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D7.6 Report on the reference and policy scenario modelling results

WP7 – Model Inter-Comparisons, Global Stocktake & Scientific Assessments

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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.

2. Dissemination and uptake

The report is intended as a reference document for all stakeholders to review the reference and mitigation modelling performed in the context of PARIS REINFORCE.

3. Short summary of results (<250 words)

This deliverable outlines the methods, logic, and structure behind the global mitigation scenarios performed in PARIS REINFORCE, and also graphically outlines summarised results from these scenarios. The results show the gap between current climate change mitigation ambitions and Paris-compliant targets, and how a diverse set of models attempt to fill this gap through energy system transformations. Finally, the deliverable summarises co-created national and regional deep mitigation scenarios performed in WPs 5 and 6, aimed to inform global scenarios in the final model iteration.

4. Evidence of accomplishment

This report.

Preface

PARIS REINFORCE will develop a novel, demand-driven, IAM-oriented assessment framework for effectively supporting the design and assessment of climate policies in the European Union as well as in other major emitters and selected less emitting countries, in respect to the Paris Agreement. By engaging policymakers and scientists/modellers, PARIS REINFORCE will create the open-access and transparent data exchange platform I²AM PARIS, in order to support the effective implementation of Nationally Determined Contributions, the preparation of future action pledges, the development of 2050 decarbonisation strategies, and the reinforcement of the 2023 Global Stocktake. Finally, PARIS REINFORCE will introduce innovative integrative processes, in which IAMs are further coupled with well-established methodological frameworks, in order to improve the robustness of modelling outcomes against different types of uncertainties.

NTUA - National Technical University of Athens	GR
BC3 - Basque Centre for Climate Change	ES
Bruegel - Bruegel AISBL	BE
Cambridge - University of Cambridge	UK
CICERO - Cicero Senter Klimaforskning Stiftelse	NO
CMCC - Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici	IT
E4SMA - Energy, Engineering, Economic and Environment Systems Modelling Analysis	IT
EPFL - École polytechnique fédérale de Lausanne	CH
Fraunhofer ISI - Fraunhofer Institute for Systems and Innovation Research	DE
Grantham - Imperial College of Science Technology and Medicine - Grantham Institute	UK
HOLISTIC - Holistic P.C.	GR
IEECP - Institute for European Energy and Climate Policy Stichting	NL
SEURECO - Société Européenne d'Economie SARL	FR
CDS/UnB - Centre for Sustainable Development of the University of Brasilia	BR
CUP - China University of Petroleum-Beijing	CN
IEF-RAS - Institute of Economic Forecasting – Russian Academy of Sciences	RU
IGES - Institute for Global Environmental Strategies	JP
TERI - The Energy and Resources Institute	IN

Executive Summary

This deliverable outlines the methods, logic, and structure behind the global mitigation scenarios performed in PARIS REINFORCE, and also graphically outlines summarised results from these scenarios. The results show the gap between current climate change mitigation ambitions and Paris-compliant targets, and how a diverse set of models attempt to fill this gap through energy system transformations. Finally, the deliverable summarises co-created national and regional deep mitigation scenarios performed in WPs 5 and 6, aimed to inform global scenarios in the final model iteration.

Contents

1 **Introduction** 8
2 **Methods** 11
2.1 Employed models and preparation 11
2.2 First modelling iteration scenarios 16
2.2.1 Scenario logic 17
2.2.2 Scenario protocol 18
2.3 Second modelling iteration scenarios 25
2.3.1 Scenario logic 25
2.3.2 Scenario Protocol 26
3 **Results of first global iteration** 31
3.1 Emissions 31
3.2 Energy system 33
3.2.1 Primary energy 35
3.2.2 Final energy 37
3.3 Other results 45
4 **Summary of regional and national modelling results** 47
4.1 EU runs (WP5) 47
4.1.1 Scenario rationale 47
4.1.2 Results 49
4.2 Non-EU national runs (WP6) 51
4.2.1 Scenario rationale 51
4.2.2 Results 52
5 **Conclusions** 55
References 56
Appendix 61

Table of Figures

Figure 1: High-level workflow setting out interaction between global and national/regional modelling, informed by stakeholder engagement and stakeholder preference elicitation exercises 9
Figure 2: Number of policies implemented in each model by region. 17
Figure 3: Graphical illustration of modelling protocol for CP_price scenario 20
Figure 4: Graphical illustration of modelling protocol for NDC_price scenario 21
Figure 5: EU and China examples for applying long-term pledges 29
Figure 6: Global CO_2 emissions from fossil energy use for all models in reference & mitigation scenarios 32
Figure 7: Global temperature increase and ranges for all scenarios and models (see Appendix) 33
Figure 8: Global primary energy consumption in reference scenarios in 2030 and 2050 for all models 35
Figure 9: Global primary energy consumption in mitigation scenarios (and CP_Intensity for comparison) in 2030 and 2050 for all models 36
Figure 10: Global final energy consumption in reference scenarios in 2030 and 2050 for all models 37

Figure 11: Global final energy consumption in mitigation scenarios (and CP_Intensity for comparison) in 2030 and 2050 for all models 38
Figure 12: Global industry final energy consumption in reference scenarios in 2030 and 2050 for all models....39
Figure 13: Global industry final energy consumption in mitigation scenarios (and CP_Intensity for comparison) in 2030 and 2050 for all models 40
Figure 14: Global residential and commercial final energy consumption in reference scenarios in 2030 and 2050 for all models....41
Figure 15: Global residential and commercial final energy consumption in mitigation scenarios (and CP_Intensity for comparison) in 2030 and 2050 for all models....42
Figure 16: Global transport final energy consumption in reference scenarios in 2030 and 2050 for all models....43
Figure 17: Global transport final energy consumption in mitigation scenarios (and CP_Intensity for comparison) in 2030 and 2050 for all models 44
Figure 18: Carbon sequestration in 2030 and 2050 per model and scenario....45
Figure 19: Carbon prices until 2050 for all models and mitigation scenarios and CP_intensity 46
Figure 20: EU sector reduction of CO_2 emissions from energy and industrial processes (w.r.t. 1990) in the EU Core scenario....49
Figure 21: EU primary and final energy consumption by fuel in the EU core scenarios (in Mtoe/y.). 50
Figure 22: EU industry, buildings and transport final energy consumption by fuel in the EU Core scenarios (in Mtoe/y.). 51
Figure 23: CO_2 emissions in reference and deep mitigation scenarios from WP6 scenarios....52
Figure 24: Primary energy consumption in EJ/yr for reference and deep mitigation scenarios from WP6 53
Figure 25: Final energy consumption in EJ/yr for reference and deep mitigation scenarios from WP6 53
Figure 26: Mix of electricity generation in EJ/yr for reference and deep mitigation scenarios from WP6 54

Table of Tables

Table 1: Outline of global scenario context in PARIS REINFORCE 9
Table 2: Specifications and employment of global models....11
Table 3: Overview of input harmonisation....13
Table 4: Socio-economic assumptions and data sources. See Supplementary Text 4 for details on harmonisation 14
Table 5: Techno-economic assumptions....16
Table 6: Constraints in each scenario on i) emissions and ii) year of net-zero, to be run by models going to 2100. 22
Table 7: Post-Glasgow updated NDC pledges to be applied in the second global modelling iteration. 26
Table 8: Long-term emissions targets to be applied in the second global modelling iteration....27
Table 9: List of regional models which inform the global LTS_ADV scenario....47
Table 10: New EU Core Scenarios 48
Table 11: Synthesis of main GHG emissions reduction targets in the EU27 in the EU core scenarios 48
Table 12: Synthesis of main GHG emissions reduction targets in the UK in the EU core scenarios....49
Table 13: Non-EU Scenarios 51

1 Introduction

The goal of the Paris Agreement is to limit global warming to “well below 2°C and pursue efforts to limit temperature increase to 1.5°C” (UNFCCC, 2020). Although global emissions are still increasing, climate policies are clearly having an effect (Le Quéré et al., 2019; Roelfsema et al., 2020) and common ‘no policy’ baselines represent increasingly unlikely futures (Grant et al., 2020; Hausfather & Peters, 2020). PARIS REINFORCE has undertaken some rigorous global modelling exercises to measure the state of global climate change mitigation efforts (Sognnaes et al., 2021), as well as the transformations required to reach Paris-compliant levels of mitigation.

While many existing global climate change mitigation scenarios explore emissions pathways below baselines (IPCC, 2014, 2018), the majority of these are based on ‘backcasting’ (a concept defined by Robinson (1990)), meaning they identify pathways that meet pre-defined climate targets. Backcasting scenarios typically represent climate policy using economy-wide carbon prices that ensure that emissions reductions necessary to meet the pre-defined climate target take place when and where they are cheapest (sometimes following periods of delay or staged accession (Kriegler et al., 2015)). Real-world climate mitigation, however, will likely differ from such backcast pathways for two reasons. First, the Paris Agreement’s design around nationally determined contributions (NDCs) means mitigation effort will vary between countries and over time. Second, real-world climate policies consist of a mixture of different policy instruments (Eskander and Fankhauser, 2020; Meckling and Jenner, 2016), with implied carbon prices that vary by sector (Bataille et al., 2018). More recently, more scenarios and studies have been focusing on forecasting the emissions impacts of actually implied policies, although these are either single-model studies (IEA, 2021) or do not extrapolate ambitions beyond 2030, hence not being able to provide potential temperature outputs (Roelfsema et al., 2020).

The scenario framework in PARIS REINFORCE intends to overcome the traditional shortcomings of modelling climate change mitigation in roughly 3 steps:

1. By modelling current policy efforts and mitigation ambitions from all major countries, the PARIS REINFORCE modelling tools forecast where emissions are realistically headed if no additional efforts are undertaken.
2. Subsequently, post-2025 backcasting scenarios are performed on top of global policies up to 2025 to explore the gap between actual action and required action to reach Paris-compatible levels of mitigation.
3. Finally, through interactions with national stakeholders in many countries, national and regionally focused models in WPs 5 and 6 are employed to co-create national/regional mitigation scenarios closing the climate action gap in line with local policy priorities, and global models are once again used to adopt these scenarios creating global co-created mitigation scenarios.

Figure 1 graphically shows the workflow on the interchanges between global and national/regional scenarios, and Table 1 maps out how the modelled global scenarios within WP 7 relate to one another and how they evolved over time (from first to second iteration), as well as interactions with other WPs. Since the COVID-19 pandemic occurred during step 1 of the modelling workflow, which has delayed the entire process, additional scenarios are run in-between steps 2 and 3. First, in the context of WP 4, the impact of green recovery packages throughout the world is measured using different global models, on top of pre-pandemic policy baselines (van de Ven et al., n.d.). Second, since global climate ambitions have been upgraded around the COP26 in Glasgow, a new set of forecasting scenarios is required taking into account the latest set of ambitions.

