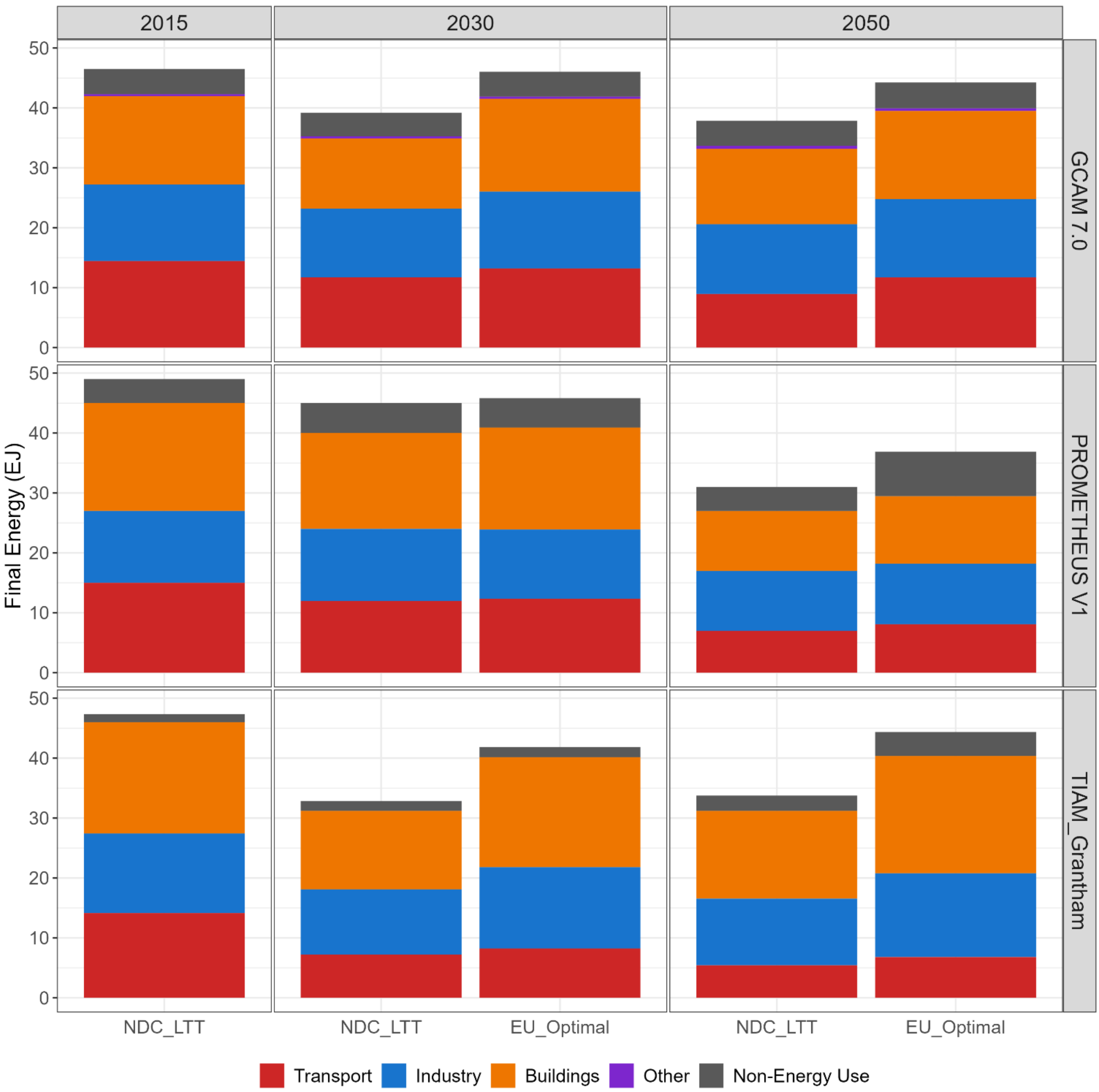

Figure 17: Final energy consumption by sector in the EU, by model and year

Comparing the percentage of final energy that comes from renewable energy (Figure 18), including solar, wind, hydropower, geothermal, and bioenergy, the NDC_LTT scenarios have a higher renewable energy percentage than EU_Optimal in 2030. This is a direct response to the renewable energy percentage requirement imposed by the Renewable Energy Directive in NDC_LTT. By 2050, all scenarios meet over 48.5% of final energy demand with renewable energy sources. The gap in renewable deployment between the scenarios increases in 2050 in GCAM and PROMETHEUS. The greater percentage of renewables in 2050 in NDC_LTT is not only a result of lower final energy; the total renewable energy production is also higher in both GCAM and TIAM, by 2 EJ and 1.5 EJ, respectively. While 2050 renewable energy production is slightly lower in NDC_LTT in PROMETHEUS, the non-bioenergy renewable energy production is larger than in EU_Optimal.

This apparent conundrum – lower final energy demand and greater renewable energy production in NDC_LTT, yet similar emissions outcomes between the scenarios – is due to greater negative emissions from bioenergy with carbon capture and storage (BECCS) in the EU_Optimal scenario. In PROMETHEUS, an extra 4.1 EJ of primary

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energy comes from BECCS in 2050 in the EU_Optimal scenario. EU_Optimal carbon sequestration from BECCS in 2050 is 231 MtCO2 higher in GCAM and 73 MTCO$_2$ greater in TIAM compared to BECCS in NDC_LTT. The negative emissions produced from greater BECCS utilisation allows the EU_Optimal scenario to offset higher final energy production and lower total renewable deployment.

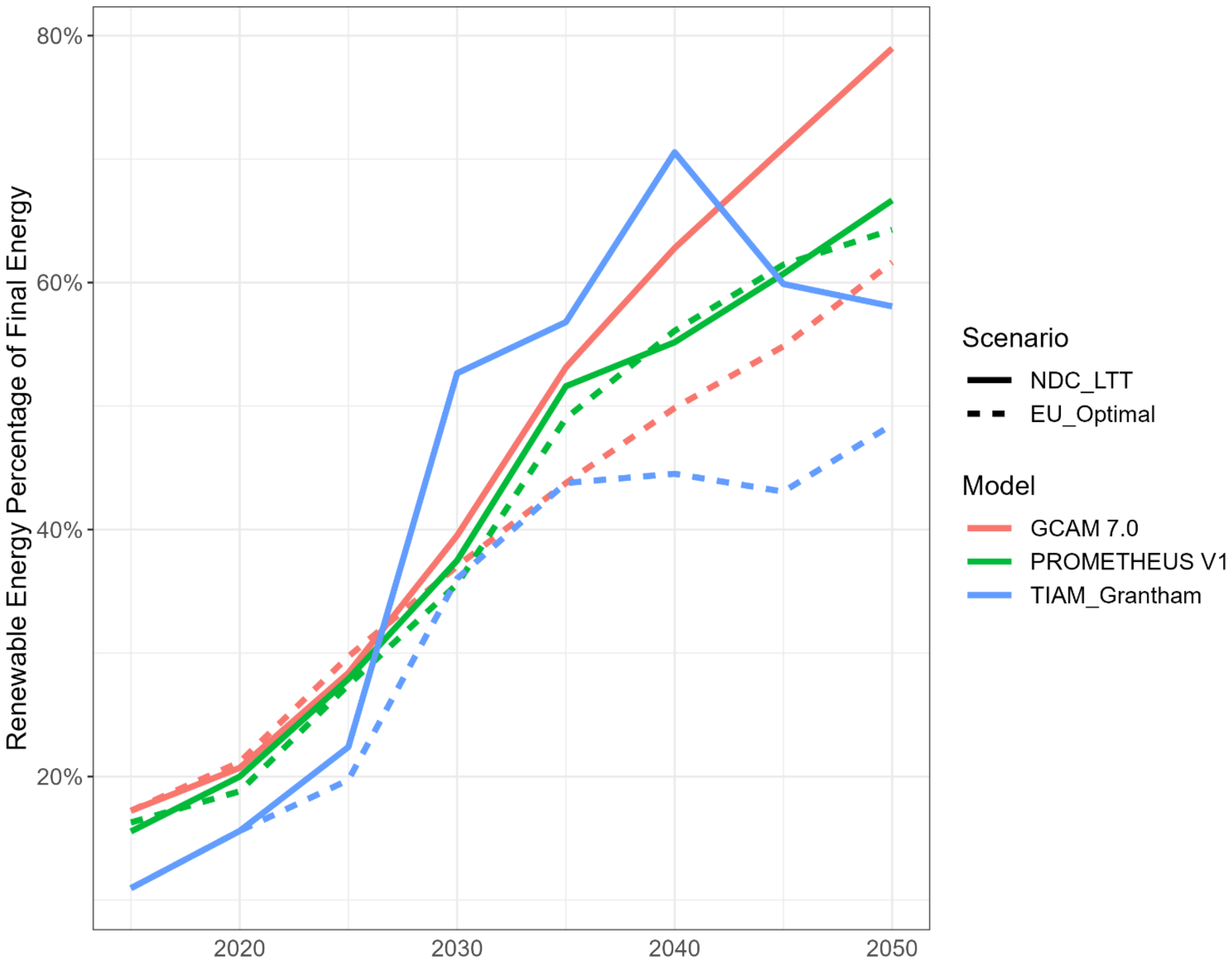

Figure 18: Percentage of final energy originating from renewable sources.

3.4 Conclusions

The NDC_LTT and EU_Optimal scenarios demonstrate two viable but differing pathways to achieve the EU's NDC and long-term emissions target. The primary difference in these scenarios is the demand side vs supply side approach to emissions mitigation. As a result of the Energy Efficiency Directive, more emphasis is placed on reducing energy demand and resulting end-use sector emissions in NDC_LTT. Across the models, final energy consumption is nearly 15% lower in 2030 and nearly 19% lower in 2050. By reducing energy demands, the NDC_LTT scenario reduces the reliance on more controversial and unproven carbon capture and storage technologies [98]. This may also point out to structural constraints in the models, as most models have greater ability to reduce emissions via supply side strategies while demand response is generally more poorly understood and represented in IAMs and energy models [99]. However, it is also important to understand potential negative effects of reduced demand – such as greater energy poverty [100]. For example, demand is most reduced in buildings in the NDC_LTT scenarios. This might be achieved through building retrofits that increase energy efficiency but could also indicate that demand for heating and/or cooling are unmet for some vulnerable

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populations. Given its importance in differentiating the scenario with the Fit-for-55 included from the model cost optimal approach, further research into the realism of the energy demand reduction seen here and an understanding of pathways to achieve these reductions is highlighted in D5.6.

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development goals without negative emission technologies. Nature Energy, 3(6), Article 6. https://doi.org/10.1038/s41560-018-0172-6

[100] Streimikiene, D., Lekavičius, V., Baležentis, T., Kyriakopoulos, G. L., & Abrhám, J. (2020). Climate Change Mitigation Policies Targeting Households and Addressing Energy Poverty in European Union. Energies, 13(13), Article 13. https://doi.org/10.3390/en13133389

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5. National Mitigation Pathways of Major Emitters

The task 4.3 is focused on developing strategies to reduce greenhouse gas emissions in major emitting regions outside of Europe. The goal is to create mitigation pathways that can achieve both short-term NDC objectives and long-term Paris Agreement targets for net-zero emissions using national-level models.

During the first policy response mechanism cycle, a series of mitigation modelling exercises were conducted for non-European countries. The cycle included the countries of USA, China, and India. This deliverable includes the initial version of low-carbon scenarios that were developed with the input of stakeholders from these countries. Each country-specific section reports on the steps taken to engage with stakeholders, the insights received from the workshop participants, and how the feedback was incorporated into the study design for each country-level scenario. Different research themes emerged by these interactions at the national level. During the US stakeholder meeting, deeper state-level analysis was deemed necessary whereas stakeholders emphasized the importance of decarbonising the building sector in India. In China, stakeholders emphasized the need to include material constraints and COP28 commitments in the modelling analysis.

5.1 India's Mitigation Scenarios

5.1.1 Context and Objective

The objective of the event was to discuss the current trends and elicit feedback from key stakeholders, and to draw insights from national experiences to understand the possible policy priorities to attain net-zero emissions by 2070 as committed by Hon'ble Prime Minister of India, Shri Narendra Modi at COP26 in Glassgow.

The NDC commitment of achieving Net Zero by 2070 necessitates to decarbonisation of India's economy along with being energy independent by 2047. Decarbonisation of India's economy requires the decarbonisation from power (electricity production) sector, industry sector, transport sector, building sector, agriculture sector, etc. which contribute to substantial GHG emissions at national level. The various stakeholders participated in the event highlighted that there is a need to prioritise the decarbonisation of India's building sector as there is a huge policy gap both at design as well as implementation level. Its building space which is to be constructed is to increase by more than 2.5 times during 2015-2050. Also, there is a lack of scientific literature and peer-review research studies that focuses on decarbonisation of residential as well as commercial buildings of India aligned with country's updated NDC commitments to the UNFCCC. The two research questions that emerged from the stakeholder engagement were identified:

i) What are the decarbonisation strategies for the building sector in India?

ii) What should be the policy priorities for the building sector of India towards Net Zero 2070?

5.1.2 List of Stakeholders

The event was aimed to promote an open discussion between government officials, industry leaders, researchers, and academia. The event had an open discussion between various stakeholders such as government officers (#4), Industry leaders (#10), Researchers (#10), Academia (#6), etc. which is around 30 stakeholders in total to get the feedback on research questions mentioned above.

5.1.3 Overview of India's Building Sector

India's building sector accounts for 33% of its total final energy consumption which is increasing at around 8% annually[9], due to increased housing and cooling space demand, higher appliance ownership, increased access to

[9] http://dx.doi.org/10.1016/j.enpol.2017.07.013

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modern cooking fuels[10], and income effects[11,12,13]. Building and construction sectors contributed around a third of GHG emissions (including operational as well as embodied emissions) in India. Its floor area is projected to increase more than 2.5 times i.e. from 16 billion m^2 in 2015 to 58 billion m^2 in 2050[14]. The increase in floor space will add its current stock of air-conditioners from 30 million units in 2018 to 240 million units in 2030 and more than 1100 million units in 2050[15].

Providing thermal comfort and reliable electricity to all citizens of India will be a key challenge as its building stock is projected to grow supported by policies such as Housing for All being implemented under Ministry of Housing and Urban Affairs[16]. This will offer emerging opportunities to leapfrog to advanced building energy codes, net-zero energy or carbon buildings, low-energy cooling innovations, energy-efficient and smart appliances, etc.[17,18]. Key elements that can boost decarbonisation of building sector include increasing energy efficiency to reduce energy demand during its operation, reducing embodied energy to reduce its lifecycle emissions, increase in use of renewable energy, accelerating retrofits, through integrative building design, promoting adoption of low-carbon practices, occupant behaviour, etc[19,20].