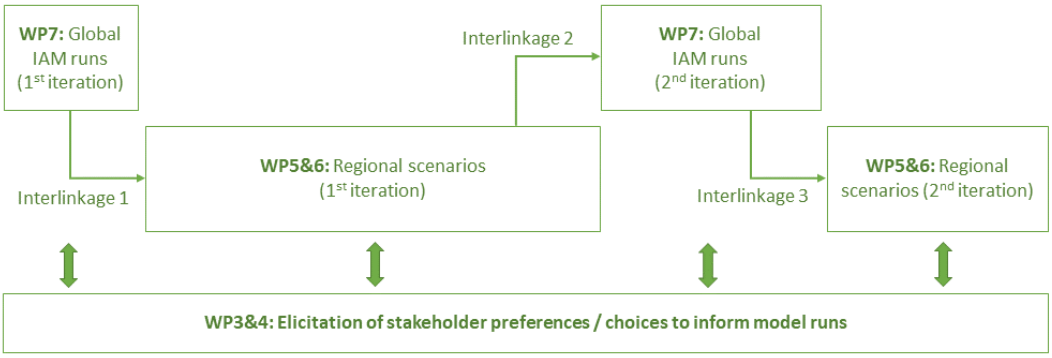


Figure 1: High-level workflow setting out interaction between global and national/regional modelling, informed by stakeholder engagement and stakeholder preference elicitation exercises.

Table 1: Outline of global scenario context in PARIS REINFORCE

Timeline		**1st Modelling Iteration (2020-2021; pre-pandemic assumptions)**	**2nd Modelling Iteration (2022; post-pandemic & COP26)**
Model input Harmonisation		Applying pre-pandemic projections: • Population and GDP • Fossil fuel prices • Techno-economic parameters	• Updated GDP and fossil fuel price projections → Covid-19 pandemic and recovery, Ukraine conflict • Updated techno-economic projections
Criteria for Scenario development	*Reference scenarios*	Exploring the long-term impact of *pre-pandemic* climate ambitions for 2030: • Explicit energy and climate policies • Initial NDCs from COP21 in Paris (2014-2015) • Extrapolated effort until 2050/2100	Exploring the long-term impact of *COP26 (Glasgow)* climate ambitions for 2030: • Updated energy and climate policies • Updated NDCs from COP26 in Glasgow (2021) • Extrapolated effort until 2050/2100
	Mitigation scenarios	Exploring long-term transformations required to move from current policies (up to 2025) to *Paris-compliant climate targets* (1.5-2ºC through *global action*)	Exploring the impact of announced *long-term climate ambitions and strategies on the national level* beyond 2030, e.g. Net-Zero pledges.
Interaction with other WPs in PARIS REINFORCE		Comparison of global (WP7) and national (WPs 5 & 6) model outcomes; including global results in national stakeholder workshops.	Mimicking stakeholder-informed national/regional scenarios (WPs 5 & 6) as "long term strategies" in global mitigation scenarios

Overall Objective	Towards Global Stocktake & Ratcheting Ambitions

This deliverable outlines the method and scenario details of all global scenarios performed within the PARIS REINFORCE project (Section 2), as well as the results of those scenarios (Section 3) and a summary of the results from WPs 5 and 6 scenarios that inform the final set of global modelling runs (Section 4).

2 Methods

This section outlines the tools and assumptions used among all models for the reference and policy scenarios. Section 2.1 summarises the specifications and harmonisation process of the global models used in this exercise (Deliverables D7.1 and D7.2), Section 2.2 outlines the modelling protocol applied in the first reference and policy runs, while Section 2.3 outlines the modelling protocol applied in the second set of runs.

2.1 Employed models and preparation

A total of 7 models were employed in the global modelling runs, although not all models could contribute to all scenarios due to specific model limitations. Table 2 summarises the model specifications and participation in the global runs.

Table 2: Specifications and employment of global models

Model	World regions	Time horizon	Scenario participation *			Online detailed documentation in I²AM PARIS
			1st iteration reference	1st iteration mitigation	2nd iteration (ref + mit.)	
GCAM	32	2100	4	19	✓	https://www.i2am-paris.eu/detailed_model_doc/gcam
TIAM	15	2100	4	19	✓	https://www.i2am-paris.eu/detailed_model_doc/tiam
MUSE	28	2100	4	6	✓	https://www.i2am-paris.eu/detailed_model_doc/muse
GEMINI-E3	11	2050	4	18	✓	https://www.i2am-paris.eu/detailed_model_doc/gemini_e3
ICES	45	2050	4	6	✓	https://www.i2am-paris.eu/detailed_model_doc/ices
E3ME	61	2050	4	1	?	https://www.i2am-paris.eu/detailed_model_doc/e3me
FortyTwo	50	2045	2	0	X	https://www.i2am-paris.eu/detailed_model_doc/42

Note: Scenario participation is measured by the number of scenarios in the first modelling iteration, and with a yes/no in the second modelling iteration as the number of scenarios per model is unknown yet.

An extensive harmonisation process has been taken on in preparation for the global runs. By harmonisation, we refer to the process of aligning the inputs of the different models for producing the model inter-comparison study so as to reduce model response heterogeneity to the differences behind each model structure and theory (Schwanitz, 2013). This is not to be confused with model calibration, which refers to the determination of system parameters and behaviour based on external evidence rather than econometric estimation, as is typically done in IAMs (Nordhaus, 2017). In that sense, regarding historical data on which model behaviour is developed to align to observed trajectories (e.g., emissions), harmonisation requires that model-specific calibration databases be updated to shared historical databases. Similarly, regarding future assumptions to be used as inputs necessary for producing model outputs (e.g., socio-economic and techno-economic variables), harmonisation requires that shared assumption databases be used across the models. Here, we used the methodology documented in Deliverable D7.2 and Giarola et al. (2021). It is also noted that, due to model-specific challenges, different levels of harmonisation are achieved. This means that models were (a) harmonised explicitly to, (b) checked for consistency with, or (c) not harmonised to, the shared input databases outlined in Table 3, Table 4 and the text below. Checking for consistency for a particular model and type of variable means that, although harmonisation was not feasible/carried out, the divergence of the model's input database values for this specific variable was reviewed and ensured to lie within a ±10% range of tolerance around the values of the shared database to which other models were harmonised.

In particular, focus was given to harmonising the following dimensions (Table 2 provides an overview of which parameters were harmonised by which models):

The *socio-economic development harmonisation*, which was made at the country level, consisted of a rigorous update of the Shared Socio-economic Pathway 2 (SSP) (Fricko et al., 2017) dataset, making adjustments to reflect more up-to-date sources for the European Union as well as to account for historical deviations between the SSP2 projections and historical data. Different data sources were used for short- & mid-term as well as long-term projections by country, and the "switch year" between short/mid- to long-term data sources differed by country ensuring smooth transitions in the projections. Table 3 summarises the variables and data sources as harmonised across all models. Socioeconomic assumptions are updated in the 2nd modelling iteration to reflect the economic impacts of the response to the COVID-19 pandemic and the economic recovery, as well as the military invasion in Ukraine.

The *techno-economic parameter harmonisation* was carried out by performing an update of costs, fuel efficiency, and lifetime parameters for key low-carbon technologies in power, transport, buildings, and industry. The variables and technologies harmonised are reported in Table 4. Techno-economic parameter harmonisation depends strongly on the technology coverage of the model, which, in turn, depends on the model type. All the models applied consistently have undergone either a full techno-economic harmonisation or a consistency check across all the sectors covered exogenously due to their top-down nature, except for stronger economy-focus models like ICES and FortyTwo, while GEMINI-E3 could only perform harmonisation of the power sector, which is represented with higher granularity than other sectors in the model. Techno-economic assumptions are updated in the 2nd modelling iteration to reflect the most recent trends in power technologies and to include hydrogen production in the harmonised technologies.

The level of *emissions harmonisation* varied across models and gases. All models' base years (2010 or 2015) have been compared to (i.e., checked for consistency with) a global, country-level disaggregated dataset for historical emissions of CO_2 and CH_4, the Community Emissions Data System (CEDS) for Historical Emissions (Hoesly et al., 2018). The dataset was used to ensure that the models were aligned to the latest available CEDS data (2017 version) for the energy systems emissions, rather than a sector-level calibration. Specifically, all models used the same dataset for the calibration against the historical CO_2 projections. To the extent of representing these two types of emissions, all models except for MUSE were calibrated against the CEDS historical CH_4 emissions and other pollutants. Similarly, F-gases and N_2O were calibrated respectively against the NOAA dataset (World Meteorological Organization (WMO), 2018) and the PRIMAP dataset (Gütschow et al., 2016) in GCAM, GEMINI-E3, and E3ME. PM10 emissions were calibrated against the historical CEDS databases in GCAM, and E3ME.

Fossil fuel price harmonisation in computable equilibrium models (GEMINI-E3 and ICES) and macroeconometric models (E3ME) was based on the International Energy Agency World Energy Outlook (IEA, 2019). Calibrating resource input and supply curves to match fossil fuel price trajectories is the most common approach for fossil fuel resources, making it possible to control the key variable of fossil fuel prices taken from external energy scenarios. The benchmark fossil fuel prices from 2010-2018 used annual WEO data, deflated to reflect 2018 USD values. A linear interpolation was then applied to reach the WEO fossil fuel price trajectory for the years 2030 and 2040, ensuring consistency of the input data with a standard trajectory, by holding those critical years for the global climate target. Post-2040 fossil fuel prices were extrapolated using the same rate as 2030-2040. For more information, see Giarola et al. (2021). Fossil fuel price assumptions are updated in the 2nd modelling iteration to reflect the latest WEO projections (IEA, 2021) up to 2050 as well as recently observed energy price fluctuations. In the other models, fossil fuel prices are fully endogenous and could not be harmonised.

Sectoral value added for E3ME was aligned against the EUROSTAT database (European Commission, 2020).

Interest rates and exchange rates for E3ME were aligned with the OECD database as a common and consistent database (OECD, 2018) .

Table 3: Overview of input harmonisation

	Variables	GCAM	TIAM	MUSE	FortyTwo	ICES	GEMINI-E3	E3ME
Socioeconomic data	Population	✓	✓	✓	✓	✓	✓	✓
	GDP/total income	✓	✓	✓	✓	✓	✓	✓
	Sectoral value added							(✓)
	Interest rate							✓
	Exchange rates							✓
Techno-economic data	Electricity generation	✓	✓	✓			✓	(✓)
	Road: light duty	✓	✓	✓			(✓)	
	Road: heavy duty	✓	✓	✓			(✓)	
	Heating	(✓)	✓	(✓)				
	Cooling	(✓)	✓	(✓)				
	Appliances	(✓)	✓	(✓)				
	Process heat	(✓)	✓	✓				
	Machine drives & Steam		✓					
	CHP	(✓)	✓					
	CCS/NETs		✓	✓			✓	
Fossil fuel prices	Coal market/import prices					✓	✓	✓
	Oil market/import prices					✓	✓	✓
	Gas market/import prices					✓	✓	✓
Historical emissions	CO_2 emissions	(✓)	✓	(✓)	(✓)	✓	(✓)	(✓)
	CH_4 emissions	✓				✓	✓	(✓)
	N_2O emissions	✓				✓	✓	(✓)
	F-gases	✓				✓	✓	(✓)
	Pollutants	✓						(✓)

✓means harmonised, (✓) means checked for consistency: divergence of the model's input database values for this specific variable was reviewed and ensured to lie within a ±10% range of tolerance around the values of the shared database to which other models were harmonised. No mark means that harmonisation was not applicable due to not being represented explicitly.

Table 4: Socio-economic assumptions and data sources. See Supplementary Text 4 for details on harmonisation

Variable	**Time span**	**Units**	**Data sources**	
			1st modelling iteration	2nd modelling iteration
Population: Total country population	2010-2100	Million people, growth rates	Europe: (European Commission, 2019); Rest of OECD database: short-to-medium term (OECD, 2020); long-term (KC & Lutz, 2017) Rest of the world: estimates up to 2020 (UN, 2019); post-2020 (KC & Lutz, 2017)	Europe: unchanged to first iteration (insignificant changes) Rest of OECD database: updated projections up to 2060 in line with (OECD, 2022) Rest of the world: unchanged to first iteration (no new data)
Working age Population: Total population between 15 and 64 years old	2010-2100	Million people, growth rates	Europe: (European Commission, 2019); Rest of OECD database: short-to-medium term (OECD, 2020); long-	Europe: unchanged to first iteration (insignificant changes) Rest of OECD database: updated projections

			term (KC & Lutz, 2017) Rest of the world: estimates up to 2020 (UN, 2019); post-2020 (KC & Lutz, 2017)	up to 2060 in line with (OECD, 2022) Rest of the world: unchanged to first iteration (no new data)
Gross domestic product based on purchasing-power-parity valuation	2010-2100	PPP (constant billion 2010 International $), growth rates	Europe: GDP per capita up to 2070 (European Commission, 2017); GDP per capita post-2070 (Dellink et al., 2017) Rest of OECD database: GDP growth until 2021 (OECD, 2019); short-to-medium term (OECD, 2018); long-term (Dellink et al., 2017) Rest of the world: estimates up to 2020	Europe: "Limited Recovery" scenario in D5.3[1] for GDP projections until 2060; post-2060 annual correction (Dellink et al., 2017) Rest of OECD database: GDP growth until 2027 (IMF, 2022); Post-2027 growth (OECD, 2021) with post-2060 annual correction (Dellink et al., 2017)

[1] Deliverable 5.3: "Global pathways and EU responses: A 1st European regional, national and sectoral assessment”

			(IMF, 2019); post-2020 (Dellink et al., 2017)	Rest of the world: estimates up to 2027 (IMF, 2022); post-2027 (Dellink et al., 2017)

Table 5: Techno-economic assumptions

Power	Transport	Buildings	Industry	Hydrogen
Technologies: renewables (wind, solar, nuclear, geothermal, hydro, and biomass) and non-renewable (coal, gas) technologies	Technologies: cars, buses, and trucks	Technologies: household appliances, lighting, heating and cooling	Technologies: CCS integration	Technologies: water electrolysis, natural gas reforming (including with CCS), coal gasification (including with CCS)
Variables: Costs of investment, fixed and variable operation & maintenance (O&M), capacity factors, conversion efficiencies and technical lifetimes	Variables: Costs of investment, fixed O&M, capacity factors and efficiencies.	Variables: Costs of investment and efficiency ratios between advanced and conventional technologies	Variables: CCS capture rates, CCS energy penalty, and CCS capex increase from the conventional technology	Variables: CAPEX, OPEX, efficiency, CCS capture rate, technical lifetime
Sources: Napp et al., 2014; Mantzos et al., 2017	Sources: Napp et al., 2014; Mantzos et al., 2017; NREL, 2017	Sources: Mantzos et al., 2017	Sources: Schorcht et al., 2013; Gardarsdottir et al., 2019;	Sources: Collodi et al., 2017
* Costs of investments in 2020 updated in 2nd modelling iteration				* Harmonisation only applied in 2nd modelling iteration

2.2 First modelling iteration scenarios

Pre-2020 Nationally Determined Contributions (NDCs) and current policies were implemented at the level of model regions as ambition to 2030 (the period for which NDCs are most frequently stated and for which current policies' impact can reasonably be projected).

Current policies are implemented according to the database of such policies by region, as detailed in the CD-Links policies database (Roelfsema et al., 2020). The CD-Links database was updated with assumptions on policies from more up-to-date sources for the key emitting regions, notably the IEA policies database (IEA, 2020). The combined database included 340 national and supra-national policies. The models differ in the level of policy implementation due to technological and sectoral granularity, which differs across the models used. A representation of the number of policies implemented in each region by each model is shown in Figure 1. Notably, models such as the computable equilibrium ones, like ICES, have their primary strengths in implementing system-level policies such as the European cap and trade system for CO_2 emissions, the share of renewables, or carbon tax, but a lower capacity to implement technology-oriented fuel efficiency standards.

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 (e.g. for the USA pledge of reducing emissions in 2025 by 26-28% relative to 2005, we applied 26%).

The deeper mitigation scenarios (2°C to 1.5°C compatible) follow Current Policies to 2025 and begin mitigation efforts starting immediately thereafter, without delays and not following NDC targets for 2030.

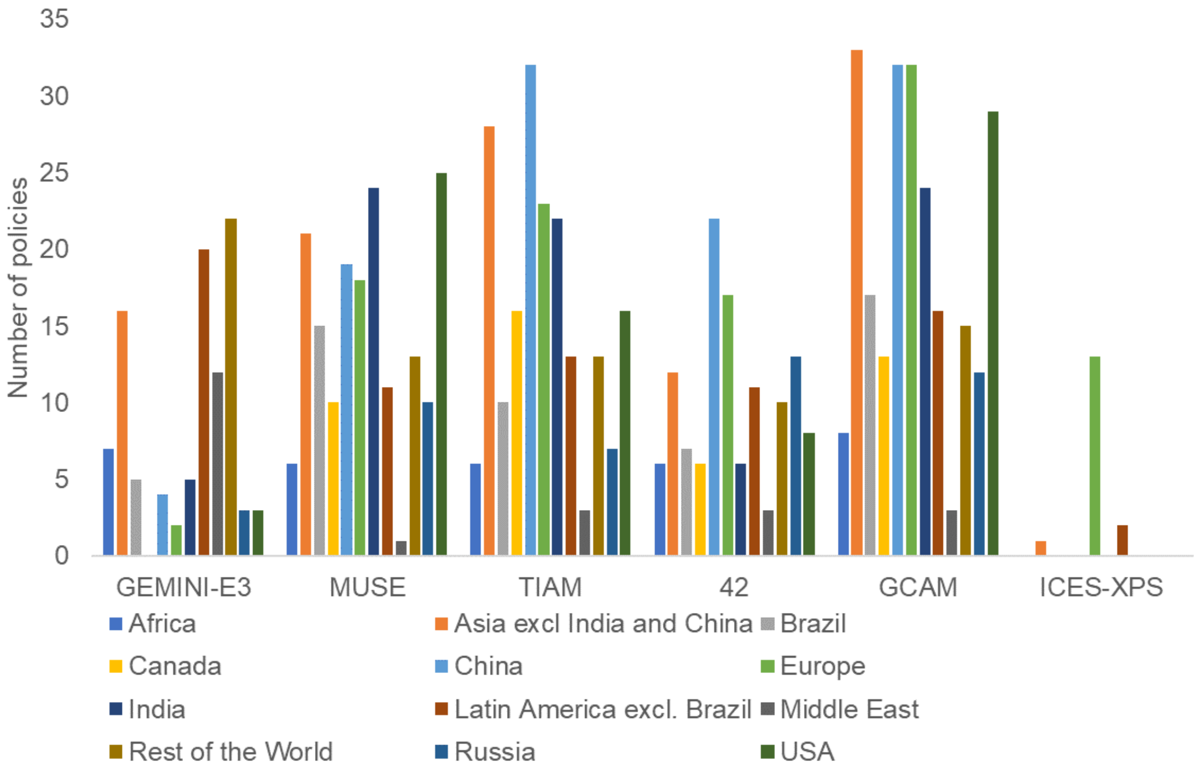


Figure 2: Number of policies implemented in each model by region.

Note: Number of current policies implemented in each model by region. Numbers are not shown for E3ME because their baseline already includes policies, which makes counting more complicated.

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 (CP_Price, and CP_Intensity for current policies; NDC_Price, and NDC_Intensity for NDCs) as well as the deeper mitigation scenarios (1.5°C, 1.75°C and 2°C).

The scenario protocol describes how NDCs, in this study, are implemented on top of current policies.

2.2.1 Scenario logic

The reference scenarios in the 1st modelling iteration were designed to reflect pre-2020 levels of mitigation efforts in different world regions, taking pre-2020 policies (in the rest of this section referred to as "current policies") as the starting point. Two of the scenarios reflect the efforts implied by current policies (CP) and two of the scenarios reflect additional efforts implied by NDCs (NDC) on top of current policies.

Two methods are used to extend the mitigation efforts implied by current policies and NDCs to 2030 (the period for which NDCs are most frequently stated and for which current policies' impact can reasonably be projected) beyond 2030, resulting in four scenarios in total. Each method represents one way of using common IAM variables to interpret and measure mitigation efforts:

- _Price: The carbon prices that, on their own (absence of other current policies), achieve (in each region of each model) the same levels of emissions as current policies and NDCs in 2030. These carbon prices are named "equivalent carbon prices" (ECPs).
- _Intensity: The rate of change in emission intensity of GDP in each region up to 2030.

The two measures of mitigation effort are used to extend regional mitigation efforts beyond 2030 in the following manner:

- _Price: By extending the ECPs in each region, growing at the rate of GDP per capita from 2030 onwards, to represent a "constant" economic burden from carbon pricing, as proxied by the ratio of the carbon price to per capita income over time. Fujimori et al. (2016) similarly use constant carbon prices post 2030 to assess the long-term implications of INDCs.
- _Intensity: By keeping the rate of change in emission intensity of GDP constant after 2030. This method is used by Fawcett et al. (2015) and VanDyck et al. (2016) to assess the long-term implications of INDCs. Cai et al. (2017) explain how emissions intensity targets can be implemented in models with endogenous GDP based on an iterative method.