5.1.4 Model Description

In the current study, the Asia-Pacific Integrated Model (AIM)/Enduse India (AIM/Enduse-India), a bottom-up, techno-economic energy system model is used, which is built on a disaggregated, sectoral representation of the economy. The model has been used in the current study to capture the major sectors of the energy and environment systems in India and quantify the impacts of multiple objectives (climate change mitigation, energy, and climate security) of existing and future policies related to emissions reductions, energy efficiency, technology transitions and so on. The energy supply (e.g. power generation, refineries, coal supply) module is endogenously linked with energy end-use sectors (industry, transport, buildings, and agriculture). This is a national level model with high sectoral, temporal, and technological granularity. The model has been developed to estimate the future development of primary and final energy mix, emissions from the energy system, electricity generation mix and capacity additions and related energy costs and prices for various sectors under alternative policy, socioeconomic and technology assumptions. In this study, we use the model to project the future energy system transformation pathways in the building sector of India. Further information about the model is provided in Vishwanathan et al. 2023[21] and Vishwanathan et al. 2021[22].

5.1.5 Scenario Description

Two main scenarios are explored, namely the current policy scenarios (CPS) and enhanced NDC (En. NDC) scenario (Vishwanathan et al. 2023). We have improved in the power and building sector based on updates in policies and stakeholder engagement. More details on the scenario can be found below.

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[10] https://iea.blob.core.windows.net/assets/1de6d91e-e23f-4e02-b1fb-51fdd6283b22/India_Energy_Outlook_2021.pdf
[11] http://ozonecell.nic.in/wp-content/uploads/2019/03/INDIA-COOLING-ACTION-PLAN-e-circulation-version080319.pdf
[12] https://eta-publications.lbl.gov/sites/default/files/lbnl-6674e.pdf
[13] https://doi.org/10.1016/j.energy.2017.09.004
[14] https://aeee.in/tackling-embodied-carbon-from-indias-building-sector/
[15] https://www.iea.org/reports/the-future-of-cooling
[16] https://pmaymis.gov.in/
[17] https://aeee.in/building-and-communities/
[18] http://ozonecell.nic.in/wp-content/uploads/2019/03/INDIA-COOLING-ACTION-PLAN-e-circulation-version080319.pdf
[19] https://doi.org/10.1016/j.jclepro.2019.119260
[20] https://www.thehindu.com/news/cities/bangalore/decarbonisation-of-building-and-construction-sector-imperative-to-achieve-indias-net-zero-target/article67302971.ece
[21] https://www.sciencedirect.com/science/article/pii/S2211467X23001025
[22] https://iopscience.iop.org/article/10.1088/1748-9326/ac08bf/meta

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Sector	Current policy scenarios (CPS)	Enhanced NDC Scenario (En. NDC)
Power production	250 GW renewables in 2030; Transmission and Distribution (T&D) losses reduce by 6–7%; Phase out old, inefficient fossil plants by 2040.	500 GW renewables in 2030; T&D losses decline by 8–10%; Phase out old, inefficient fossil plants by 2030.
Industry	Improve Energy Efficiency (EE) through Perform, Achieve, and Trade (PAT) Cycles.	Ratcheting EE through deepening of PAT Cycles in energy intensive sectors.
Transport	Ethanol blending: 5%; EV penetration: 30% of all new cars by 2030.	Ethanol blending: 10%; EV penetration: 30% of all new cars by 2030.
Buildings	EE AC penetration: (i) reduce cooling demand across sectors by 10%–15% by 2040, (ii) reduce refrigerant demand by 10%–15% by 2040, (iii) Reduce cooling energy requirements by 5%–10% by 2040.	EE AC penetration: (i) reduce cooling demand across sectors by 15%–30% by 2050, (ii) reduce refrigerant demand by 15%–30% by 2050, (iii) Reduce cooling energy requirements by 10%–20% by 2050.

5.1.6 Initial Results

All scenarios are projected to exceed the NDC1 target of reduction in emission intensity of the GDP, which is estimated to be higher than 33–35% (NDC Goal 3) ranging between 45 and 55% in 2030 relative to the 2005 level. This is closer to the updated NDC targets (NDC2).

Energy consumption in the residential sector is determined by the behavior of households, the ownership of various assets and appliances, and the amount of energy used by each appliance, while energy consumption in the commercial sector depends on the evolution of floor space. In the CPS scenario, the rate of ownership of electric, cooling, and heating appliances has increased due to rapid urbanisation and rising household incomes. This increase in En. NDC is higher than CPS scenario in 2030 (Figure 19). Increased technical efficiencies, EE and building improvements lead to a slight decrease in En. NDC scenario when compared to CPS scenario.

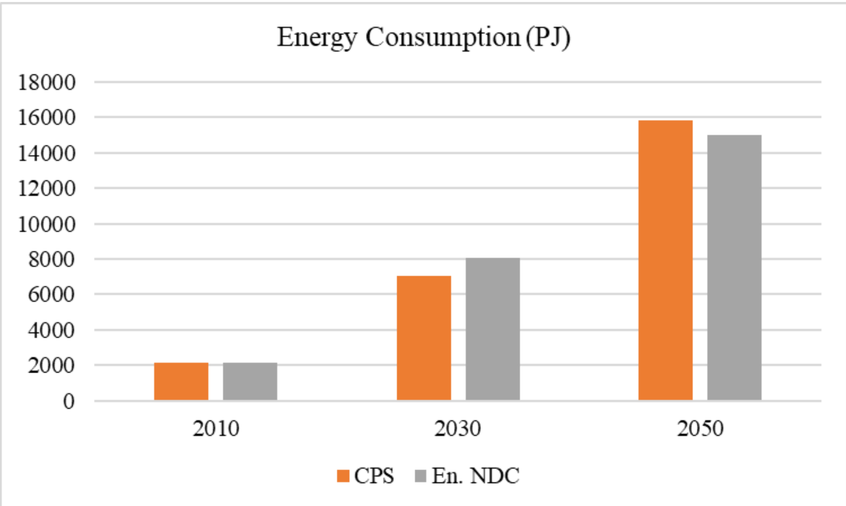

Figure 19: Energy demand in building sector of India

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In the past decade, policy interventions through regulatory (emission standards), economic (subsidies, taxes, tariffs) and information-related (labelling) instruments have led to reduced growth of Indian CO_2 emissions from the building sector (Figure 20). The latter was also driven by changes in economic structure and the electricity regulatory framework through a combination of on-going policies in addition to En. NDC. The En. NDC scenario considers ratcheted shift traditional biomass towards LPG and PNG and electrification after 2035. This move towards cleaner fuels presents an increase in direct CO2 emissions in buildings (between 2010 and 2030) when compared to CPS scenario followed by significant decrease between 2030 and 2050. This may be due to the increase in the quantity of appliances per household even though there is a significant decrease in the share of biomass use.

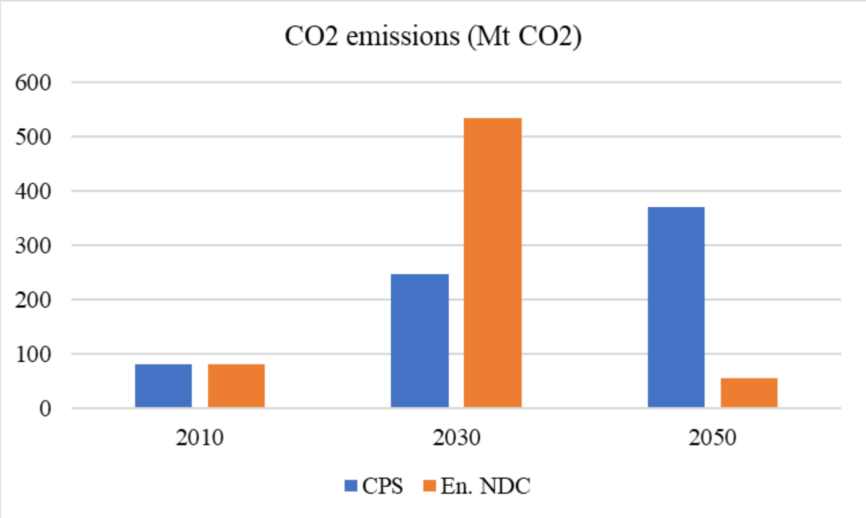

Figure 20: CO_2 emissions from building sector of India

5.2 Setting an ambitious and plausible 2035 NDC for the United States

5.2.1 Introduction

The United States, as the world's largest economy and second largest emitter, has an important role to play to ensure the delivery of sufficiently high levels of global ambition. The country has pledged to reduce emissions by 50-52% below 2005 levels by 2030 through its nationally determined contribution (NDC), with a long-term strategy to reach net-zero by 2050 [1,2]. Recent U.S. actions have made substantial contributions toward its climate targets: the historic Inflation Reduction Act (IRA) of 2022 and the Bipartisan Infrastructure Law (BIL) of 2021 are estimated to provide well over $1 trillion for clean energy and carbon storage incentives, transportation infrastructure, methane reduction measures, and more—a collective investment estimated to reduce emissions by 33-40% by 2030 [3–7].

At the same time, U.S. states, cities, and other non-federal entities have also been an important force behind increasing U.S. climate ambition [8–12]. For example, sub-national governments have been establishing renewable electricity targets, electric vehicle (EV) sales targets, building codes to increase efficiency and electrification, and more.13–15 Other non-federal actors, such as businesses and non-governmental organisations, have established innovative partnerships and collaboration through coalitions that have also supported climate action (i.e America Is All In, United States Climate Alliance). The policy authorities of these subnational governments and other non-federal actors collectively are contributing substantially to emissions reductions for 2030 [11,12].

With the next cycle of target setting under the Paris Agreement approaching, countries will be updating and submitting new NDCs over the next two years. To this end, there is a growing need for the United States to

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assess potential pathways toward a new, maximally ambitious 2035 NDC that would be in line with its net-zero goal by 2050, but also rooted in a plausible and attainable set of policy actions that can be delivered through both federal and non-federal actions. In this study, we examine pathways toward an ambitious and plausible 2035 NDC through policies, measures, and actions from both federal and non-federal actors.

Building upon previous work on federal and non-federal climate action, we provide an analysis of options that would enable the United States to not only meet its 2030 NDC, but also be on a path by 2035 toward net-zero in 2050 [11]. We use an integrated assessment model, combined with analysis to account for state-level climate actions, to first quantify the implications of existing actions, including IRA and major climate policies across all sectors and greenhouse gases. Then, we develop a comprehensive suite of new and expanded policy actions, including extending IRA provisions, and ratcheting up non-federal climate targets. We find that a comprehensive policy platform of federal, state, and other policies can deliver reductions in net GHGs of 65% below 2005 levels by 2035.

5.2.2 Scenario development

We use an enhanced version of GCAM-USA in this analysis to estimate the magnitude of potential economy-wide emissions reductions in the United States through 2035. The analysis centers around two scenarios: *Current Policies* and *Enhanced Ambition*. The *Current Policies* scenario includes the climate and energy provisions of the Inflation Reduction Act (IRA), the Bipartisan Infrastructure Legislation (BIL), and several other federal and non-federal climate policy actions. The *Enhanced Ambition* scenario assumes enhanced action from non-federal actors – states, cities, and businesses – with additional federal regulatory actions to achieve an ambitious new 2035 emissions reduction target. Both scenarios include top-down and bottom-up policy representation, with the latter building on previously developed methodology for aggregating non-federal actions to the state-level for implementation in GCAM-USA [16–20]. A detailed description of our methodology is provided in the following sections.

Current climate policy landscape in the United States

The recently passed Inflation Reduction Act (IRA) and Bipartisan Infrastructure Law (BIL) provide over a trillion in funds toward clean energy tax credits, electrification and energy efficiency measures, methane emissions reductions, and the expansion of electric vehicle charging infrastructure [21,22]. Existing executive actions include the Corporate Average Fuel Economy (CAFE) standards, which mandate the fuel efficiency of passenger cars and light duty trucks, and New Source Performance Standards (NSPS) under the sections 111(b) and (d) of the Clean Air Act (CAA), which set pollution limits on fossil fuel electricity generation.

Across sectors, subnational policies have the capability to build upon federal actions. States and cities are setting their own economy-wide emissions reductions goals and formulating policies to help them achieve their targets [23,24]. Within the power sector, state-level clean energy targets and local zoning ordinances can accelerate decarbonisation of electricity, such as Maryland's renewable portfolio standard (RPS), which mandates that electricity suppliers must procure 50% of their electricity from renewable sources by 2030, and the city of Austin's target of carbon-free electricity by 2035 [25,26]. Building sector mitigation can be hastened through state and city-level appliance standards and efficiency targets, such as legislation passed in the San Francisco Bay Area that bans new sales of nitric oxide (NO) and nitrogen dioxide (NO2)-emitting space heaters and water heaters, beginning with water heaters in 2027 [27]. Transportation decarbonisation measures include sales targets and incentives for phaseout of combustion engines, such as California's Advanced Clean Trucks (ACT) rule, which an increasing number of states are adopting, and investment in public transportation like the Indianapolis Public Transportation Corporation's (IndyGo) expansion of public bus routes and rollout of hybrid and electric buses [28,29]. Mandates for more stringent management of fugitive methane and hydrofluorocarbon (HFC) emissions alongside incentives for carbon capture utilisation and storage (CCUS), like New Mexico's 2022 legislation limiting venting and flaring at oil and gas sites, can similarly use subnational levers for industrial emissions reductions [18,30].

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Current Policies scenario

The *Current Policies* scenario includes existing federal policies – including several climate and energy provisions from the BIL and the IRA – and non-federal policies. Altogether, we find that these current policies can reduce emissions 45% below 2005 levels by 2035. Existing state-level RPS, CAFE standards, and several tax credits from the IRA for renewable electricity generation, zero-emissions vehicles (ZEVs), and carbon capture and storage (CCS) are among the key policy drivers in this scenario.

Enhanced Ambition scenario

The IRA, along with additional policies and actions from Congress, the federal government, states, cities, and businesses, collectively provide a major boost to climate action in the United States. Yet these existing policies will not be enough on their own for the United States to meet its 2030 climate target and achieve ambitious reductions through 2035 and beyond. Thus, our *Enhanced Ambition* scenario models greenhouse gas (GHG) emissions reductions achievable under a comprehensive, "all-in" climate strategy that builds upon the policy framework in the *Current Policies* scenario with enhanced non-federal and federal action. Altogether, these actions have the potential to deliver a 52% reduction in GHG emissions from 2005 levels by 2030, thus fulfilling its 2030 NDC, and a 65% reduction by 2035. Some of the additional policy actions modelled in this scenario include a full phaseout of unabated coal-fired electricity generation by 2030, accelerated adoption of ZEV in light-duty vehicle, bus, and freight truck markets, ramped up electric appliance standards, more stringent standards and oil and gas methane, as well as extensions of the existing IRA tax credits beyond their legislated sunset dates.

5.2.3 State tiering

State-level climate action in the United States varies considerably from across the country. For example, some states aim to achieve 100% ZEV sales in light duty vehicle (LDV) markets by 2035, while other states have less ambitious ZEV sales targets, and some lack ZEV sales targets entirely. Therefore, to account for the unequal ambition and urgency with which states implement policies and actions to reduce emissions, and to facilitate our scenario analysis, we group states into three different tiers. State-level tiering reflects the propensity of a state to take further climate action based on the strength of their past and current climate policies. Tier 1 states have been leading the way on climate action in the United States, while Tier 2 states have some policies in place, but tend to move slower. The rest of the states, categorized as Tier 3, have taken limited steps to advance climate action, and are assumed to be least likely to enact ambitious climate legislation.

- **Tier 1 states:** California, Colorado, Connecticut, Delaware, the District of Columbia, Hawaii, Illinois, Maine, Maryland, Massachusetts, Minnesota, New Hampshire, New Jersey, New Mexico, New York, Oregon, Pennsylvania, Rhode Island, Vermont, and Washington
- **Tier 2 states**: Arizona, Iowa, Michigan, Missouri, Nevada, North Carolina, Ohio, Virginia, and Wisconsin
- **Tier 3 states:** Alabama, Alaska, Arkansas, Florida, Georgia, Idaho, Indiana, Kansas, Kentucky, Louisiana, Mississippi, Montana, Nebraska, North Dakota, Oklahoma, South Carolina, South Dakota, Tennessee, Texas, Utah, West Virginia, and Wyoming

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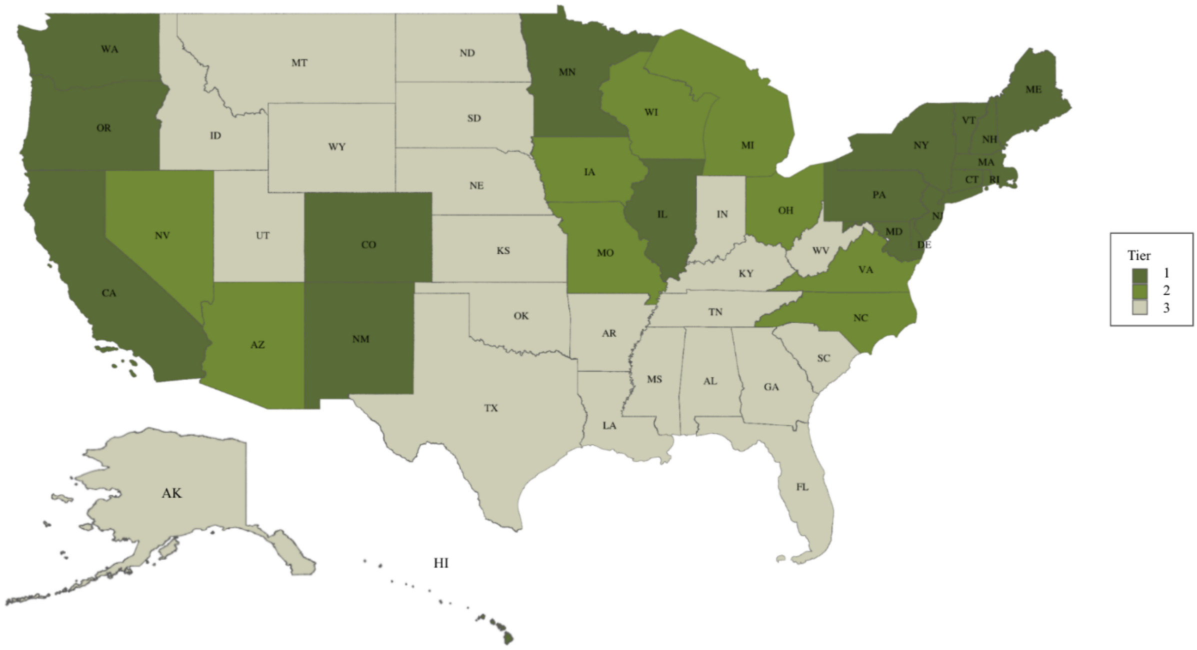

Figure 21: **State tiers used in the *Enhanced Ambition* scenario.**

5.2.4 Economy-wide Analysis

Overview of GCAM-USA-CGS

Our analysis uses a version of the open-source Global Change Analysis Model[23] (GCAM) to estimate the aggregate impact of federal and non-federal climate policies and actions on economy-wide emissions reductions in the United States. Specifically, we use GCAM-USA, a state-level version of GCAM. We refer to the version of GCAM-USA used in this study as GCAM-USA-CGS.

GCAM is an integrated assessment model (IAM) that covers the energy, land, water, climate, and socioeconomic systems. The global version of GCAM groups the world's countries into 32 geopolitical regions with representation of the energy and socioeconomic systems for each region. The United States is one of the 32 regions. GCAM represents the global climate system and uses 235 water basins and 384 land regions to represent global water and land systems. GCAM tracks emissions and sinks of carbon dioxide (CO_2), 16 other GHGs, and several air pollutants.

The state-level version of GCAM used in this analysis, GCAM-USA, disaggregates the U.S. energy and economy components into 50 states and the District of Columbia while maintaining the same level of detail as GCAM for water and land sectors. The energy system in GCAM-USA has representations of depletable primary sources such as coal, gas, oil, and uranium, in addition to renewable resources such as biomass, hydropower, solar, wind, and geothermal. Energy transformation processes like oil refining and electricity generation are represented at the state-level in GCAM-USA. These energy carriers, in turn, are used to deliver services to state-level end users in the buildings, transportation, and industrial sectors. The electric power sector includes representations of a range of power generation technologies, including those fuelled by fossil fuels and bioenergy (with and without CCS), renewables, and nuclear power.

GCAM-USA is a market equilibrium model. The model solves for equilibrium in each period by finding a set of market prices such that supplies and demands are equal to one another in all markets as the actors in the model adjust the quantities of the commodities they buy and sell. GCAM operates in 5-year time-increments, with each new period starting from the conditions that emerged in the last, with most technologies vintaged such that a

[23] https://www.i2am-paris.eu/detailed_model_doc/gcamv2022

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portion of existing stocks at any point carry over into future time periods.

GCAM-USA-CGS is based on the open-source release of GCAM-USA 6.0 [31]. GCAM-USA-CGS has been updated for the purposes of this study to reflect changes such as the most recent estimates of future renewable energy costs [32]. The model is also calibrated to the latest non-CO2 marginal abatement cost curves from the U.S. Environmental Protection Agency (EPA) [33].

Overview of modelling approach

Policy representation in our modelled scenarios builds upon bottom-up aggregation tools and data analysis to evaluate and quantify the impacts of policies and climate actions in isolation and within specific sectors. Throughout, we took care to avoid potential double counting of potential emissions reduction drivers from nested governance levels. We then used this information in GCAM-USA-CGS to estimate the economy-wide implications of associated policies.

All modelled policies in GCAM-USA-CGS are implemented at the state and/or national levels. Therefore, policies and actions from city governments, businesses, and institutions were aggregated to the state-level or assumed to be embedded within or supportive of the state and/or national level policy representation in the model, and therefore not explicitly modelled to remove risk of double counting potential emissions reductions. Detailed descriptions of policy representation in GCAM-USA-CGS can be found in Tables 6-9.

Model parameters in GCAM-USA-CGS varied according to information from our bottom-up aggregation analysis or changed directly for policy drivers where bottom-up aggregation was either not feasible or not necessary in the case of small-scale potential impacts. The purpose of this analysis is to assess the national emissions reduction potential in the United States for the policies modelled in our scenarios. Accordingly, non-federal policies and actions are only modelled to the extent that doing so would have a meaningful impact on the national-level emissions outcome. In some policy areas, we did not specify state-level variation in policy implementation – for example, with bus electrification – as assessment of the national-level emissions impact does not require state-level precision.

The policies and actions described below were compiled up until August 2023. Nor or changed policies and actions taken after this point are not included in this analysis.

Modelled IRA provisions

Both scenarios include over 20 IRA provisions, which are listed below. Detailed assumptions for these policies are described in Tables 6-9.

Electricity

- Section 13101: Production tax credit (PTC)
- Section 13102: Investment tax credit (ITC) extension
- Sections 13701 & 13702: New clean electricity PTC and ITC
- Section 13302: Residential clean energy credit
- Section 13015: PTC for existing nuclear
- Section 50144: Energy infrastructure reinvestment financing
- Section 13104 – 45Q: Extension of credits for captured CO_2

Transportation

- Section 13401 – 30D: Clean vehicle credit
- Section 13404: Alternative refuelling property credit
- Section 13403 – 45W: Commercial clean vehicle credit

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- Sections 13201, 13202, and 13203: Extension of incentives for biofuels

Buildings

- Section 13303: Energy efficient commercial building deduction
- Sections 13301 – 25C, 13304, and 50121: Energy efficient home improvement credit, Energy efficient home credit, and Home energy efficiency credit
- Section 51022: High efficiency home rebate program

Industry and other sectors

- Section 13104 – 45Q: Extension of credits for captured CO_2
- Section 13204 – 45V: Production credit for clean hydrogen
- Section 13501 – 48C: Manufacturing investment tax credit for advanced energy projects
- Section 50161: Advanced industrial facilities deployment program
- Section 60113: Methane emissions reduction program

Core model assumptions

The results of this study depend on many assumptions about how the U.S. and the world might evolve in the future. This study uses a set of core assumptions for drivers including economic growth, population growth, fossil fuel prices, demand impacts of the COVID-19 pandemic, and technology costs (Table 5). Our core assumptions draw from a set of data sources that are referenced in other parts of this appendix, for example U.S. Energy Information Agency (EIA)'s Annual Energy Outlook (AEO) [34] and Rhodium Group [35]. Economic impacts associated with COVID-19 in 2020 and subsequent recovery in the following years have also been incorporated into these assumptions.

Table 5: Core Assumptions for GCAM-USA-CGS Analysis

Drivers	Scenario assumptions
Economic Growth	Overall gross domestic product (GDP) decreases by 3.5% year-on-year on average in 2020, then increases by 2.1% per year on average through 2035.
Population Growth	Population grows by 0.61% per year on average through 2035.
Fuel Prices	Gas price is assumed to drop by 19.5% year-on-year in 2020, increase by 89% in 2021, then decrease at an average rate of 7.1% per year through 2025. Prices increase 0.1% on average between 2025 and 2035. Oil price is assumed to drop by 33.9% year-on-year in 2020, increase by 78.4% in 2021. Prices increase at an average rate of 0.7% per year between 2021 and 2035.
Transportation Energy Demand	Transport sector energy demand is assumed to decrease by 6.9% from 2015 levels in 2020, with recovery through 2030.
Industry Energy Demand	Industry sector energy demand is assumed to decrease by 3.1% from 2015

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	levels in 2020, with recovery through 2030.
Buildings Energy Demand	Buildings sector energy demand is assumed to decrease by 1.9% from 2015 levels in 2020, with recovery through 2030.
Technology Costs	Technology costs are updated with the National Renewable Energy Laboratory (NREL) Annual Technology Baseline 2022 assumptions.[32]

Electricity modelling assumptions

In this and subsequent sections the modelling assumptions are provided in tables that identify the type of policy, the specific portion of the policy (where relevant), and column with a description of the assumptions used in the *Current Policies* scenario, followed by a description (where different) of how the policy is modelled in the *Enhanced Ambition* scenario.

Table 6. Implementation of Policy Assumptions for the Electricity Sector in GCAM-USA-CGS

Type of Policy	Modelled Policy	*Current Policies* Scenario	*Enhanced Ambition* Scenario
Federal – IRA	Section 13101: PTC	Modelled as a $26/MWh subsidy for solar, wind and geothermal technologies through 2024. We assume that all projects pay prevailing wages. A 7.5% reduction in the credit value is assumed due to the transferability provision.	
	Section 13102: ITC extension	Modelled as a 30% subsidy for offshore wind and storage technologies through 2024, with the simplifying assumption that all projects pay prevailing wages. A 7.5% reduction in the credit value is assumed due to the transferability provision.	
	Sections 13701 and 13702: New clean electricity PTC and ITC	Modelled in the same way as sections 13101 and 13102 through 2030, with phasedown after 2030.	In addition to the assumptions under *Current Policies*, the subsidies are extended through 2035.
	Section 13302: Residential clean energy credit	Modelled by updating the rooftop ITC, which results in an additional 0.7GW/yr increase in electricity generation from rooftop solar photovoltaic (PV) on the lifetime of the credit through 2035.	
	Section 13015: PTC for existing nuclear	Modelled as a $15/MWh subsidy for nuclear technologies through 2030, with the simplifying assumption that all projects pay prevailing wages. We assume that these incentives, in combination with non-federal incentives and ZEV credits, prevent the economic retirement of nuclear plants. As such, we model Georgia Vogtle units 3&4 coming online by 2025, and maintain	

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		nuclear capacity at today's levels.	
	Section 50144: Energy infrastructure reinvestment financing	Modelled as $250 billion in loans and guarantees used to accelerate the retirement of coal-fired power generation and fund the construction of renewable electricity-generating capacity. We estimate this to accelerate the retirement of 38 GW of additional coal-fired capacity beyond already-scheduled retirements by 2030.	
	Section 13104 - 45Q: Extension of credits for captured CO_2	Credits for CO_2 captured by projects that commence construction between 2023 and 2032 are applied to CCS technologies at a value of $51/ton. These credits assume that half of projects meet prevailing wage and apprenticeship requirements, but do not assume that all projects meet these requirements and receive the full credit value available ($85/ton). CCS technology deployment endogenously responds to these subsidies.	Credits for CO_2 captured by projects that commence construction between 2023 and 2032 are applied to CCS technologies at a value of $68/ton.These credits assume that half of projects meet prevailing wage and apprenticeship requirements, but do not assume that all projects meet these requirements and receive the full credit value available ($85/ton). CCS technology deployment endogenously responds to these subsidies.
Federal – Regulations	CAA section 111(b) Standards for New Stationary Combustion Turbines	Not explicitly modelled in this scenario.	New proposed federal standards under CAA section 111(b) require at least 90% CCS for any new baseload natural gas builds in all states by 2035. This was modelled by reducing new baseload natural gas power plants without CCS starting in 2025 and eliminating new baseload natural gas power plants without CCS by 2030. This reflects an expectation that investors will change their behaviour in anticipation of the 2035 policy target, especially in light of the 111(d) emissions guidelines described below. Retention and investment in low capacity factor peaking plants were assumed to be supportive of these measures and were not explicitly modelled.
	CAA section 111(d) Emission Guidelines for Existing Fossil Fuel-Fired	Not explicitly modelled in this scenario.	New proposed federal standards under CAA section 111(d) for large, frequently used combustion turbines include two pathways: 96% low-GHG hydrogen in 2038 or 90% CCS in 2035. This was modelled by

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	Sources		mandating that all high-capacity factor natural gas power plants either retrofit with CCS by 2035 or cease operating (as determined by the economics of retrofitting). EPA is taking comment on standards for lower capacity factor other stationary combustion turbines, so low-capacity factor peaking plants were not subject to the retrofit requirements.
Non-federal	RPS	Current state-level RPS targets are modelled. City- and utility-level goals were assumed to be supportive of these state-level targets and additional only in cases where a higher percentage is targeted. These were implemented by setting a minimum % of total electricity load to be met by renewable generation.	RPS targets of at least 75% by 2035 for high ambition states and 55% for moderate ambition states are assumed. City- and utility-level goals were assumed to be supportive of these state-level targets and additional only in cases where a higher percentage is targeted. These were implemented by setting a minimum % of total electricity load to be met by renewable generation.
	Cap and Trade	The Regional Greenhouse Gas Initiative (RGGI) is modelled as a 30% reduction in power sector emissions below 2020 levels by 2030 in participating states.	
Coal phaseout		Not explicitly modelled in this scenario	Coal is phased out by 2030 due to a combination of market forces, state coal-exit policies, and regulatory compliance costs. This was modelled by setting a national constraint on coal power to reach zero by 2030, and by prohibiting the buildout of new coal plants in all states.