To increase the realism of how emissions reductions take place in all the examined scenarios, current policies are represented explicitly both in 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 deeper mitigation scenarios are designed to explore the required transformations to reach Paris-compliant temperature targets, departing from current policies up to 2025. After 2025, these policies are assumed to remain in place as "constant" or "minimum" bounds on effort. In contrast to the reference scenarios, the mitigation scenarios assume uniform global action (post-2025) translated into a global economy-wide carbon price. These deeper mitigation scenarios function mostly as a rough representation of the required action and thus the difference between these scenarios and the reference scenarios is treated as the climate action gap. The mitigation pathways are designed by the consortium models that run until 2100 and are decided based on an optimisation procedure to reach climate targets by 2100 at least costs (5% discount rate), without limits in terms of overshoot or technological constraints.

2.2.2 Scenario protocol

2.2.2.1 All scenarios

- Current policies are explicitly represented in CP and NDC scenarios both before and after 2030 (reference runs) / 2025 (mitigation runs).
- The implementation of current policies after 2025/2030 as "constant" or "minimum" levels depends on the model:
    - For models that have detailed representations of energy systems (MUSE, TIAM, GCAM), current

policies are simulated as constraints. For example, where current policies represent the achievement of a minimum share of renewables in power generation, or minimum vehicle efficiency standards, then these policies are kept constant (i.e. a constant minimum share of renewables, or constant minimum vehicle efficiency) beyond 2030. Note that the renewables shares, or vehicle efficiency levels, are not kept constant, but rather at a constant minimum bound—this allows the models to simulate over-achievement against these policy targets as for example, the cost-competitiveness of renewables or more efficient vehicles drives them to do so.

- For macroeconomic models, such as the computable general equilibrium (CGE) models ICES and GEMINI-E3, policies are more commonly applied as minimum subsidy levels to specific low-carbon technologies, to encourage their uptake. In such cases, these subsidies are held constant in the period beyond 2030, to simulate a continuation of policy support for these technologies.

The steps for implementing each scenario are given below.

2.2.2.2 CP_Price scenarios

1) Implement current policies to 2030. Record emissions in 2030 in all modelled regions.
2) Re-run the model without current policies, using regional economy-wide carbon prices to reach the levels of emissions in 2030 recorded in Step 1. Depending on the model, the emissions in 2030 can be implemented as caps, allowing the model to find the corresponding carbon prices endogenously. The resulting scenario forms the first part (up to 2030) of the CP_PriceOnly scenario. The "equivalent carbon prices" (ECPs) in 2030 are the carbon prices that reproduce the emissions caused by current policies to 2030 in each region (i.e. the emissions recorded in Step 1).
3) Run the model from 2030 until the end of the modelling period(2050 or 2100, depending on the model time horizon) with the ECPs growing with GDP per capita in every region. The starting point should be the end point of the scenario run in Step 2 (not the end point of the scenario run in Step 1). Record emissions trajectories (to 2050 or 2100) for all modelled regions. The resulting scenario forms the second part (post-2030) of the CP_PriceOnly scenario.
4) Re-run the model from the beginning, with:
    a. Current policies to 2030, kept as constant or minimum levels after 2030.
    b. The emissions trajectories in Step 3, as regional emissions caps. Depending on the model, the carbon prices needed above current policies in each region to achieve the required emissions reductions may be computed endogenously by the model.

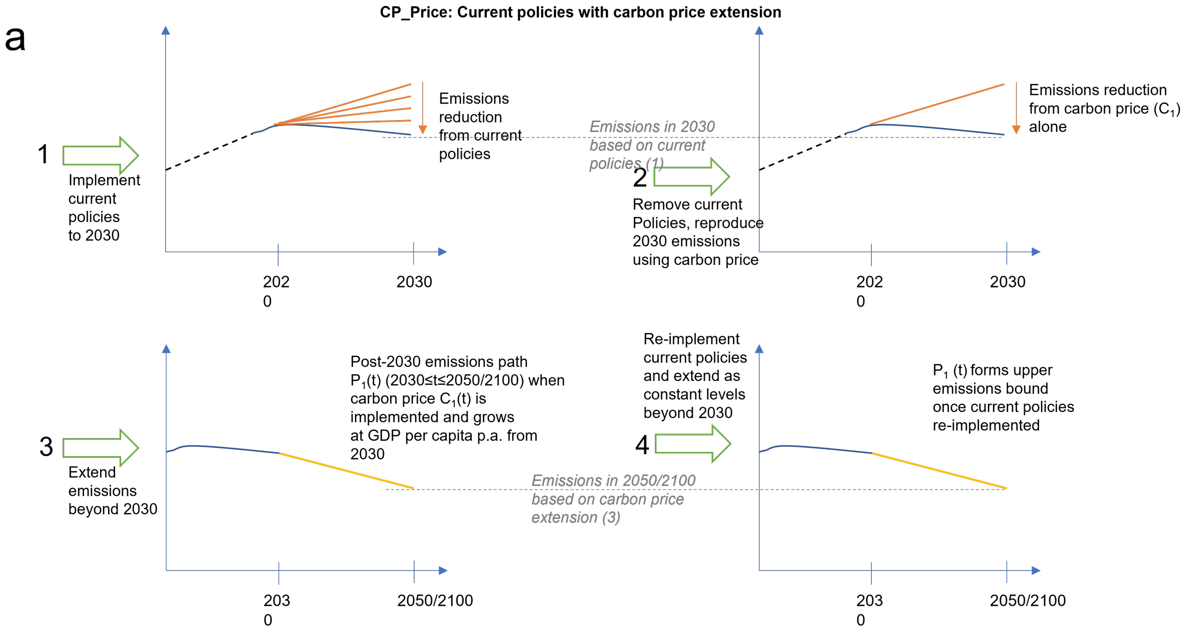


Figure 3: Graphical illustration of modelling protocol for CP_price scenario

CP_PriceOnly scenarios

CP_PriceOnly scenarios represent intermediate steps in the procedure described above to obtain CP_Price scenarios.

2.2.2.3 CP_Intensity scenarios

1) Implement current policies to 2030. Record the resulting emissions in every region in the modelled period and compute the annualised rate of change of emissions intensity (emissions per GDP) in every region to 2030.

2) Starting with regional emissions in 2030 recorded in Step 1, compute regional emissions pathways to the end of the modelling period (2050 or 2100) by applying the annualised rate of change of emissions intensity computed in Step 1 beyond 2030. This step does not involve running the model.

3) Re-run the model from the beginning, with

   a. Current policies to 2030, kept as constant or minimum levels after 2030.

   b. The emissions trajectories in Step 2, as regional emissions caps. Depending on the model, the carbon prices needed above current policies in each region to achieve the required emissions reductions may be computed endogenously by the model.

2.2.2.4 NDC_Price and NDC_Intensity scenarios

Up to 2030, there are two cases:

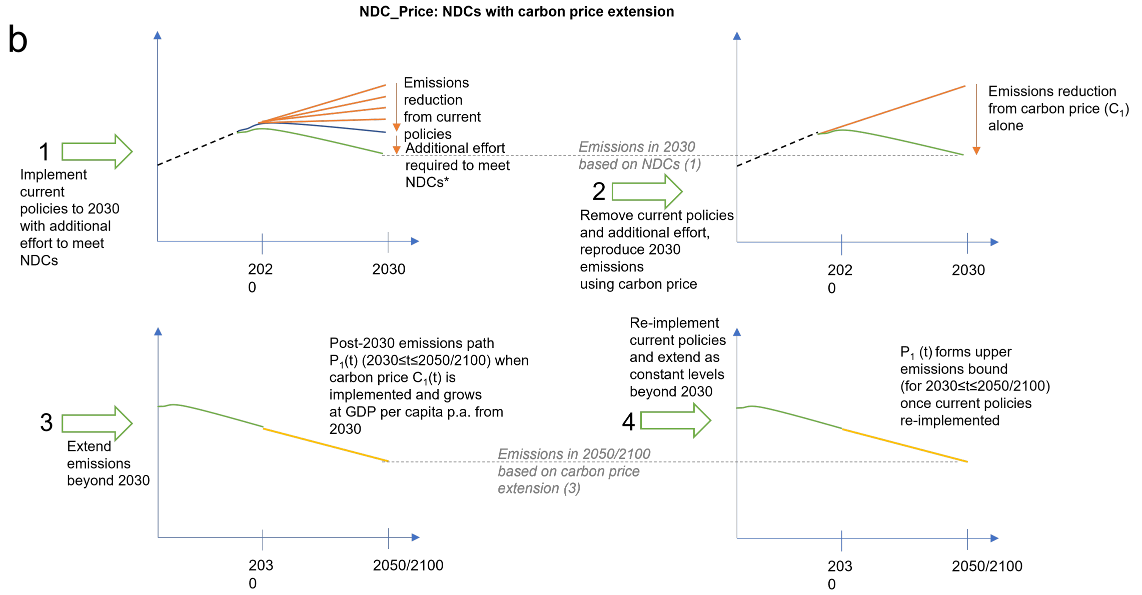
1) For regions where emission reductions in CP_Price scenarios are equal to or exceeding NDC targets, NDC_Price scenarios are set equal to CP_Price scenarios.

2) For regions where emissions reductions in CP_Price scenarios do not achieve the reduction proposed in NDC targets, additional mitigation efforts are implemented in NDC_Price scenarios to ensure NDC targets are met in 2030. Depending on the model, the additional effort can be implemented as an emissions cap

on top of current policies, allowing the model to endogenously determine the carbon price needed (in addition to current policies) to reach NDC targets.

Post-2030:

In NDC_Price and NDC_Intensity scenarios, the post-2030 extension is done in the same way as in CP_Price and CP_Intensity scenarios, the only differences being (in the second cases) the level of emissions in each region in 2030.



*For most models additional effort will be represented by the carbon price required (on top of current policies) to meet NDC targets. This carbon price is independent of the carbon price (C_1) in 2.
Note, if for any region, current policies outperform NDCs (i.e. current policies lead to larger emissions reductions than NDCs), emissions are defined by current policies, not the NDC targets.

Figure 4: Graphical illustration of modelling protocol for NDC_price scenario

2.2.2.5 Deeper mitigation scenarios

This design protocol applies to models that run to 2100 since it applies end-of-century CO_2 budgets consistent with three temperature outcomes by 2100. All scenarios follow Current Policies to 2025 and begin mitigation efforts starting immediately thereafter (so no delays, no following NDCs[2]). The first timestep following 2025 should be on the path to meeting the target cumulative emissions budget. In order to avoid backtracking on current policies, these policies should be extended as a minimum ambition bound beyond 2025. The socioeconomic drivers should be the same as those used for the reference scenarios.