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Transportation sector modelling assumptions

Table 7. Implementation of Policy Assumptions for the Transportation Sector in GCAM-USA-CGS

Type of Policy	Modelled Policy	*Current Policies* Scenario	*Enhanced Ambition* Scenario
Federal – IRA	Section 13401 - 30D: Clean vehicle credit	This tax credit has a maximum value of $7,500 with an EV being eligible for half of the credit if its battery meets domestic assembly requirements and other half of the credit is contingent upon a specific share of the minerals used in the battery being sourced for North American or other free trade countries. We assume that the U.S. auto manufacturing sector will reorient itself so that all new EVs produced by 2030 will meet these requirements, and that by 2025, half of EVs sold will meet these requirements. If the car meets the battery assembly and mineral sourcing requirements, a consumer can receive the full value of the tax credit provided that their income does not exceed the income eligibility threshold and that the sales price of the car does not exceed manufacturer's suggested retail price (MSRP) eligibility thresholds. We find that 89% of Americans meet the income requirement and further assume that they would only purchase EVs that meet the MSRP threshold. Altogether, this yields an EV tax credit with an effective value of $6,673, implemented as a capital cost reduction. We assume that for the 2031-2035 model period that the tax credit takes on a value 40% of the 2030 value because it is scheduled to expire in 2032.	In addition to the assumptions under *Current Policies*, the tax credit is extended to be available through 2035.
	Section 13404: Alternative refuelling	This credit is assumed to be a $1,000 property credit available for LDV charging infrastructure for individuals in rural and low-income	In addition to the assumptions under *Current Policies*, the tax credit is extended to be available through

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	property credit	census tracts. Based on census data, 17.4% of Americans live in counties that are either rural or low-income, so the $1,000 property credit is modelled as a weighted average national subsidy of $174 for capital infrastructure cost for EVs. We assume that for the 2031-2035 model period that the tax credit takes on a value 40% of the 2030 value because it is scheduled to expire in 2032.	2035.
	Section 13403 - 45W: Commercial clean vehicle credit	This tax credit is modelled as a $40,000 capital cost reduction for electric heavy duty freight trucks, and a $7,500 capital cost reduction for electric medium duty and light duty freight trucks. We assume that for the 2031-2035 model period that the tax credit takes on a value 40% of the 2030 value because it is scheduled to expire in 2032.	In addition to the assumptions under *Current Policies*, the tax credit is extended to be available through 2035.
	Sections 13201, 13202, and 13203: Extension of incentives for biofuels	Implemented as subsidies in 2025 for biodiesel, cellulosic ethanol, Fischer Tropsch (FT) biofuels, cellulosic ethanol with CCS, and FT biofuels with CCS. We assume that jet fuel is the first market for FT biofuel, and FT biofuels therefore receive the aviation fuel credit.	In addition to the assumptions under *Current Policies*, the tax credit is extended to be available through 2035.
Federal – BIL	Section 11401 and 11403: Grants from charging and fuelling infrastructure, Carbon reduction program, and National Electric Vehicle Formula Program	BIL's $10.7 billion investment in LDV EV charging infrastructure is implemented as an $802 reduction in per vehicle charging infrastructure cost, based on modelled vehicle fleet size in GCAM-USA-CGS 6.0, for model periods 2025 and 2030.	
	Section 11115 and 11403:	BIL's $4.24 billion investment in medium- and heavy-duty truck EV charging infrastructure is implemented as a $9,211 reduction in per vehicle charging	

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	Congestion mitigation and air quality improvement program, and Carbon reduction program	infrastructure cost, based on fleet size in GCAM-USA-CGS 6.0, for model periods 2025 and 2030.	
	Sections 71101 and 30018: Clean school bus program and Grants for buses and bus facilities	BIL's \$5 billion investment in school bus electrification is implemented as a \$25,000 reduction in per vehicle purchase cost for model periods 2025 and 2030. A \$2.625 billion investment in transit bus electrification is implemented as a \$29,167 reduction in per vehicle purchase cost for model periods 2025 and 2030.	
Federal – Regulations	CAFE standards for LDVs	Internal combustion engine GHG performance standards are modelled to reflect efficiency improvement rates from recently updated CAFE so that nationally, fuel efficiency reaches 166 gCO_2/mi for new passenger cars and 219 gCO_2/mi for new SUVs by 2030. Note: these are based on the National Highway Traffic Safety Administration (NHTSA) minimum standard and are not inclusive of ZEVs.	Federal internal combustion engine GHG performance standards are improved so that nationally, fuel efficiency reaches 143 gCO_2/mi for new passenger cars and 193 gCO_2/mi for new SUVs by 2030.
	GHG emissions standards for freight trucks	Internal combustion engine GHG performance standards are modelled to reflect efficiency improvement rates existing GHG emissions standards for heavy duty gasoline- and diesel-powered engines.	Same as in the *Current Policies* scenario through 2025. Efficiency is assumed to improve further by 5% from 2026-2030 and again from 2031-2035.
	Accelerated retirement of old, inefficient LDVs	Not explicitly modelled in this scenario.	Modelled as a "cash-for-clunkers" style program that accelerates the retirement of LDVs produced in 2015 and prior, effectively reducing the share of the 2015 and prior vintage cars remaining on the road in 2030 from 28% to 18%.

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Non-federal	LDV ZEV sales mandates and targets	California and the 10 other states that have adopted ZEV sales targets consistent with California's Advanced Clean Cars (ACC) II legislation are assumed to achieve their passenger car sales target of 68% electric in 2030 and 100% in 2035. Additionally, the 5 states that have only adopted legislation consistent with California's ACC I legislation are modelled to have ZEV sales reach 22% in 2025.	Tier 1 states are assumed to achieve ZEV sales shares equivalent to targets set by California. Tier 2 and Tier 3 states are assumed to achieve these sales shares but on a delayed schedule, 3 years later (Tier 2 states) and 6 years later (Tier 3 states) than Tier 1 states.
	LDV ZEV incentives	Major existing incentives for LDV ZEVs at the state-, utility-, and district-level from the Alternative Fuels Data Center are modelled at the state-level as reductions in per vehicle capital cost. Altogether, these are equivalent to a national average capital cost reduction for LDV EVs of $826 per vehicle.	
	Freight truck ZEV sales mandates and targets	California and 12 other states are assumed to achieve sales targets for electric trucks through 2035 consistent with California's ACT legislation.	Tier 1 states are assumed to achieve ZEV sales shares equivalent to targets set by California. Tier 2 and Tier 3 states are also assumed to achieve these sales shares but on a delayed schedule, 3 years later (Tier 2 states) and 6 years later (Tier 3 states) than Tier 1 states.
	Bus ZEV incentives and sales targets	Not explicitly modelled in this scenario.	A combination of federal and non-federal investments and fleet procurement targets lead to 100% electrification of new bus sales in 2030. This was modelled by raising the national-level sales shares to reach 100% electric by 2030.
	Vehicle miles travelled (VMT) reductions	Not explicitly modelled in this scenario.	Federal investment, state and local planning lead to annual average per capita passenger transportation demand reductions ranging from 0.75% to 1.25% in all states from 2025-2035 (consistent with current ambition in Tier 1 states). Annual average per capita VMT reductions were modelled as state-level service demand reduction rates for passenger mode transit.

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Building sector modelling assumptions

Table 8. Implementation of Policy Assumptions for the Buildings Sector in GCAM-USA-CGS

Type of Policy	Modelled Policy	*Current Policies* Scenario	*Enhanced Ambition* Scenario
Federal – IRA	Section 13303: Energy efficient commercial building deduction	This provision is estimated to reduce commercial HVAC costs by 3%. This was modelled as a 3% subsidy for commercial high-efficiency heating and cooling technologies in 2025 and 2030.	In addition to the assumptions under *Current Policies*, the subsidies are extended through 2035.
	Sections 13301 - 25C and 13304 and 50121: Energy efficient home improvement credit, Energy efficient home credit, and Home energy efficiency credit	Modelled by improving shell efficiency in residential buildings based on the AEO 2022 "Alternative Policies – Extended Credit" case.[36]	
	Section 51022: High efficiency home rebate program	Modelled as a subsidy to high-efficiency technologies in residential buildings in 2025 and 2030. Two-thirds of consumers are assumed to be eligible for this credit, so this was implemented as a weighted average across all consumers with the effective value of the credit modelled to be 66% of each of the following: $1,750 to electric heat pump water heaters, $4,000 to electric heat pumps for space heating, $420 to electric ovens, $420 to electric heat pump clothes dryers, $1,600 for high-efficiency air conditioning.	In addition to the assumptions under *Current Policies*, the subsidies are extended through 2035.
Non-federal	Energy efficiency standards (EERS)	Current state-level EERS were modelled by reducing state-level building service demands. However, the energy savings yielded are insignificant at the national level.	Heightened EERS and building codes were modelled by reducing state-level building service demands. This leads to national energy savings of up to 7% for residential buildings and up to

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			10.7% for commercial buildings by 2035. See Section 5 for more details.
	Electrification incentives	Not explicitly modelled in this scenario.	Zero emissions appliance standards were modelled by driving space heating and water heating sales to 100% electric by 2030 in Tier 1 states and 2035 in Tier 2 states. The residential and commercial buildings sectors each achieve 67% electrification by 2035. See Section 5 for more details.

Industry and other sectors modelling assumptions

Table 9. Implementation of Policy Assumptions for Industry and Other Sectors in GCAM-USA-CGS

Type of Policy	Modelled Policy	*Current Policies* Scenario	*Enhanced Ambition* Scenario
Federal - IRA	Section 13104 - 45Q: Extension of credits for captured CO_2	Credits for CO_2 captured by projects that commence construction between 2023 and 2032 are applied to relevant technologies at a value of $51/ton for CCS. These credits assume that half of projects meet prevailing wage and apprenticeship requirements, but do not assume that all projects meet these requirements and receive the full credit value available ($85/ton). Existing credits for captured CO_2 at $85/ton is implemented as a subsidy for cement and ethanol CCS respond to these subsidies endogenously, resulting in 9 $MtCO_2$ annual sequestration by 2035.	As a result of this subsidy, it is assumed that all states with cement production install CCS capability for 40% of cement produced by 2035, consistent with California's 40% goal.[37] This subsidy is also assumed to result in sequestration levels from ethanol CCS consistent with Rhodium Group's analysis by 2035 [38]. A small amount of CCS in the paper and pulp industry is modelled, well below the U.S. share of global potential identified in the literature [39]. Sequestration was exogenously specified across various industrial sectors, resulting in 85 $MtCO_2$ annual sequestration.
	Section 13204 - 45V: Production credit for clean hydrogen	Modelled as different subsidies to hydrogen technologies depending on their carbon intensities. Fossil hydrogen without CCS is assumed to claim 45Q instead. 50% of projects are assumed to pay prevailing wages.	

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	Section 13501 - 48C: Manufacturing investment tax credit for advanced energy projects	Designates $10 billion for industrial and manufacturing facilities aiming to equip themselves with technology to curtail GHG emissions. This was modelled by specifying electrification rates aligned with an Energy Innovation analysis on low-temperature heating in the industrial sector [40].	
	Section 50161 - Advanced industrial facilities deployment program	Designates $5.8 billion towards advanced industrial technology at energy intensive industrial and manufacturing facilities. This was assumed to result in faster equipment stock turnover for fossil fuels, modelled by shortening the average lifetime of existing industrial facilities.	In addition to the assumptions under *Current Policies*, we assume that new coal is not used as a fuel source in all industries.
	Section 60113: Methane emissions reduction program	This provision has a fee of \$1,500/tCH_4 (\$60/tCO_2e) on fugitive methane, modelled to reduce 2.92 MtCH_4 (73 MTCO_2e) in the oil and gas sector, using the EPA's MAC curves for methane [33]. Because this fee only applies to sources covered under the EPA's GHG Reporting Program, only 39% of the emissions reductions are assumed to be achieved [41], resulting in a reduction of 2.04 MtCH_4 (51 MtCO_2e) below 2020 levels by 2030. This reduction is also inclusive of the recently finalized oil and gas methane regulations that we assume delivers all reductions achievable from the EPA's MAC's curves at a cost below \$0/tCO_2e for this sector.	An economy-wide methane fee of \$1,500/tCH_4 (\$60/tCO_2e) was modelled, using the EPA's MAC curves for methane and the activity reduction drivers for oil & gas, coal, and waste as calculated in our previous report on methane emissions reduction potential in the U.S.[42] This resulted in methane reductions of 8.72 MtCH_4 (212 MtCO_2e) below 2020 levels by 2035.
HFCs		National HFC phasedown is implemented consistent with the American Innovation and Manufacturing (AIM) Act, reducing emissions up to 47% below 2020 levels by 2035 (consistent with analysis and modelling results developed by California Air and	National HFC phasedown is implemented consistent with the AIM Act. Tier 1 states achieve additional reductions through more comprehensive measures including Significant New Alternatives Policy (SNAP) and Refrigerant Management Programs (RMP) programs, reducing emissions up to 54% below 2020 levels by 2035 (consistent with analysis and modelling results

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	Resources Board (CARB)).[24]	developed by CARB) [12].
Land use, land-use change and forestry (LULUCF)	LULUCF emissions for CO_2 and N_2O are specified exogenously and adapted from *America Is All In*'s forthcoming lands sector report.[43] *Current Policies* assumes full implementation of roughly $42 billion of current state and federal policies in agriculture and forestry practices, including BIL and IRA. This results in a carbon sink of 765 $MtCO_2e$ from forestry and 31 $MtCO_2e$ from agriculture, which increases sequestration potential by 30 $MtCO_2e$ from 2020 levels. For CH_4 emissions assumptions, please see *Section 60113: Methane emissions reduction program* above.	LULUCF emissions for CO_2 and N_2O are specified exogenously and adapted from *America Is All In*'s forthcoming lands sector report.[43] *Enhanced Ambition* assumes an increase of $160 billion in investments in climate-smart policies resulting from enhanced state-level action. This results in a carbon sink of 778 $MtCO_2e$ from forestry and a carbon sink of 62 $MtCO_2e$ from agriculture, which increases sequestration potential by 74 $MtCO_2e$ from 2020 levels. For CH_4 emissions assumptions, please see *Section 60113: Methane emissions reduction program* above.
Economy-wide GHG targets	Not explicitly modelled in this scenario.	Tier 1 states are assumed to achieve their near- and long-term economy-wide GHG targets. Economy-wide GHG constraints were modelled for states that were more than 1 $MtCO_2e$ away from their target in 2035, including California, Washington, and New Jersey.
Direct air carbon capture and storage (DACCS)	Not explicitly modelled in this scenario.	DACCS is included as an additional mitigation option, resulting in 31 $MtCO_2$ of annual removals by 2035. This level of removal is consistent with announced DACCS facilities in the United States [44].

[24] Emissions impacts from national and state-level HFC regulations were derived from a short-lived climate pollutant tool developed by CARB and extrapolated to additional states. We used the tool's Kigali phasedown scenario as a proxy for the impact of the AIM Act.

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5.2.5 Results

Assessing the emissions impacts of Current Policies and Enhanced Ambition

The *Current Policies* scenario delivers a 40% reduction in GHG emissions in 2030 and a 44% reduction in 2035, relative to 2005 levels (Figure21). Emissions decrease only slightly through 2050. Between 2020 and 2030, the average rate of emissions reduction is 123 $MtCO_2e$/year. The rate between 2030 and 2035 is around half that at 60 $MtCO_2e$/year, as existing policies begin to expire or impacts otherwise taper off.

In contrast, the *Enhanced Ambition* scenario includes expanded and new actions from both the federal government and non-federal actors and delivers 53% (52.6%) in emissions reductions by 2030, at the upper end of the current U.S. NDC range. By 2035, emissions reductions reach 65%, and by 2050, net zero is achieved (Figure 22). The average rate of emissions reduction from 2020 to 2030 is 208 $MtCO_2e$/year, and 167 $MtCO_2e$/year between 2030 and 2035.

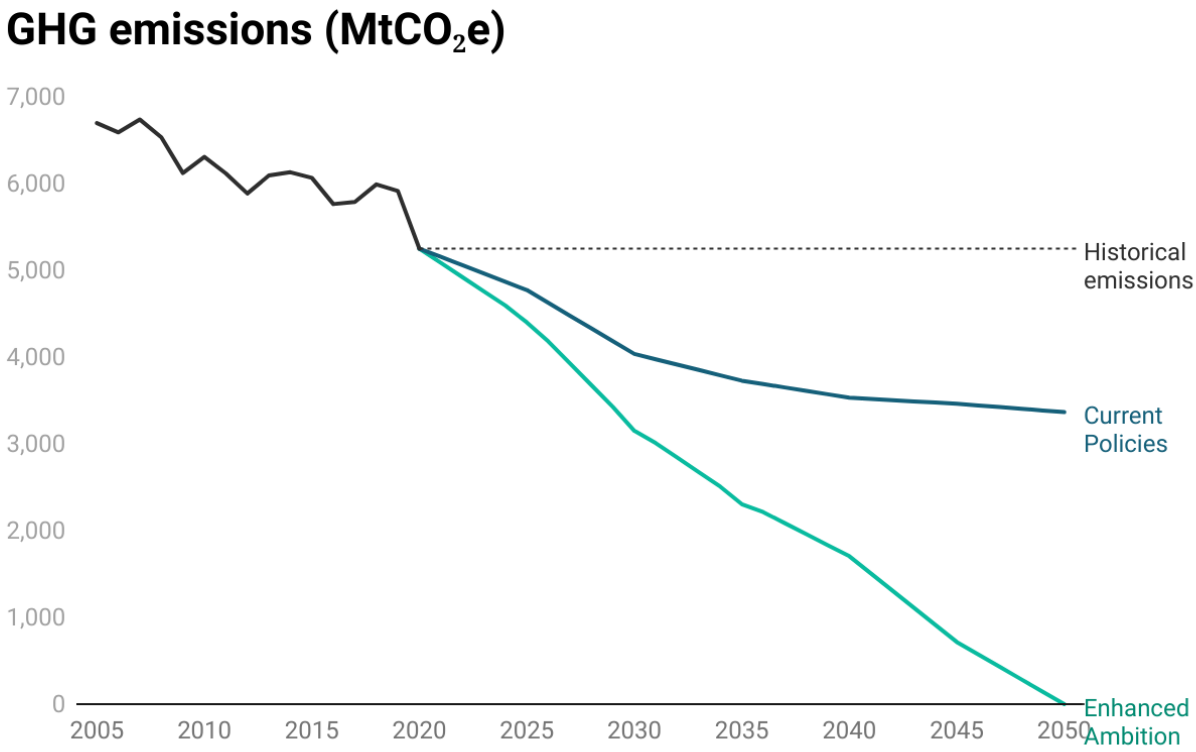

Figure 22: U.S. GHG emissions from 2005 - 2035. Historical emissions through 2020 are taken from the latest available U.S. Environmental Protection Agency (EPA) inventory [45]. The *Current Policies* scenario achieves 44% emissions reductions below 2005 levels by 2035 in the central case. The *Enhanced Ambition* scenario achieves 65% reductions in the central case.

The *Enhanced Ambition* scenario requires expanded mitigation across all sectors and greenhouse gases, with expanded emphasis in sectors like buildings, industry, and methane, paired with continued action in the electricity and transportation sectors, which still deliver the bulk of overall reductions (Fig. 22).

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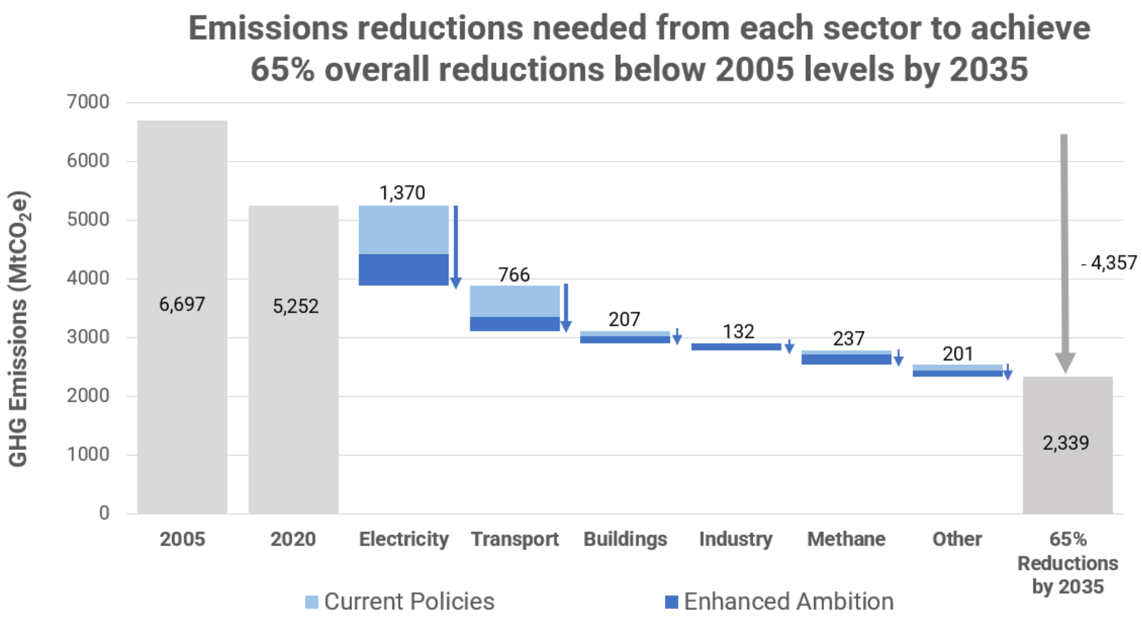

Figure 23: Combined federal and non-federal actions across the U.S. economy allow the United States to achieve a 65% reduction by 2035. Bars show GHG emissions in CO_2 equivalents, with reductions across the power, transport, buildings, industry, methane, and other sectors under *Current Policies* and *Enhanced Ambition* scenarios. Gray bars represent total emissions in 2005, 2020, and 2035. Blue bars represent emissions reductions needed from each sector between 2020 and 2035, with reductions from the *Current Policies* scenario in light blue, and the additional reductions from the *Enhanced Ambition* scenario in dark blue.

Figure 23 shows the breakdown of sectoral emissions reductions needed to achieve the 2035 reductions in the *Enhanced Ambition* scenario, starting from 2020 emissions levels. The electricity sector has the largest emissions reductions at 1,370 $MtCO_2e$ between 2020 and 2035, contributing to 47% of the overall reductions in this period. As the sector with the second largest reductions, the transportation sector contributes to 26% of the overall reductions at 766 $MtCO_2e$. Buildings, industry and methane sectors contribute to 20% of the overall reductions at 207 $MtCO_2e$, 132 $MtCO_2e$, and 237 $MtCO_2e$ respectively, while the "other" sector, which includes direct air capture (DAC), land-use, land-use change, and forestry (LULUCF) CO_2, other CO_2, nitrous oxide (N_2O), and fluorinated gases, contributes the remaining 7%.

Decarbonising the electricity grid

The electricity sector achieves the largest emissions reductions in 2035 under both scenarios. The *Enhanced Ambition* scenario achieves a 76% emissions reduction from 2020 levels by 2030 (1,105 $MtCO_2e$), declining to a 94% reduction by 2035 (1,370 $MtCO_2e$). In contrast, under *Current Policies*, the power sector achieves a 54% emission reduction by 2030 (786 $MtCO_2e$). Furthermore, little progress is made between 2030 and 2035—only a 3-percentage point increase—as IRA tax credits expire and we assume no additional enhancement of renewable electricity targets and fossil fuel power plant regulations.

Total electricity demand increases by 41% from 3,739 TWh in 2020 to 5,301 TWh by 2035 under *Enhanced Ambition*, compared to 5,153 TWh in 2035 under *Current Policies* (Fig. 23). There is not a dramatic difference in electricity demand between scenarios due to additional efficiency measures in end-use sectors under *Enhanced Ambition*. Still, to match the rapid electrification in end-use sectors, very large expansion of renewables and the use of fossil with CCS will be necessary.

Under *Enhanced Ambition*, solar generation increases by seven-fold and wind generation increases by four-fold from 2020 to 2035, with wind making up a slight majority of renewable generation. Solar generation increases

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by 803 TWh from 2020 levels in 2030 and by 1,273 TWh in 2035, while wind generation increases by 1,098 TWh in 2030 and 1,625 TWh in 2035. For comparison, the highest decadal rates of coal and gas expansion are 575 TWh (1978-1998) and 639 TWh (2009-2019), respectively [46].

The share of gas with CCS is less than 1% of the generation mix in 2025 but rises to 18% by 2035. Meanwhile, unabated coal-fired power plants retire by 2030, and unabated gas-fired generation falls by 87% from 2020 levels in 2035, with a small number of peaker gas plants and gas back-up generators remaining to stabilize the power grid. Correspondingly, *Enhanced Ambition* achieves a generation mix that is 96% powered by clean technologies (Fig. 4). Clean sources include solar, wind, geothermal, nuclear, hydropower, and biomass and CCS technologies.

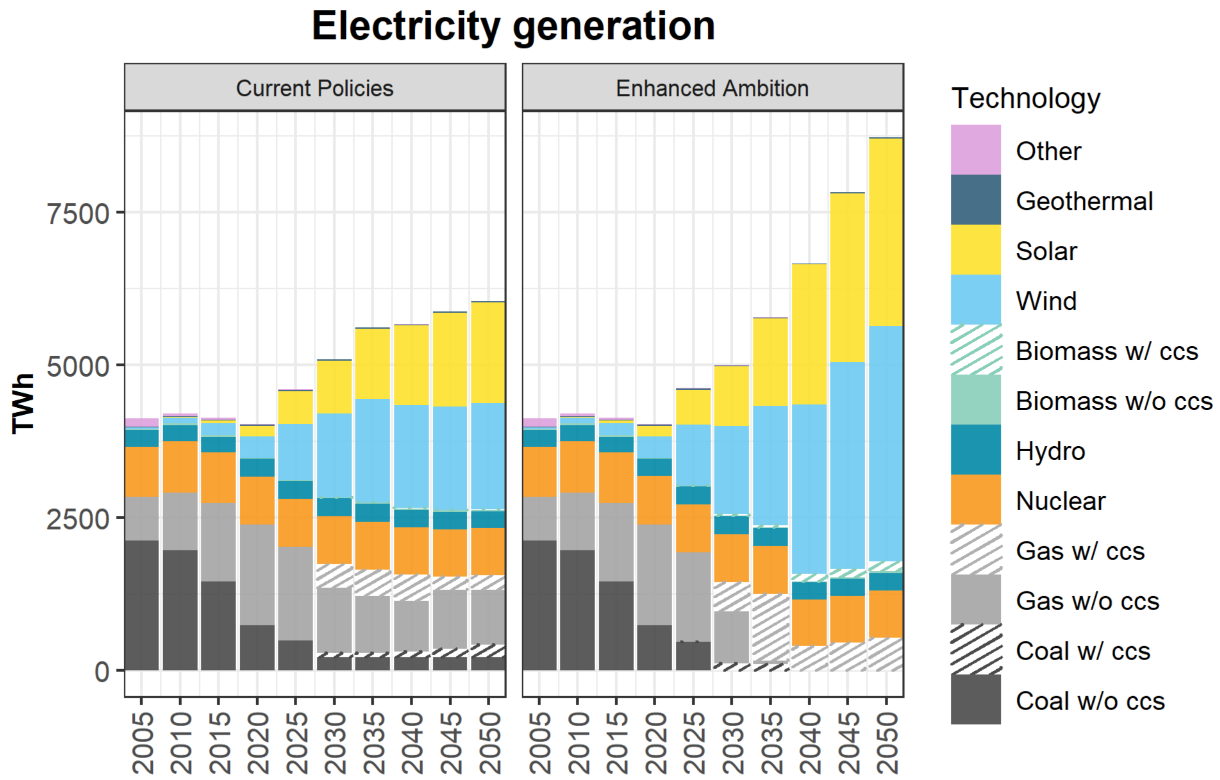

Figure 24: Electricity generation mix in units of terawatt hours (TWh) under *Current Policies* and *Enhanced Ambition*. By 2035, electricity generation reaches 50% renewable and 78% clean under the *Current Policies* scenario, and 57% renewable and 96% clean under the *Enhanced Ambition* scenario. Renewable sources include solar and wind technologies. Clean sources include solar, wind, geothermal, nuclear, hydropower, and biomass and CCS technologies.

Rapid electrification of passenger and freight vehicles

The transportation sector is the second largest source of emissions reductions in both scenarios, with electrification of road vehicles being the primary driver of these reductions. Transportation emissions under *Enhanced Ambition* decline by 48% below 2020 levels in 2035 (766 $MtCO_2e$), compared to 33% under *Current Policies* (519 $MtCO_2e$).

A combination of EV tax credits from IRA, EV charging infrastructure investments from BIL, Corporate Average Fuel Economy (CAFE) standards, and state-level incentives and mandates accelerates road transport electrification in *Enhanced Ambition.* Electric light duty vehicle (LDV) sales reach 83% by 2035, in contrast to 45% by 2035 under *Current Policies* (Fig. 25). Freight trucks reach 42% EV sales by 2035 under *Enhanced Ambition*, which more than doubles the sales under *Current Policies* (Fig. 25).

However, electric sales will take time to penetrate the existing fleet. Under *Enhanced Ambition,* national LDV stock is only 42% electrified by 2035, which is about half the share of EV sales in that year. Across states, the

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electric share of LDV stock ranges from 25% to 57% in 2035, with the majority of states achieving 44% or higher. Under *Current Policies*, the range is 18% to 54%, though most of the states achieve less than 25%.

Beyond electrification, reducing travel demand is another key lever to help meet decarbonisation goals [47]. As a result of state-level policies that target vehicle miles travelled (VMT) reductions, which aim to reduce single-occupancy vehicle use and increase the use of sustainable modes of transportation, overall passenger demand is lowered under *Enhanced Ambition*. Road passenger service is assumed to increase only by 9% from 2020 levels by 2035 under *Enhanced Ambition*, compared to 28% under *Current Policies*.