The scenarios will have these design characteristics:

1. They will follow current policies to 2025 (as per the reference scenario), and then apply that level as a minimum ambition level thereafter, recognising that from 2025 on, mitigation action should take place in line with a potentially more stringent target while allowing models to exceed the policy target in ambition

[2] New NDCs are due in the year these runs were completed (2021), so applying pre-Glasgow NDCs would make the runs obsolete. Also, the point of using 2025 is to inform the GST and action beginning right after it.

if they could (on the basis of rapidly declining technology costs, e.g.). The policy target should be set as a minimum level of ambition for the relevant indicator.

2. They will deliver cumulative emissions end-of-century budget targets consistent with 2°C, 1.75°C and 1.5°C budgets as outlined in Table 5 (3 variants). These emission budgets are supposed to achieve the said temperature targets with a 50% certainty.

3. The fourth scenario will be a variant of the 1.5°C scenario but including the additional constraint of global net-zero CO_2 emissions by 2050 (1 variant).

Models that cannot implement a cumulative emissions constraint can apply carbon price trajectories as required to deliver the target cumulative CO_2 emissions budgets. These can be existing trajectories, or they can come from models in the consortium, as long as they deliver cumulative emissions within the specified budgets.

The SR15 budgets include CO_2 emissions from land use and forestry (FOLU). Arguably, they may need to be adjusted to reflect energy use and process emissions only. However, we will assume a net-zero FOLU end-of-century cumulative emissions budget. This means that post-2050, FOLU becomes a sink absorbing all 2000-2050 CO_2 emissions from FOLU. This can be justified on grounds beyond just climate mitigation: biodiversity conservation, hydrological cycle maintenance, ecosystem services provision, and indigenous population rights, to name a few. By doing it this way, the FOLU 21st-century CO_2 budget is independent of the scenario. It will be net-zero FOLU CO_2 emissions (which come from deforestation and land degradation mostly) across all scenarios over the simulation period.

Finally, this protocol focuses on energy and process CO_2 emissions. Non-CO_2 emissions, for example from agriculture, are assumed to follow a path that is consistent with the emission budgets and temperature targets mentioned in Table 5, but since these emissions are not included in most models, they are not part of the model comparison exercise.

Models going only to 2050 will have to apply carbon prices at a level sufficient to place their emissions trajectories within the range of 2050 emissions from the models that do go to 2100 (GCAM, MUSE, and TIAM) in each scenario. This raises the issue of which emissions budget to use for 2050. The pace of reduction in 2100 models can be quite steep in the 2020-2050 period in order to meet more stringent budgets. Therefore, we have opted for the three 2100 models to run the TCRE CO_2 budgets for each temperature outcome and provide the range of 2050 emissions from each run. Then, based on these ranges, the 2050 models will apply the 2018-2050 budgets informed by the models that go to 2100 (taking the average of those models). This means the 2100 models will have to do the runs first and then the 2050 models will follow. It also means 2050 models may need to only run the 66th percentile cases, so 3 scenarios.

Table 6 summarises the scenario names and carbon budgets of the four scenarios.

Table 6: Constraints in each scenario on i) emissions and ii) year of net-zero, to be run by models going to 2100.

Scenario name	Approx warming since 1850-1900 (°C)	Remaining CO2 emissions budget (GtCO2 from 1.1.2018) (50th TCRE percentile*)	Year of net-zero CO2
CP_1p5	1.50	580	none
CP_1p75	1.75	1040	none
CP_2deg	2.00	1500	none
CP_1p5_net0	1.50	580	2050

** TCRE: transient climate response to cumulative emissions of carbon, assessed by AR5 to fall likely between 0.8–2.5°C/1000 PgC (Collins et al., 2013), considering a normal distribution consistent with AR5 (Stocker, 2014). Values are rounded to the nearest 10 GtCO2.*
Source for emissions budgets: IPCC SR15 Ch 2, Table 2.2

2.2.2.6 Variation across models

All modelling groups were asked to follow the scenario protocol as closely as possible. In order to ensure the ability to do so, the scenario protocol was designed in a thorough iterative process involving all modelling groups. Individual modifications were made only when model structures meant that this was necessary. In the end, only E3ME, which does not use optimisation and does not compute carbon prices endogenously from emissions caps, had to modify the scenario protocol slightly to fit with the model structure. Model-specific details regarding the specifics of the scenario implementation are listed here.

GCAM

Energy and land-related current policies have been applied to 16 out of 32 regions, while NDCs have been applied for all regions and covering all GHGs, based on INDC interpretations as provided by Fawcett et al. (2015), and adapted to the socioeconomic assumptions applied in this deliverable. In order to avoid discontinuities between the last Current Policies/NDC year (2030) and the first extrapolation year (2035), the extrapolation is only applied to those GHGs that are explicitly constrained by the current policies/NDCs. That means that in the *CP* scenarios, extrapolations in all regions are only applied to CO_2 (from energy, industry and LULUCF), while in the *NDC* scenarios extrapolations are only applied to CO_2 in those regions where energy and land-related policies were more restrictive than NDCs, and therefore no additional measures have been used to constrain GHGs on top of the applied policies. This was the case for Argentina, Brazil, China, EU, India, Indonesia, and South Africa. This does not mean that non-CO_2 gases are not affected in *CP* and partially *NDC* scenarios: energy and land-related policies focusing on CO_2 might indirectly also affect non-CO_2 emissions, and GCAM uses a model-implicit abatement curve for certain industrial and agricultural process emissions, which responds to the sector-wide CO_2 price.

For the deeper mitigation runs, GCAM directly applied temperature targets instead of cumulative emissions, where non-CO_2 GHG emissions are taxed at the same CO_2-equivalent rate as fossil CO_2 emissions, using the AR5 100-year GWP values, while FOLU CO_2 emissions are taxed at 10% of the rate of fossil CO_2. The implicit CO_2 budgets (from energy and industrial processes) for all temperature targets were compared and in line with those in Table 6.

TIAM

Non-energy sector's current policies are not implemented in the *CP* scenarios in TIAM.

MUSE

MUSE Global applies by default a global emission trajectory. In this deliverable, where emissions limits were applied region-by-region the carbon budget approach was solved first for each individual region and then applying a super-loop using the converged carbon prices as price trajectories in a global simulation.

To contain the computation burden, which might result from the starting value of the carbon price and its endogenous step-change, the carbon price can either remain constant or escalate. An endogenous reduction of the carbon price was not envisaged in the algorithm, assuming this approach to best mimic a continuous carbon mitigation effort avoiding technology lock-in exacerbated by the agent-based and limited foresight nature of the model. For this reason, the scenarios were implemented with this principle. In the emissions intensity policy extension, either binding targets were reached using a pre-defined tolerance, or those upper bounds were not reached when the energy system outperforms the emission limit. In the GDP growth extension method, a carbon price equivalent was applied as a price trajectory to estimate the corresponding energy systems emissions.

GEMINI-E3

All policies included in the *CP* scenario have been translated into targets, which are implemented through taxes and subsidies. The Russian policies aiming to decrease the coal share in the total primary energy supply, for instance, are implemented by taxing coal consumption. In the case of policies linked to the deployment of renewable electricity generation, these are implemented through a subsidy on renewable electricity generation. For aggregated regions (such as Africa), policies were detailed at the national level and aggregated by considering their respective contribution to the region (e.g. the renewable target in electricity for Africa is a weighted average of each national policy).

Some policies related to energy efficiency improvement are difficult to implement in the model due to a lack of sufficient technological granularity. For post-2030 mitigation efforts, a carbon price was introduced in each country/region and applied to all GHG emissions (CO_2, CH_4, N_2O and fluorinated gases) excluding LULUCF.

ICES-XPS 1.0

NDC targets were applied only to energy-related CO_2 emissions.

CP and *NDC* scenario extensions assuming the same 2020-2030 emissions intensity change were achieved directly targeting emissions intensity and endogenously deriving the carbon price (which is consistent with the required abatement, but also with the policy cost in terms of GDP).

E3ME 6.1

CP scenarios:

Extrapolation of carbon prices was carried out from 2030 to 2050, in line with real GDP per capita growth from the recalibrated E3ME baseline; differences between extrapolated carbon prices and the E3ME carbon price assumptions were added on top of the recalibrated E3ME baseline from 2030 onwards.

Extrapolation of the emissions intensity rate was implemented with average carbon intensity, based on GDP and CO_2 emissions from the E3ME baseline, reapplied to GDP projections to give implied emission targets for each region by 2050; differences between these emission targets and the E3ME baseline emission levels projected for 2050 were reconciled by adjusting a number of regional assumptions from 2030 onwards (capacity for different generation technologies, the uptake rate of generation technologies and vehicle types).

NDC scenarios:

Where additional policies (over and above current policies) were assumed in the IEA Stated Policies scenario, those assumptions were added on top of the current policies assumptions. Such policies include generation capacity constraints, technology mix for power generation, heating and road transport, fossil fuel regulations, restrictions or ambitions for reducing fossil fuel trade, increases in carbon prices and/or implementation of a carbon price in new sectors. Where no additional policies were identified from the IEA Stated Policies scenario and a region was expected to miss its NDC target by 2030 under the *CP* scenario by a significant margin, additional measures were implemented sequentially in the following order until the region was close to its NDC target: i) faster uptake of renewables for power generation and electric vehicles for road transport, ii) increased investment in energy efficiency improvements, and iii) higher carbon prices.

The two variants of the *NDC* scenario were modelled in a similar way to the Current Policies variants, with the addition of energy efficiency as one of the adjustments in the second variant.

Deeper mitigation scenarios:

Only the CP_1p5 scenario has been run.

All scenarios include the same treatment for recycling carbon revenues, which generates rebound effects in the economy. It was assumed that revenues from the carbon prices would be used by governments to partly fund energy efficiency investments. If carbon revenues were insufficient, governments would raise additional funds by increasing taxes for industries and households (with the burden being split equally between the two groups).

FortyTwo

Concerning the scenario protocol of this study, FortyTwo could not implement the CarbonPrice (_*Price*) scenarios because the model does not include a carbon price.

2.3 Second modelling iteration scenarios

Post-Glasgow Nationally Determined Contributions (NDCs) and up-to-date current policies were implemented at a regional level as ambition to 2030 (the period for which NDCs are most frequently stated and for which current policies' impact can reasonably be projected).

Compared to the first modelling iteration, current policies are also updated where applicable, and new policies were added using a variety of sources. Policy representation by model is similar to the first modelling iteration, reflecting the model differences in the level of policy implementation due to technological and sectoral granularity.

Like in the first iteration, 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. An important difference with the first iteration pertains to the legal status of the applied pledges. While in the first iteration NDC pledges that were announced in 2014-2015 and put in law or in policy documents thereafter were applied, some of the announced pledges applied in this iteration may not yet be made official. Nevertheless, to ensure consistency between countries and not discriminate announcements based on the timing of putting them into law or policy, we decided to apply all pledges that were announced in or before the COP26 in Glasgow to have a complete picture of post-Glasgow climate action (see Table 7).

The key addition compared to the first modelling iteration is the implementation of net-zero and carbon neutrality pledges (see Table 8), which should provide a long-term projection of current climate action and its impacts on global emissions and temperature.

2.3.1 Scenario logic

The scenarios in the second modelling iteration are supposed to reflect different levels of compromised post-COP26 ambitions:

1. Current policies (*CP*): level of short-term ambition that is likely to be materialised through actual policies.
2. NDCs (*NDC*): level of short-term ambition to which most countries are dedicated through law or policy, but with risks of falling short in cases of insufficient dedication and/or changes in the political landscape.
3. Long-term strategies (*LTS*): level of longer-term ambition which many countries have stated to fulfil their part in mitigating climate change, but in most cases without support from an actual policy agenda.

The first two levels of action are aiming at 2030, which is the common year for NDC targets and many policy targets. In order to forecast longer-term emission futures using current policies and NDCs, the Intensity method applied also in the first modelling iteration is applied after 2030 as a function of the ambition level up to 2030:

- _Intensity: The rate of change in emission intensity of GDP in each region up to 2030. See Section 2.2.2.3.

To increase the realism of how emissions reductions take place in all examined 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 at incorporating long-term pledges (see Table 8), predominantly net-zero emission pledges, into the modelled scenarios. These will come on top of pledged NDC targets, to create another increased level of proposed ambition. These pledges will be included in the models in two ways:

a) Including long-term pledges for all countries as a linear pathway from the 2030 NDC target (*NDC_LTS*).

b) Like (a), but for those countries that are modelled in Work Packages 5 and 6, adapt the emission pathways from those national/regional models, and also implement energy system pathways as if they were policies (e.g. integration of renewables, transport electrification). In some cases, this may also imply that emissions in the NDC targets are lower than previously applied (*LTS_ADV*).

The idea of having these two scenarios including long-term ambitions is to have two global pictures: one where the post-2030 energy system transformation towards long-term targets is informed by global model outcomes, and another one where these targets are informed by national/regional models, in many cases informed by stakeholder inputs.

2.3.2 Scenario Protocol

The protocol for implementing policies into the models, and for applying the CP/NDC_Intensity scenarios is identical to that in the first modelling iteration. Therefore, see Sections 2.2.2.1, 2.2.2.3 and 2.2.2.4 for the protocol of these scenarios, but applied with the updated set of policies and NDCs (Table 7). The novel part of the second modelling iteration is the implementation of long-term strategies, for which the rest of this protocol is about.

Table 7: Post-Glasgow updated NDC pledges to be applied in the second global modelling iteration.

Country	Target type*	New target value (lower value applied)	Base year	Target year	Relative to the previous target
China	GDP Intensity	over 65% reduction	2005	2030	Improved target
India	GDP Intensity	40-45% reduction	2005	2030	Improved target
USA	Base year	50-52% reduction	2005	2030	Improved target
EU	Base year	55% reduction	1990	2030	Improved target
UK	Base year	68% reduction	1990	2030	Improved target
Norway	Base year	50-55% reduction	1990	2030	Improved target
Japan	Base year	46% reduction	2013	2030	Improved target
South Korea	Base year	40% reduction	2018	2030	Improved target
Canada	Base year	40-45% reduction	2005	2030	Improved target
Argentina	BAU	39% reduction	2030	2030	Improved target
Chile	Cap	95 Mt CO_2eq		2030	Improved target (change from BAU to cap)
Colombia	BAU	51% reduction	2030	2030	Improved target
Equador	BAU	9-20.9% reduction	2025	2025	no target last iteration
Peru	BAU	30-40% reduction	2030	2030	Improved target

Indonesia	BAU	29.1-41.3% reduction	2030	2030	adapted (higher) BAU
Malaysia	GDP Intensity	45% reduction	2005	2030	Improved target
Singapore	Cap	65 Mt CO_2eq		2030	Improved target
Belarus	Base year	35% reduction	1990	2030	Improved target
Ukraine	Base year	65% reduction	1990	2030	Improved target
Viet Nam	BAU	9-27% reduction	2030	2030	adapted (higher) BAU

* GDP Intensity: target reducing emissions per unit of GDP relative to this intensity in a base year
* Base year: emission reduction target relative to a determined historical base year
* BAU: emission reduction target relative to the emissions in a determined business-as-usual (BAU) future emissions level
* Cap: Absolute determined cap on emissions

2.3.2.1 NDC_LTS scenario

The NDC_LTS scenario is supposed to forecast global emissions based on the full set of national pledges. Table 8 provides long-term targets for a large list of countries. These should be implemented on top of the NDC scenario, replacing the post-2030 extension method, through the following steps:

Table 8: Long-term emissions targets to be applied in the second global modelling iteration.

Country	Year	Target type	Target status	All GHGs	Comment
USA	2050	Net-zero	In policy document	yes	
UK	2050	Net-zero	in law	yes	
Sweden	2045	Net-zero	in law	yes	
European union	2050	Net-zero	in law	yes	
Germany	2045	Net-zero	in law	yes	
India	2070	Net-zero	Gov. announcement		
China	2060	Net-zero	In policy document		
Canada	2050	Net-zero	in law	yes	
Australia	2050	Net-zero	in policy document	yes	
New Zealand	2050	Net-zero	in law	yes	biogenic methane is excluded
Nigeria	2060	Net-zero	in law		
Saudi Arabia	2060	Net-zero	Gov. announcement		
Russian Federation	2060	Net-zero	Gov. announcement		
South-Korea	2050	Net-zero	in law	yes	
Japan	2050	Net-zero	in law	yes	
Brazil	2050	Net-zero	In policy document		
South Africa	2050	Net-zero	In policy document		
Malawi	2050	Net-zero	In policy document		
Argentina	2050	Net-zero	Gov. announcement		
Chile	2050	Net-zero	In policy document	yes	Plans to reach net zero through domestic actions
Vietnam	2050	Net-zero	Gov. announcement		
Thailand	2065	Net-zero	Gov. announcement		carbon neutrality by 2050 and net zero emissions by 2065
Colombia	2050	Net-zero	Gov. announcement		

Kazakhstan	2060	Carbon neutrality			carbon neutrality
Turkey	2053	Net-zero	Gov. announcement		
Italy	2050	Net-zero	Gov. announcement		
UAE	2050	Net-zero	Gov. announcement	no	Only CO_2 is covered
Switzerland	2050	Net-zero	In policy document		
Denmark	2050	Net-zero	in law	yes	
Peru	2050	Net-zero	Gov. announcement		
France	2050	Net-zero	in law	yes	
Norway	2050	90-95% reduction			
Mexico	2050	50% below 2000 emissions			

For all countries for which no long-term pledges have been announced, the scenario assumes the same emission path as in the NDC scenario. Also, if for a certain country the NDC_Intensity scenario is more ambitious than the target mentioned in Table 6, the NDC scenario outcome should be followed. This ensures that, for each model region, the NDC_LTS scenario is strictly more ambitious than the NDC scenario.

Step 1: Determining pledged long-term emission levels

Determine, for each model region, the level and timing of the long-term pledge. If the country is individually represented in the model, this is straightforward. If the country is part of an aggregated model region, the emissions level (*E*) should be calculated by applying the pledged target(s) (*LTS*) from Table 8 to the estimated emissions share of that specific country (*i*) in the entire model region (*j*) according to either the 2019 EDGAR emissions data (https://edgar.jrc.ec.europa.eu/report_2020#emissions_table), or, if available, the country´s emissions share in the aggregated NDC target for 2030, and applying the Intensity extension (*EI*) method used in the NDC scenario for the rest of the region. The following formula represents how long-term emission targets in aggregated regions are supposed to be approached:

$$E_{j,2050} = E(LTS)_{i,2050} * \left(\frac{E_{i,2019\ or\ NDC2030}}{E_{j,2019\ or\ NDC2030}}\right) + E(EI)_{j-i,2050} * \left(\frac{E_{j,2019\ or\ NDC2030} - E_{i,2019\ or\ NDC2030}}{E_{j,2019\ or\ NDC2030}}\right)$$

This might not be entirely precise as there are usually differences between expected emission trajectories of different countries in aggregated regions, but a best-possible approximation.

Most models do not include LULUCF emissions dynamically, and many do also not represent non-CO_2 GHG emissions, while most of the pledges include all GHG emissions. This can be troublesome for some countries where forestry and/or non-CO_2 emissions are very relevant (e.g., Russia, Brazil). Since GCAM does cover all GHG emissions (CO_2 from energy, industrial processes and LULUCF, as well as non-CO_2 GHGs), the results in terms of CO_2 emissions from energy and industrial processes are shared (for the 32 GCAM regions) ahead of the deadline for these runs, so that other teams can apply these emission levels. If the regional aggregation in some regions is very different to that of GCAM (e.g. less aggregated), teams can individually look for other information sources indicating the potential share of energy-related CO_2 emissions in long-term targets.

Step 2: Applying long-term emission levels

After defining the long-term emissions targets (Step 1), applying them is relatively simple in this scenario. The general rule is to just draw a linear line from the observed emissions level in 2030 in the NDC scenario (which could be identical to CP, if current policies are more ambitious than the current NDC) and to the target emissions levels in the target year. See Figure 5 for a visual example applied to the EU.

If the model only runs until 2050 and the pledge refers to a year after 2050 (e.g., 2060 for China), the emissions level in 2050 should be calculated as if it followed a linear decline to the future year (e.g., in the case of China, this refers to 1/3rd of the NDC 2030 emissions level, as 2050 is on two-thirds of the 2030-2060 stretch; see graphically in Figure 5).

After the long-term emission targets, emissions are assumed to either stay zero if the long-term target achieves net-zero emissions, or continue the linear decline towards net-zero if the long-term target is above zero.