Figure 25: **New sales for passenger (top) and freight (bottom) vehicles.**

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By 2035, EV sales for passenger cars and SUVs increase to 45% under *Current Policies* and 84% under *Enhanced Ambition*. EV sales for freight trucks increase to 18% under *Current Policies* and 42% under *Enhanced Ambition*. Note that EV sales under *Current Policies* flatten between 2030 and 2035 as a result of IRA tax credits expiring before 2035.

The role of buildings and industry

In the buildings sector, IRA electrification and efficiency incentives paired with state-level appliance standards and efficiency standards result in emissions reductions of 38% between 2020 and 2035 (207 $MtCO_2e$) under *Enhanced Ambition*, compared to 16% (85 $MtCO_2e$) under *Current Policies*. The final energy share of electricity for hot water and space heating appliances increases from 21% in 2020 to 40% by 2035, compared to 29% under *Current Policies* (Fig. 26).

The industrial sector has fewer near-term decarbonisation opportunities compared to the other sectors, though it is still an important part of reaching net zero. IRA investments in this sector increase electrification while also accelerating the retirement of older, inefficient fossil fuels, resulting in electricity shares of around 20% in both scenarios by 2035. However, *Enhanced Ambition* assumes no new coal across all industrial sectors, as well as high-ambition industrial carbon capture policies that result in 77 $MtCO_2$ sequestered from cement, ethanol, and paper pulp CCS technologies. In comparison, *Current Policies* has only 5 $MtCO_2$ of sequestration from cement and ethanol CCS technologies. Correspondingly, *Enhanced Ambition* sees emissions reduce by 12% between 2020 and 2035 (132 $MtCO_2e$), compared to a growth of 4% (43 $MtCO_2e$) under *Current Policies*.

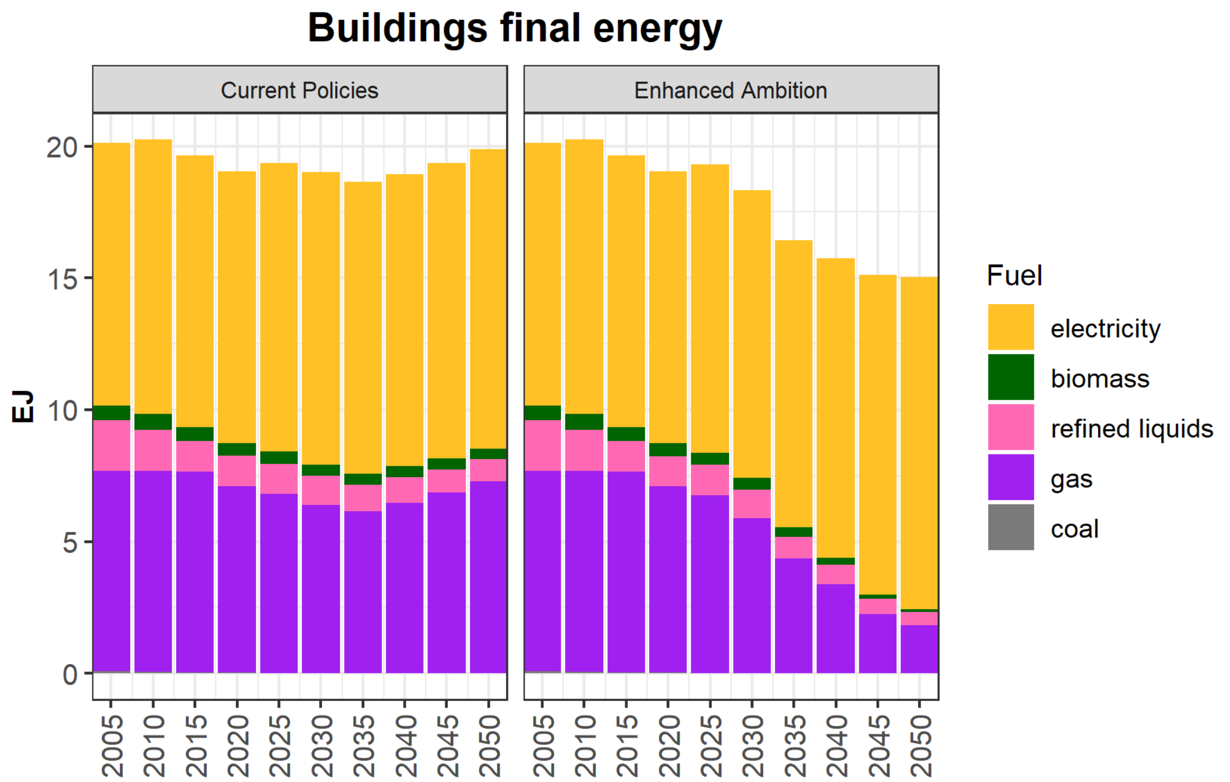

Figure 26: **Buildings sector final energy demand in the *Current Policies* and *Enhanced Ambition* scenarios, in units of exajoules (EJ).**

Under the *Enhanced Ambition* scenario, the share of electricity increases from 54% in 2020 to 66% by 2035 as a result of electrification incentives and mandates, compared to 59% under the *Current Policies* scenario. Additionally, total demand decreases in the *Enhanced Ambition* scenario because of enhanced energy efficiency measures as well the higher share of electricity, which is more energy efficient than other fuels.

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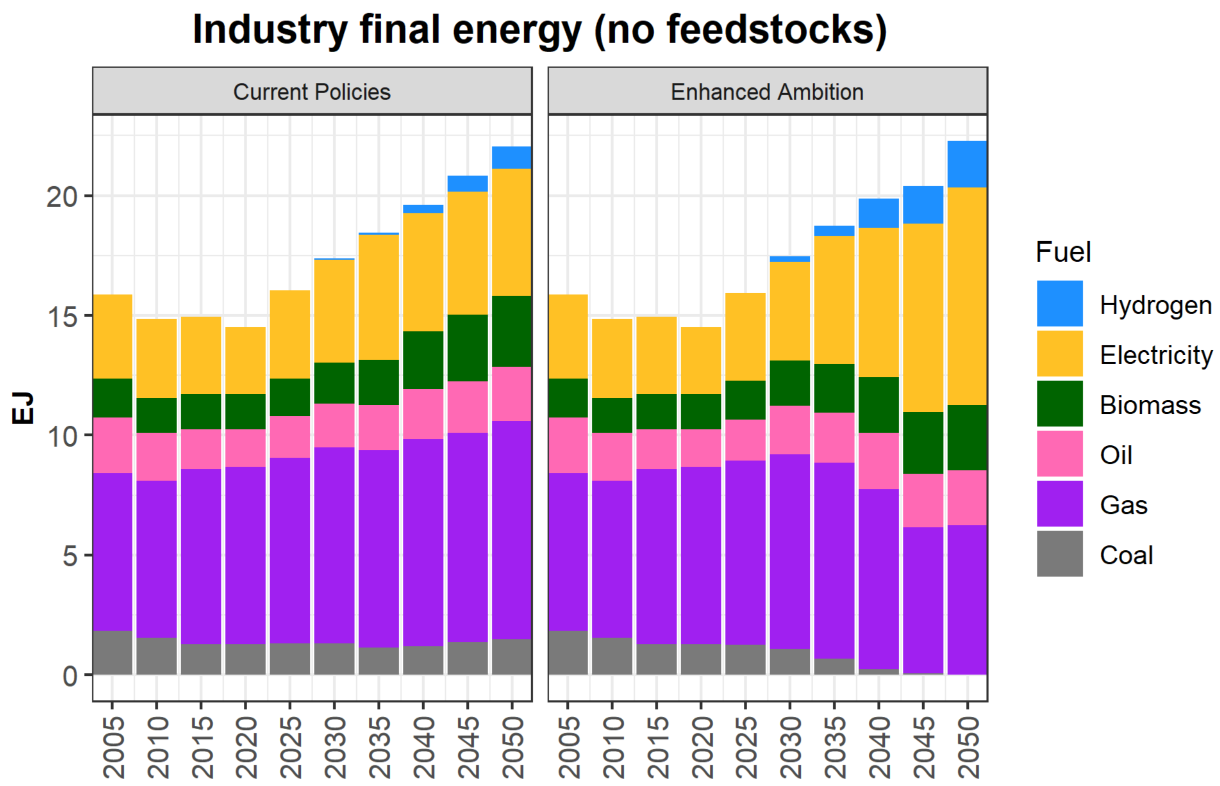

Figure 27: **Industrial sector final energy, excluding feedstocks, in the *Current Policies* and *Enhanced Ambition* scenarios, in units of exajoules (EJ).**

5.2.6 Setting the stage for 2050: methane abatement, carbon removal technologies, land sector policies

Methane also plays a critical role in near-term emissions reductions, as a potent greenhouse gas with a short lifetime. With a methane fee that covers all sources, including agriculture and waste, to incentivize emission reduction measures, *Enhanced Ambition* methane emissions decrease by 29% (237 $MtCO_2e$) between 2020 and 2035, in contrast to 5% (41 $MtCO_2e$) under *Current Policies*, as a potent greenhouse gas with a short lifetime.

Negative emissions through both natural and technological carbon removal also play a role in 2035, and will be increasingly important over the longer term for meeting net zero, as they help to balance the hard-to-abate emissions sources.[48] Historically, the LULUCF sink has remained stable or growing, but there is the possibility of it shrinking in the future if policies related to forest regrowth, forest management, and fire mitigation are not put into place, as well as uncertainties in the impact of climate change itself [49,50]. As a result of full implementation of BIL and IRA funds, and more ambitious state-level policies related to the lands sector under *Enhanced Ambition*, LULUCF sequestration increases by 73 $MtCO_2$ from 2020 to 2035, resulting in a sink of -926 $MtCO_2$ in 2035. In contrast, LULUCF sequestration increases by only 29 $MtCO_2$ under *Current Policies*, reaching a sink of -882 $MtCO_2$ in 2035.

Additionally, direct air capture (DAC) of CO_2 is introduced as a new technology after 2030 in the *Enhanced Ambition* scenario. As a result of IRA tax credits, which allow up to \$180/tCO_2 captured for storage from DAC, and state-level initiatives, DAC sequesters 31 $MtCO_2$ in 2035.

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5.2.7 Discussion and Conclusion

Key actions and challenges for 2035

Broadly speaking, the bulk of emissions reductions in the 2020's are expected to come from continued deployment of low-cost renewables and improved efficiency in the power sector, combined with increasing levels of reductions in transportation emissions through EV deployment. This analysis shows that from 2030 to 2035, we continue to see rapid and large decreases in the power and transportation sectors under high ambition pathways. However, we also find that substantial reductions across other sectors of the economy will be needed. Electrification and efficiency improvements in the buildings and industry sectors, sequestration from CCS and DAC technologies, additional methane mitigation – particularly for fossil fuels and agriculture – and enhancing the land sink will all be part of achieving a pathway on track to net zero in 2050.

In the electricity sector, the *Enhanced Ambition* scenario includes continued, rapid reductions in unabated fossil power, with all coal-fired power plants either retired or retrofitted with CCS by 2030, and all large, frequently used natural gas-fired power plants retired or retrofitted with CCS by 2035.

This level of fossil fuel phaseout is possible through the full implementation of IRA's Energy Infrastructure Reinvestment provision, which provides up to $250 billion to transition away from fossil fuels, finalisation, and enforcement of proposed EPA regulations to equip new and existing coal- and natural gas-fired power plants with CCS technologies, and rapid expansion of non-federal renewable energy goals. However, updating and expanding existing transmission and distribution systems will also be needed to better support renewable and clean energy integration, which currently has 1 TW of zero-carbon generation capacity currently stuck in the interconnection queue [51]. Additionally, in response to growing demand and the increase in variable renewable energy sources, it will be critical to maintain grid reliability through enhanced grid management practices and investment in storage technologies [52].

The rapid electrification of end use sectors will also pose challenges for 2035. In the transportation sector, key new policies include the widespread adoption and implementation of California's regulations for passenger car and freight truck EV sales, the early retirement of old, inefficient vehicles, and expanded incentives that lower the costs of EVs. Though not explicitly modelled in our study, this level of EV adoption entails additional policies in the forms of commitments from automakers, municipal fleet targets, subsidies for low- and middle- income consumers, and additional investments in the buildout of sufficient EV charging infrastructure. Scaling the electrification of freight trucks will be especially challenging, given the limited supply of electric trucks at present, the charging needs across state borders, and high associated costs, especially for long-haul trucks [53]. Additionally, some uncertainties remain about the capacity of vehicle supply chains to meet these goals, as many materials necessary for EV production have been classified as critical or near-critical supply risks, such as lithium, cobalt, nickel, and platinum [54]. Moreover, the extraction process for critical minerals is associated with substantial environmental justice concerns [55].

Across all sectors, the extension of IRA provisions beyond their legislated sunset dates will be another important element for 2035 reductions. In the year since its passage, IRA has accelerated renewable energy deployment, leading to the announcement of 272 new clean energy projects in EV, wind and solar, and battery manufacturing, totalling over $270 billion in new investments [56].

This level of clean energy investment in the United States is unprecedented, surpassing eight years' worth of historical clean energy investments [57]. Beyond clean energy technologies, IRA also allocates over $20 billion in funds for various land sector initiatives and introduces a substantial fee for oil and gas methane, which would apply to facilities not covered by the EPA methane regulations. By lowering the costs of clean energy, IRA investments can motivate both federal and non-federal actors to seek more ambitious climate action. For instance, the recent proposed standards from EPA address technologies that receive subsidies from IRA, including CCS and hydrogen [58]. This level of momentum and innovation across all levels of society could stall if IRA's provisions are left to expire as written.

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This analysis assumes a full implementation of IRA climate and energy provisions. However, the effectiveness of some provisions is dependent on the uptake by state, local and individual actors. Lack of outreach and education may lead to missed opportunities in taking advantage of the full tax credit for provisions such as residential building rebates. Furthermore, it is also possible that some policies could be watered down upon finalisation. IRA's clean vehicle tax credit, for example, may not deliver the full scale of emissions reductions as assumed in this analysis if automakers face challenges meeting the eligibility requirements on mineral sourcing and battery assembly for this tax credit.

Modelling limitations and further considerations

The model used for our research, GCAM-USA-CGS, has many features that make it well-suited for this type of analysis. These include its ability to offer full coverage of all emitting sectors across the economy, beyond standard energy sector CO_2-only studies, as well as its ability to link the U.S. states with regions in the rest of the world. Additionally, the model includes dynamic feedbacks across sectors, a rich technological representation, and emissions, energy, and trade details for 50 states. Even so, our analysis has some limitations. The model has difficulty capturing the uncertainty in building out transmission and distribution infrastructure– which other studies have shown to be critical in power sector decarbonisation [59]. Additionally, though our analysis shows a key role for CCS technologies towards 2035, there is still considerable uncertainty as to the viability of these technologies at scale [60].