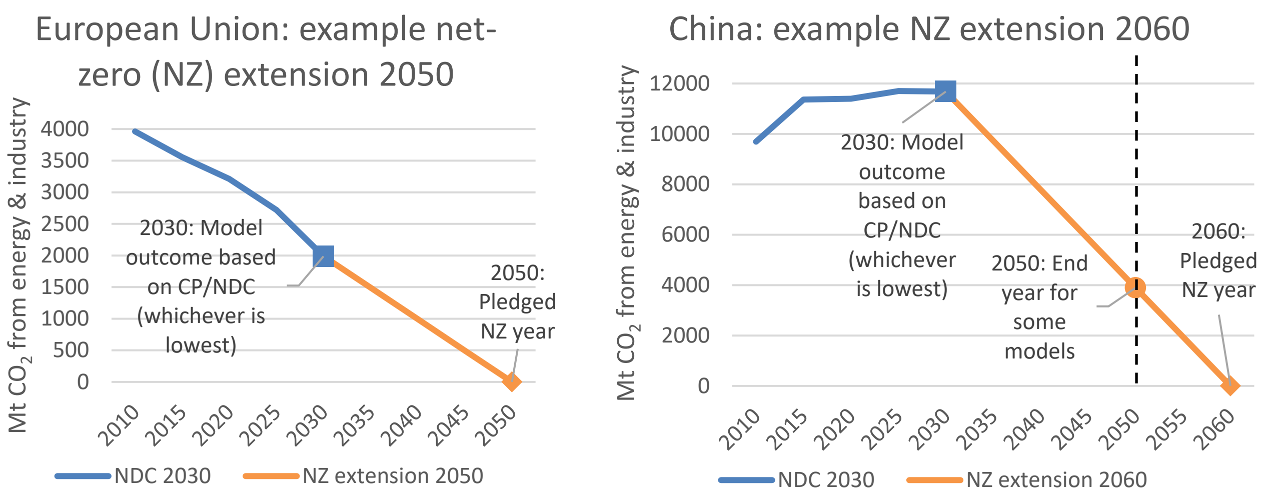


Figure 5: EU and China examples for applying long-term pledges

2.3.2.2 LTS_ADV scenario

The LTS_ADV scenario also represents national long-term mitigation targets, but, differently than the NDC_LTS scenario, the entire long-term mitigation pathways (starting from 2020 towards the last modelling year) from models in WPs 5 and 6 are reconstructed in terms of emission pathways, primary and final energy use, non-fossil shares, electrification and bio-energy shares, within each global model´s possibilities. Therefore, the countries/regions, for which this scenario diverts from the NDC_LTS scenario, are the following:

- European Union (+ UK)
- China
- United States
- India
- Russia
- Brazil
- Canada
- Mexico
- Central Asia Caspian region

If one of these countries/regions is part of a significantly bigger region in the model (e.g., Canada in ROW for GEMINI-E3), partially reconstructing an existing scenario is difficult so the NDC_LTS scenario can be followed. However, if there are just small representation differences (e.g., EU-28 in WEU+EEU for TIAM), national model outputs can be scaled before implementation.

As model structures and dynamics differ, the WP 5 and 6 scenarios can likely not be represented identically, but a maximum effort should be done as if regional model outputs were “current policies” which are implemented for the CP. This means that groups can use similar policy files as applied for the previously run scenario, but likely adjusting policy targets and expanding policies in time and towards all regions in the above list, to represent WP 5 and 6 results from their first modelling year to either the last year of their own model, or the last year of the model outcome they are replicating, whichever comes first. If the last year of the global model is later than the scenario it is replicating, it should assume constant targets at the level of the last year from the scenario it is replicating for the remaining years.

Emissions and energy system outcomes from the WP5 and 6 scenarios that are ought to be replicated are provided by all the teams and, if more than one model participated in a one national/regional modelling exercise, either an average of modelling outcomes (if feasible and sensible) or a “best-choice” is selected before providing the data to the global modelling teams.

3 Results of first global iteration

In this section, results from the first iteration of reference and mitigation runs will be laid out and briefly discussed. For each indicator, the results for the reference and mitigation runs will be shown in different figures. However, to improve comparison, the CP_Intensity model outcome is included in the results of the mitigation runs. For some models, the results for this scenario slightly differ from the results of the same scenario in the reference runs, since there were small model updates in between the reference and mitigation runs, and the CP_Intensity scenario (not the other reference scenarios) was re-run if this was the case.

3.1 Emissions

Focus is given on global energy CO_2 emissions to 2050 as all examinded IAMs represent these emissions sources as a minimum. Current policy constrained scenarios reach levels of emissions between 32-36 $GtCO_2$ in 2030 and 26-40 $GtCO_2$ in 2050 (Figure 6a) and NDC constrained scenarios reach levels of emissions between 30-34 $GtCO_2$ in 2030 and 23-38 $GtCO_2$ in 2050 (Figure 6b). Global differences in emissions between current policy and NDC constrained scenarios arise because not all regions are on track to meet their NDC targets.

The method used to extend efforts post-2030 in reference scenarios can have a large impact on emissions by 2050 (Figure 6a & b). The impact is larger for some IAMs (GEMINI, ICES, GCAM) than for others (TIAM, MUSE, E3ME)—FortyTwo includes only emissions intensity extensions. In models where the difference is large, carbon price extensions lead to higher emissions than emissions intensity extensions. This implies that a constant rate of emissions intensity reductions post-2030 requires carbon prices that increase faster than per capita incomes (as is assumed in the carbon price extension method), making our intensity scenarios more optimistic with regards to future efforts than our price scenarios.

The transient climate response to cumulative carbon emissions (TCRE) is applied to calculate the temperature changes implied by energy CO_2 emissions and GCAM is used to account for assumptions around the greenhouse gases not represented in all models (see Appendix). Across the range of scenarios considered, a median 2100 temperature outcome of 2.2-2.9°C was found (Figure 7). As expected, NDC constrained scenarios demonstrate lower 2100 temperatures than current policy constrained scenarios, reflecting their greater ambition by 2030 at a global level. In addition, and as expected from their greater optimism on effort, intensity scenarios provide lower 2100 temperature estimates than price scenarios. Because the examined temperature range considers all emissions intensity scenarios from all models, but carbon price scenarios from only 3 out of 6 models, the low end of our temperature range is more robust than the high end (see Appendix).

While scenario choice has a significant impact on emissions projections in the forecasting reference scenarios, the model used matters more (Figure 6a & b). Some models (TIAM, MUSE) project significant emissions reductions by 2050 in all scenarios, whereas others (GEMINI) project either stable or increasing emissions in all scenarios. In general, differences in emissions between current policy and NDC constrained scenarios are smaller than differences in emissions between different models. The model used to project where emissions are headed is thus a better predictor of emissions (and temperature outcomes) than the scenario used. This finding is in line with other studies that have shown that model differences play an important role in scenario analysis (Jaxa-Rozen and Trutnevyte, 2021; Krey et al., 2019). This study further demonstrates that the impacts of different post-2030 mitigation assumptions can also be highly model-dependent, despite the harmonisation of key modelling inputs. Sognnaes et al. (2021) elaborate on the sources of the model differences for the reference scenarios.

For the mitigation scenarios, which are based on the backcasting principle, logically model differences in terms of emissions are smaller (Figure 6c-f). As all models are supposed to reproduce an emission path that is compatible with 2ºC, 1.75ºC and 1.5ºC futures for 2100, only the distributions of emissions over time can differ, but cumulative emissions are supposed to be similar. The results in Figure 6c-e show that 2ºC compatible scenarios require CO_2 emissions from fossil energy in 2050 to drop to 20-25 Gt, 1.75ºC requires a drop to 17-20 Gt, and 1.5ºC would need fossil CO_2 emissions in 2050 to be below 13 Gt.

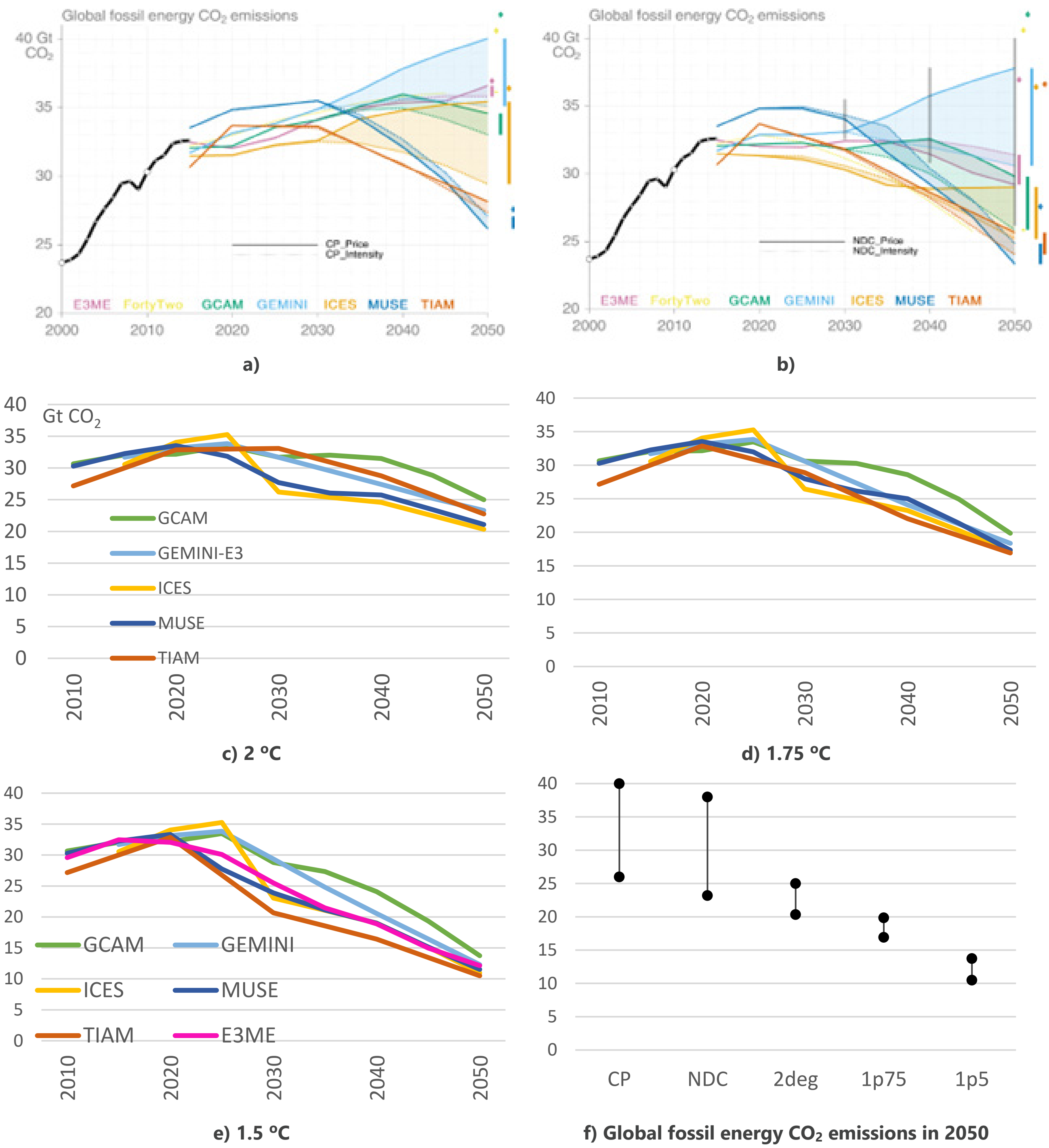


Figure 6: Global CO_2 emissions from fossil energy use for all models in reference & mitigation scenarios