Despite these limitations, our analysis provides valuable information on the magnitude and variety of actions needed to set a U.S. 2035 NDC target that will be both sufficiently ambitious and, though likely challenging, also plausible to achieve. While no strategy can generate absolute certainty, embedding ambitious climate action at multiple levels of government can support a more effective and durable climate strategy, and can mitigate potential political backsliding if future elections return less climate-friendly governments. Moreover, a U.S. commitment to an appropriately ambitious 2035 NDC would also encourage other countries to ratchet up their own ambition in their NDCs, helping curb overall global emissions to keep the goals of the Paris Agreement within reach.

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5.4 Mitigation scenarios for China

5.4.1 Introduction

In 2015, China set its nationally determined action objectives by 2030. By the end of 2019, it had delivered on its 2020 climate action targets ahead of schedule. In 2020, China announced the **updated Nationally Determined Contributions** (NDC), namely strive to carbon dioxide peaking before 2030 and achieve carbon neutrality before 2060, lower its carbon dioxide emissions per unit of GDP by over 65 percent from the 2005 level, increase the share of non-fossil fuels in primary energy consumption to around 25 percent by 2030, increase the forest stock by 6 billion m^3 from the 2005 level and its total installed capacity of wind and solar power to over 1.2 billion kW by 2030.

China's NDC document does not clarify whether achieving carbon neutrality by 2060 refers to carbon dioxide neutrality or greenhouse gas neutrality. In this study, IMACLIM macroeconomic model and China-MORE energy model were introduced to explore the difference between CO_2 neutrality and GHGs neutrality, and macroeconomic impacts of achieving CO_2 neutrality and GHGs neutrality. Two research questions emerged from the stakeholder engagement:

i) Decarbonisation under geopolitical pressure and technological constraints

ii) *The role of discount rates on mitigation pathways*

5.4.2 Scenario narrative and protocol

- BAU: Business as usual scenario, the emission path based on current policies and technologies.
- CO2 ZERO: Net zero CO2 emissions by 2060. Based on China First NDC (updated submission). "In 2020, China announced the updated NDC, namely strive to carbon dioxide peaking before 2030 and achieve carbon neutrality before 2060, lower its carbon dioxide emissions per unit of GDP by over 65 percent from the 2005 level, increase the share of non-fossil fuels in primary energy consumption to around 25 percent by 2030".
- GHG ZERO: Net zero GHG emissions by 2060. As non-CO2 GHGs account for more than 20% of total emissions in China, a more ambitious target was introduced to this scenario, which is all kinds of GHGs emission should be net zero by 2060.

5.4.3 Key assumptions considered.

The population, urbanisation rate and GDP parameters adopted in China's modelling were based on SSP2 scenario. The historical data during 2015 to 2020 were calibrated with the actual data.

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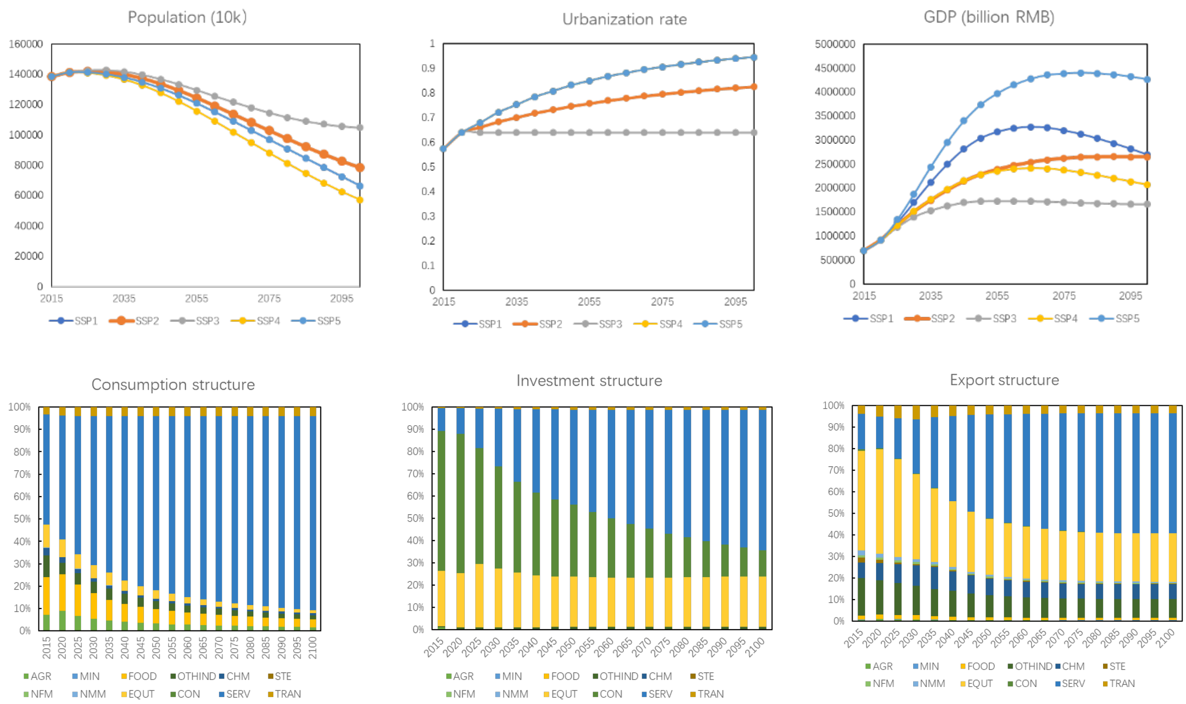
Figure 28 Key socio-economic assumptions considered in these scenarios



The consumption, investment and export structure set in China's modelling were assumed to be close to the average level of EU so that China will achieve the target to become a moderated developed country by 2035.

5.4.4 Model Description

China-MORE model

The China-MORE model is a Bottom-Up (BU) model. Compared with the IMACLIM-China model, China-MORE is technology-rich, and the inside technical substitutions are highly reliable. For the demand is exogenous, China-MORE lacks reflecting the socio-economic structure, and the partial equilibrium structure ignores the rebound effects, ignoring the inter-sector impacts.

IMACLIM-China

The IMACLIM-China belongs to top-down model, or simply called TD model. As a general equilibrium model, IMACLIM-China can represent the input-out relationship among different economic sectors, suitable for macro-economic analysis of climate policies, including carbon taxes and carbon market. The CGE model describes the substitution relationship between inputs based on elasticity, but the substitution relationship may be not achievable in actual word, especially considering the limitation of technologies. What's more, non-CO2 GHG emissions and industrial process CO2 emissions are usually characterized based on values of sectors, causing low accuracy.

Considering the advantages and disadvantages of these two models, the team linked these models to combine their advantages, and avoid disadvantages.

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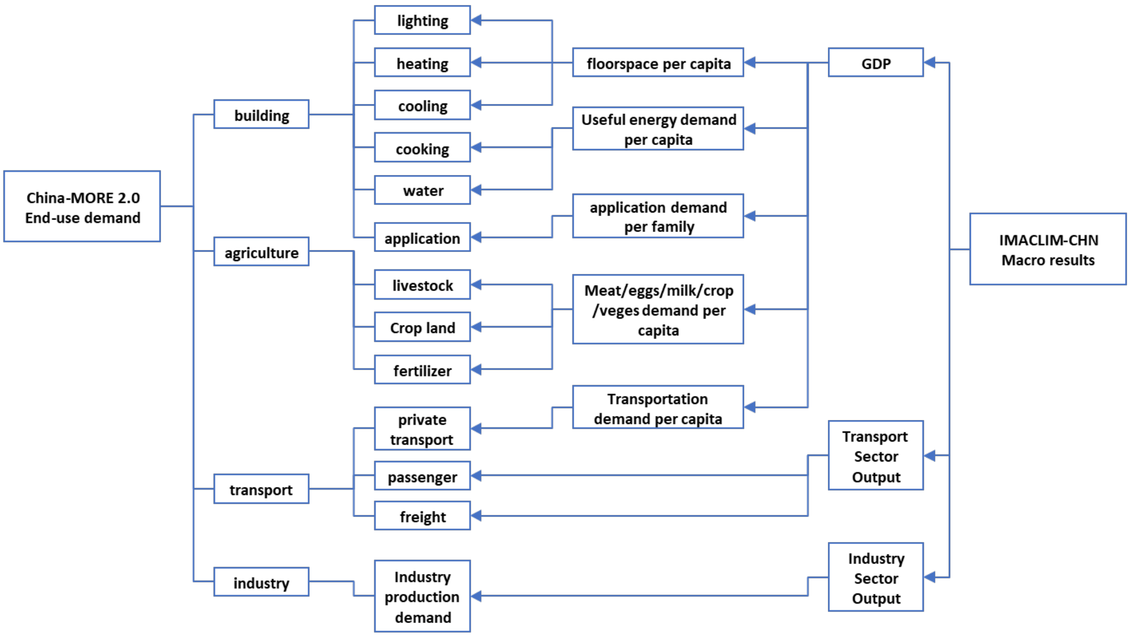


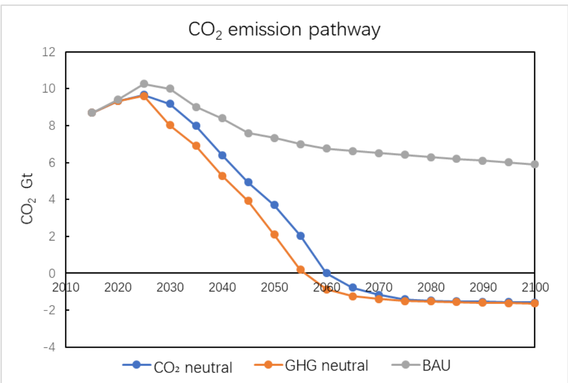
Figure 29 Link between IAMCLIM-CHN and China-More 2.0

4.3.5 Main results

Emissions and carbon price

The GHG emissions will peak in 2025 under all scenarios, but the peak level ranges from 11.5-12.8 Gt CO_2-eq. Neither CO2 nor GHG emissions will not reach net-zero under the BAU scenario. While there will be 1 Gt CO_2-eq of GHG emissions under the CO2 neutral scenario.

Under the CO2 neutral and GHG neutral scenarios, China's CO2 emissions will drop rapidly after 2025. Under the GHG neutral scenario, CO2 emissions will reach zero around 2055, which means 5 years earlier achievement of CO2 neutral with a 20% higher carbon price compared with CO2 neutral scenario. The carbon price in 2060 are 917 RMB and 1,222 RMB respectively under the CO2 neutral and GHG neutral scenario (Figure 30).



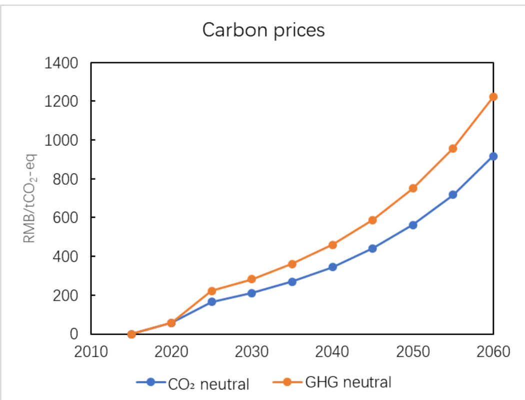


Figure 30 Emissions and carbon price pathways in three scenarios

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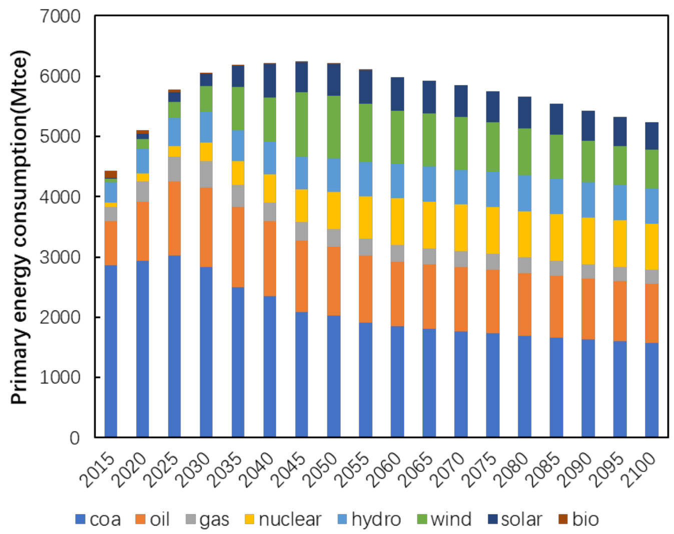
Energy system transformation

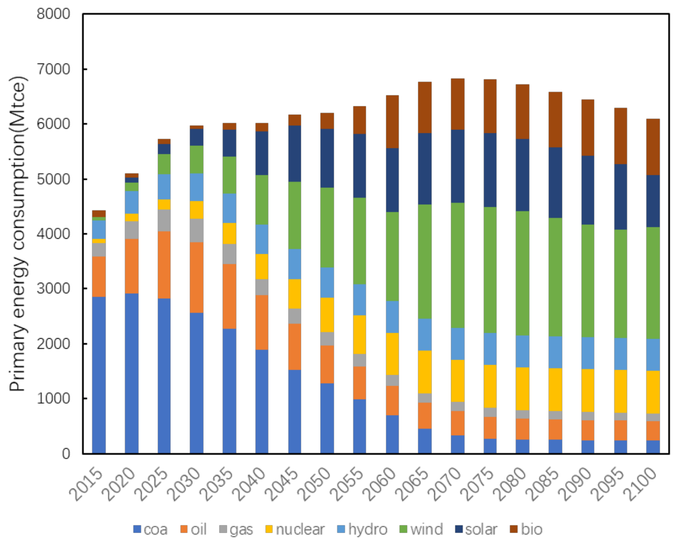
Under the BAU scenario, total primary energy consumption will enter a plateau after 2030, with a peak around 2035. With the implementation of the NDC policy and the gradual reduction of the cost of RE, China's energy structure will be gradually optimized, and the proportion of coal in primary energy will gradually decrease from 65% to 30% (Figure 31).

Under the CO2 neutral scenario, total primary energy consumption will also enter a plateau around 2030. After 2050, with the deepening of electrification, total primary energy consumption will rise again. China's energy structure will be changed significantly, and the proportion of coal will drop to about 10% by 2060. The proportion of fossil energy will drop to 20% (Figure 31).

Under the GHG neutral scenario, total primary energy consumption increases slightly compared to CO2 neutral scenario, and the energy demand peak will be five years earlier than that under the CO2 neutral scenario. The progress of fossil energy phasing out will be about five years ahead of the CO2 neutral scenario. Coal's share will drop to about 6% by 2060. The proportion of fossil fuel will drop to 15% at that time (Figure 31).



BAU



CO2 NEUTRAL

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GHG NEUTRAL

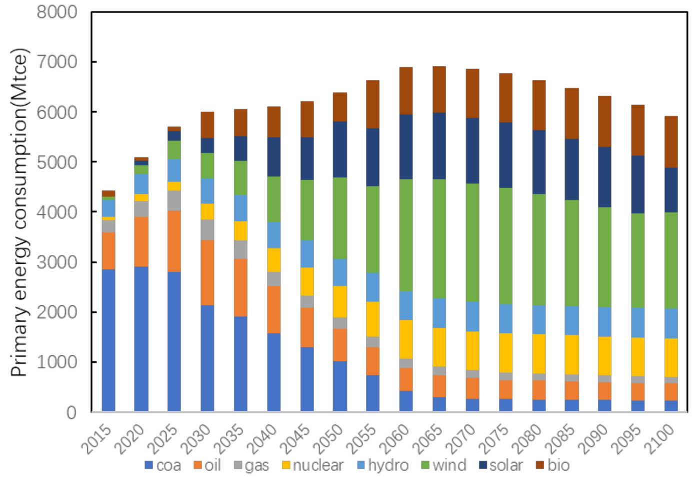

Figure 31 Primary energy consumption in three scenarios

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6. ANNEX

Annex Table 1: NDC targets before COP 28

Country Name	Target type	NDC__target_percentage_reduction unconditional(%)	NDC_target_percentage_reduction conditional(%)	NDC_REFERENCE_base_year	NDC_target_emissions_unconditional(MtCo2/yr)
El Salvador	Reduction v. BAU	39	61		0.49
Haiti	Reduction v. BAU	6.32			1.196
Nicaragua	Reduction v. BAU	10			69
Saint Lucia	Reduction v. BAU	16			0.637
Saint Vincent and the Grenadines	Reduction v. BAU	22			0.484
Yemen	Emissions reduction target	1	14	2020	43.3719
Mali	Reduction v. BAU	22.6			94.547
Albania	Reduction v. BAU				12
Argentina	Absolute emissions target				349
Benin	Reduction v. BAU	20.15			193.23
Burkina Faso	Reduction v. BAU	11.6			104.577
Burundi	Reduction v. BAU	3	20		6.64838
Chad	Reduction v. BAU	0.5	19.3		84.5352
Andorra	Reduction v. BAU	55			0.2316
Côte d'Ivoire	Reduction v. BAU	30.41	98.95		83.508
Dominica	Emissions reduction target	45		2014	0.0924
Dominican Republic	Reduction v. BAU	7	27		47.43
Ecuador	Reduction v. BAU	9	20.9		69.979
Grenada	Emissions reduction target	40		2010	0.13014
Honduras	Emissions reduction target	16		2015	8.4

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Lebanon	Reduction v. BAU	20	31		31.1608
Peru	Absolute emissions target				179
Djibouti	Reduction v. BAU	40			0.2
Guatemala	Reduction v. BAU	11.2	22.6		515.04
Guinea	Emissions reduction target	9.7	17	1994	2.0956
Lesotho	Reduction v. BAU	10			5.1417
Niger	Reduction v. BAU	12.57(aflou)+10.60(energy)	22.75(aflou)+45(energy)		104.0546
Senegal	Reduction v. BAU	7.03	29		35.106
South Africa	Absolute emissions target				420
Costa Rica	Absolute emissions target			2012	9.11
Uruguay	Absolute emissions target			2019	0.009267
Dem. Rep. Congo	Reduction v. BAU	21.46	32.19		11.781
Equatorial Guinea	Emissions reduction target	35		2019	2.899
Eritrea	Emissions reduction target	12	38.5	2010	7.128
Ethiopia	Reduction v. BAU	14	68.8		347.01
Fiji	Reduction v. BAU	10	20	2013	2.07
Georgia	Emissions reduction target	35	57	1990	25.649
Ghana	Absolute emissions target			2019	64
Guinea-Bissau	Reduction v. BAU	10	30		16.38
Israel	Emissions reduction target	27		2015	58
Jamaica	Reduction v. BAU	25.4	28.5		5.3712
Kazakhstan	Emissions reduction target	15	25	1990	324.7
Kenya	Reduction v. BAU	32			104.04
Kiribati	Reduction v. BAU	8	23.8		0.12604

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Kyrgyzstan	Reduction v. BAU	15.97	43.62		12.5070252
Laos	Reduction v. BAU	60			41.6
Liberia	Reduction v. BAU	10	54		11.1861
Malawi	Reduction v. BAU	51			16.66
Maldives	Reduction v. BAU	26			2.442
Marshall Islands	Emissions reduction target	45		2010	0.10175
Mauritius	Reduction v. BAU	40			4.14
Mexico	Reduction v. BAU	35	40		644.15
Mongolia	Reduction v. BAU	22.7	44.9		57.4339
Morocco	Reduction v. BAU	18.5	45.5		115.73
Mozambique	Reduction v. BAU				47
Myanmar	Reduction v. BAU				557.05
Namibia	Reduction v. BAU	14	91		20.78362
New Zealand	Emissions reduction target	50		2005	42.961
Nigeria	Reduction v. BAU	20	47		362.4
Oman	Reduction v. BAU	4	7		120.24384
Pakistan	Reduction v. BAU	15	50		1362.55
Palau	Reduction v. BAU	48			0.068
Papua New Guinea	Reduction v. BAU				-8.284
Paraguay	Emissions reduction target	0.1	20		39.6
Philippines	Reduction v. BAU	2.71	72		324.977787
Qatar	Reduction v. BAU	25			109.5
Rwanda	Reduction v. BAU	16	38		10.164
Samoa	Emissions reduction target	26		2007	0.26048

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Sao Tome and Principe	Reduction v. BAU	27			0.292
Saudi Arabia	Reduction v. BAU	37.66806705			460.0256587
Seychelles	Reduction v. BAU				0.82
Solomon Islands	Reduction v. BAU	33	45		0.67134
Somalia	Reduction v. BAU	30			75
Sudan	Reduction v. BAU	40			41
Tajikistan	Emissions reduction target	30	40	1990	24.871
Tonga	Emissions reduction target	13		2006	0.10701
Uzbekistan	Emissions reduction target	35		2010	121.6254
Angola	Emissions reduction target	14	24	2015	92.88
Armenia	Emissions reduction target	40		1990	15.0708
Australia	Emissions reduction target	43		2005	318.687
Austria	Emissions reduction target	55	NA	1990	30.06
Bangladesh	Reduction v. BAU	6.73	21.85		381.85
Barbados	Reduction v. BAU	20	35		1.5664
Belarus	Emissions reduction target	35	40	1990	70.42425
Belgium	Emissions reduction target	55	NA	1990	64.305
Botswana	Emissions reduction target	15		2010	7.055
Brazil	Emissions reduction target	50		2005	1176
Brunei Darussalam	Reduction v. BAU	20			23.6
Bosnia and Herzegovina	Emissions reduction target	12.8	17.8	2014	16.866224
Cambodia	Reduction v. BAU	41.6			90.52
Cameroon	Emissions reduction target	12	35	2010	29.92
Canada	Emissions reduction target	40	45	2005	438

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Cape Verde	Reduction v. BAU	24			0.764
Central African Republic	Reduction v. BAU	11.82	24.28		15.5584792
Chile	Absolute emissions target				95
Colombia	Reduction v. BAU	51			169.44
Congo	Emissions reduction target	21.46	31.19	2017	8.16816
Bulgaria	Emissions reduction target	55	NA	1990	37.1925
Croatia	Emissions reduction target	55	NA	1990	11.31345
Cyprus	Emissions reduction target	55	NA	1990	2.47455
Czech Republic	Emissions reduction target	55	NA	1990	86.46345
Denmark	Emissions reduction target	55	NA	1990	35.2854
Estonia	Emissions reduction target	55	NA	1990	16.461
Finland	Emissions reduction target	55	NA	1990	20.45115
France	Emissions reduction target	55	NA	1990	234.9756
Germany	Emissions reduction target	55	NA	1990	579.24
Greece	Emissions reduction target	55	NA	1990	45.7821
Hungary	Emissions reduction target	55	NA	1990	41.23035
Indonesia	Emissions reduction target	31.89	43.2	2030	1954.0759
Iceland	Emissions reduction target	55	NA	1990	5.98095
Ireland	Emissions reduction target	55	NA	1990	27.7434
Japan	Emissions reduction target	46		2013	760.32
Italy	Emissions reduction target	55	NA	1990	233.09595
Latvia	Emissions reduction target	55	NA	1990	6.1524
Liechtenstein	Emissions reduction target	40		1990	142.32
Lithuania	Emissions reduction target	55	NA	1990	19.26945

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Luxembourg	Emissions reduction target	55	NA	1990	5.72895
Macedonia, the former Yugoslav Republic of		51		1990	5.831
Malta	Emissions reduction target	55	NA	1990	1.1781
Moldova, Republic of	Emissions reduction target	70		1900	10.8246
Monaco	Emissions reduction target	55	NA	1990	0.0459
Montenegro	Emissions reduction target	35		1990	2.9783
Netherlands	Emissions reduction target	55	NA	1990	103.02075
Norway	Emissions reduction target	55	NA	1990	18.6642
Poland	Emissions reduction target	55	NA	1990	200.8548
Portugal	Emissions reduction target	55	NA	1990	30.01005
Romania	Emissions reduction target	55	NA	1990	102.83985
Russian Federation	Emissions reduction target	30		1990	2472.4
San Marino	Emissions reduction target	20		2005	0.1704
Serbia	Emissions reduction target	33.3		1990	49.449379
South Korea	Emissions reduction target	40		2018	436.56
Slovakia	Emissions reduction target	55	NA	1990	29.02185
Slovenia	Emissions reduction target	55	NA	1990	6.48135
Spain	Emissions reduction target	55	NA	1990	114.2163
Thailand	Reduction v. BAU	30	40		388.5
The Bahamas	Reduction v. BAU	30			4.55
The Gambia	Reduction v. BAU	49.7			3.288
Togo	Emissions reduction target	20.51	50.57	2010	23.847
Trinidad and Tobago	Reduction v. BAU	15			606
Türkiye	Reduction v. BAU	41			693.25

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Tuvalu	Emissions reduction target	60		2010	0.008
Uganda	Reduction v. BAU	5.9	24.7		140.0208
United Arab Emirates	Reduction v. BAU	39.5			182
Sweden	Emissions reduction target	55	NA	1990	11.3139
United States of America	Emissions reduction target	50	52	2005	3317.5
Vietnam	Reduction v. BAU	15.8	43.5		781.2918
Zambia	Reduction v. BAU	25	47		90.45
Switzerland	Emissions reduction target	50		1990	24.11145
Egypt	Other	33			500
Jordan	Reduction v. BAU				33.64
Kuwait	Reduction v. BAU	7.4			131
Singapore	Absolute emissions target				60
Micronesia	Emissions reduction target	28	35	2000	0.108
United Kingdom	Emissions reduction target	68		1990	260.288
Ukraine	Emissions reduction target	65		1990	397.305

Annex Table 2: long term targets before Cop28

Country name	Long term target_year	Target type	Reduction values (%)	Target value	Comparison year
Antigua and Barbuda	2040	Absolute emissions target		0	
Haiti	2050	Absolute emissions target		0	
Panama	2050	Absolute emissions target		0	
Argentina	2050	Absolute emissions target		0	
Andorra	2050	Absolute emissions target		0	
Dominican Republic	2050	Absolute emissions target		0	
Lebanon	2050	Absolute emissions target		0	
Peru	2050	Absolute emissions target		0	
South Africa	2050	Absolute emissions target		0	
Costa Rica	2050	Absolute emissions target		0	
Uruguay	2050	Absolute emissions target		0	

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Equatorial Guinea	2050	Emissions reduction target	50	2.23	
Ethiopia	2050	Absolute emissions target		0	
Fiji	2050	Absolute emissions target		0	
Ghana	2070	Absolute emissions target		0	
Israel	2050	Emissions reduction target	85	8.7	2015
Kazakhstan	2060	Absolute emissions target		0	
Laos	2050	Absolute emissions target		0	
Liberia	2050	Absolute emissions target		0	
Malaysia	2050	Absolute emissions target		0	
Maldives	2030	Absolute emissions target		0	
Marshall Islands	2050	Absolute emissions target		0	
Mexico	2050	Emission reduction target	50	226.0735	2000
New Zealand	2050	Absolute emissions target		0	
Oman	2050	Absolute emissions target		0	
Papua New Guinea	2030	Absolute emissions target		0	
Saudi Arabia	2060	Absolute emissions target		0	
Solomon Islands	2050	Absolute emissions target		0	
India	2070	Absolute emissions target		0	
Australia	2050	Absolute emissions target		0	
Austria	2040	Absolute emissions target		0	
Belgium	2050	Absolute emissions target		0	
Brazil	2050	Absolute emissions target		0	
Cambodia	2050	Absolute emissions target		0	
Canada	2050	Absolute emissions target		0	
Cape Verde	2050	Absolute emissions target		0	
Chile	2050	Absolute emissions target		0	
China	2060	Absolute emissions target		0	
Colombia	2050	Absolute emissions target		0	
Croatia	2050	Absolute emissions target		0	
Cyprus	2050	Absolute emissions target		0	
Czech Republic	2050	Absolute emissions target		39	
Denmark	2050	Absolute emissions target		0	
Estonia	2050	Absolute emissions target		0	
Finland	2050	Absolute emissions target		0	
France	2050	Absolute emissions target		0	
Germany	2050	Absolute emissions target		0	
Greece	2050	Absolute emissions target		0	
Hungary	2050	Absolute emissions target		0	
Indonesia	2050	Absolute emissions target		540	
Iceland	2050	Absolute emissions target		0	
Ireland	2050	Absolute emissions target		0	
Japan	2050	Absolute emissions target		0	

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Italy	2050	Absolute emissions target		0	
Latvia	2050	Absolute emissions target		0	
Liechtenstein	2050	Absolute emissions target		0	
Lithuania	2050	Absolute emissions target		0	
Luxembourg	2050	Absolute emissions target		0	
Malta	2050	Absolute emissions target		0	
Monaco	2050	Absolute emissions target		0	
Netherlands	2050	Absolute emissions target		0	
Norway	2050	Emission reduction target	80-95	2.0738	1990
Poland	2050	Absolute emissions target		0	
Portugal	2050	Absolute emissions target		0	
Romania	2050	Absolute emissions target		0	
Russian Federation	2050	Emission reduction target	80	706.4	1990
South Korea	2050	Absolute emissions target		0	
Slovakia	2050	Absolute emissions target		0	
Slovenia	2050	Absolute emissions target		0	
Spain	2050	Absolute emissions target		0	
Thailand	2065	Absolute emissions target		0	
The Gambia	2050	Absolute emissions target		0	
Tunisia	2050	Absolute emissions target		0	
Türkiye	2053	Absolute emissions target		0	
Tuvalu	2050	Absolute emissions target		0	
United Arab Emirates	2050	Absolute emissions target		0	
Sweden	2045	Absolute emissions target		0	
United States of America	2050	Absolute emissions target		0	
Vietnam	2050	Absolute emissions target		0	
Zimbabwe	2050	Reduction v. BAU	0.5	32.4	
Switzerland	2050	Absolute emissions target		0	
Kuwait	2060	Absolute emissions target		0	
Singapore	2050	Absolute emissions target		0	
Micronesia	2050	Absolute emissions target		0	
Belize	2050	Absolute emission target		0	
United Kingdom	2050	Absolute emissions target		0	
Seychelles	2050	Absolute emissions target		0	
Solomon Islands	2050	Absolute emissions target		0	
Ukraine	2050	Emission reduction target	0.69	273.699	1990
Nepal	2045	Absolute emissions target		0	
Bahrain	2060	Absolute emissions target		0	
Vanuatu	2050	Absolute emissions target		0	

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