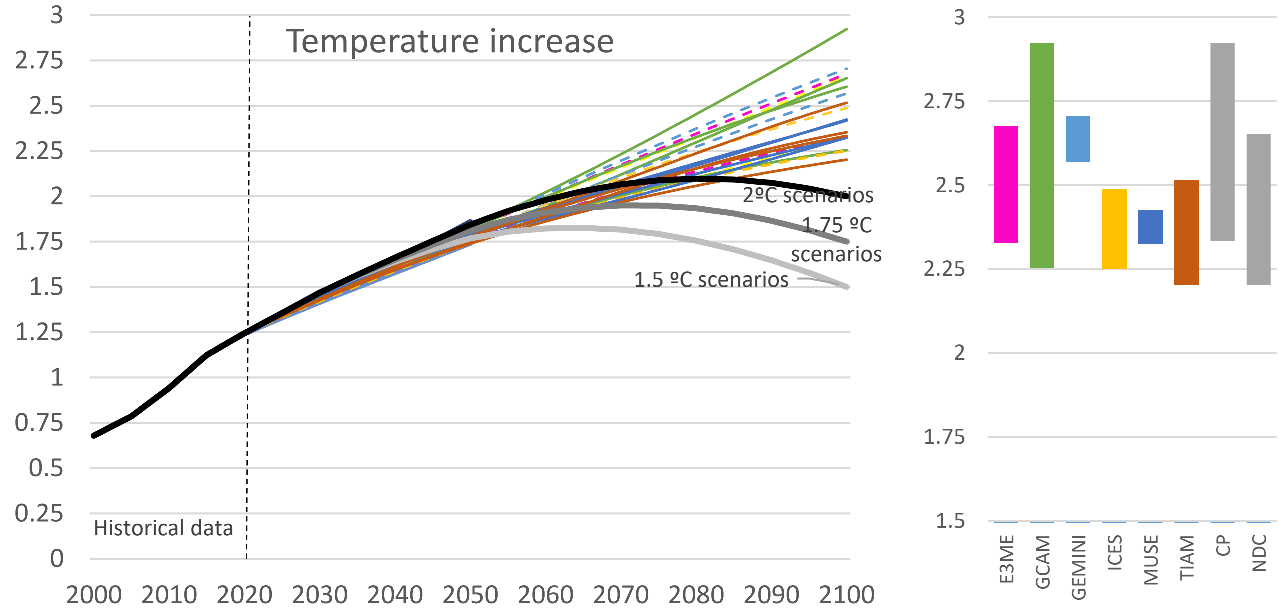


Figure 7: Global temperature increase and ranges for all scenarios and models (see Appendix)

Continued (coloured) lines represent 2100 projections from models that project until 2100, while interrupted lines represent temperature outcomes through emissions intensity extrapolation of models that project until 2050. Greyscale lines represent backcasted mitigation targets.

3.2 Energy system

Behind differences in global energy CO_2 emissions across models and scenarios lie differences in final energy demand (Figures 10& 11). Relatively lower global final energy demand in MUSE and TIAM helps explain the lower energy CO_2 emissions in these models. Total final energy demand alone, however, is not sufficient to explain the level of CO_2 emissions. ICES, for instance, has the highest final energy demand in 2050 in all scenarios but, due to a high share of electricity in final energy (and fewer solids), does not end up with the highest emissions. Over time, electricity in ICES, which is characterised by a low share of fossil fuels (and higher shares of hydro and nuclear) (Figure 8), displaces gases and solids in the industry and residential and commercial sectors, but not in transport where most other models show higher degrees of electrification (Figures 12, 14 and 16).

Among the robust findings it is observed that global final energy demand generally (with the exception of MUSE between 2030 and 2050) increases over time, as reflected also in global primary energy (Figure 8). This indicates higher decarbonisation of the energy system in those models where energy CO_2 emissions decline (TIAM, MUSE, and in some scenarios ICES, GCAM, and E3ME). Global final energy demand is lower in NDC constrained scenarios than in (corresponding) current policy constrained scenarios, and lower in intensity scenarios than in (corresponding) price scenarios, thus matching the ordering of CO_2 emissions in these scenarios. Global final energy in all scenarios and all models is reduced with steeper emission reductions, with the only exception to this being MUSE, which has a very low baseline final energy demand in 2050 compared to other models (Figure 10). This contributes to very low energy CO_2 emissions in MUSE in 2050 (Figure 6).

With deeper mitigation, fewer fossil fuels and more renewable energy is consumed in all models, although model differences are demonstrated: E3ME and GCAM have a clear preference for solar energy; wind energy is more prominent in ICES and TIAM, while ICES foresees a strong demand in hydro whereas MUSE in geothermal energy. Nearly all models also foresee an increase in bioenergy use with increasing mitigation efforts (Figure 9). In terms of final energy, all models foresee an increasing rate of electrification with time, and with mitigation effort (Figures 10 and 11), although absolute electricity use in GEMINI-E3 drops with deeper mitigation. Total final energy use declines with mitigation efforts in all models and all sectors (Figures 13, 15 and 17), with the exception of ICES and MUSE in the industry sector. Only GCAM and GEMINI-E3 were able to run global net-zero emission scenarios for 2050. Comparing these scenarios for primary and final energy, it is clear that, in such extreme mitigation pathways, GCAM tends to go through energy substitution with renewable alternatives, while GEMINI-E3 tends towards energy conservation.

Looking at the different end-use sectors shows that industry sector pathways are most model-dependent (Figures 12 and 13): while most models opt for efficiency gains through electrifications over time and with deeper mitigation, the industry sector in GEMINI-E3 and MUSE reduces overall final energy use (either through demand reduction or efficiency improvements beyond energy substitution). In contrast, residential and commercial pathways differ less in terms of total final energy use, but Figures 14 and 15 show a clear split between the models regarding the future use of solid fuels, with GCAM, MUSE and TIAM leaving a significant share of final demand covered by solid fuels, and E3ME, GEMINI-E3 and ICES showing a quick phase-out of fossil fuels in residential and commercial energy demand. Finally, the role of liquid fuels in the transport sector remains prominent in all models and scenarios, despite partial electrification efforts in all models.

3.2.1 Primary energy

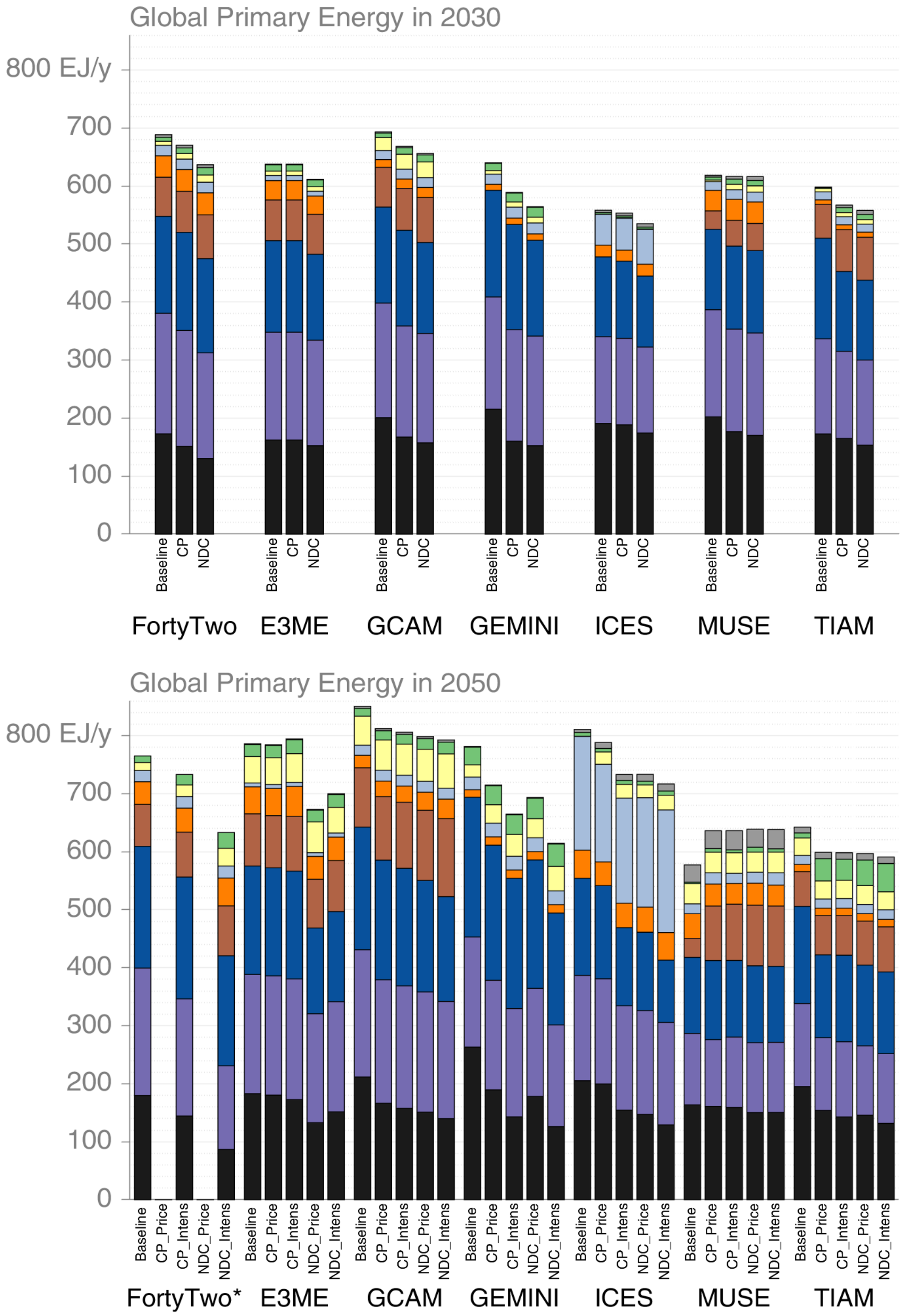


Figure 8: Global primary energy consumption in reference scenarios in 2030 and 2050 for all models

2030

2050

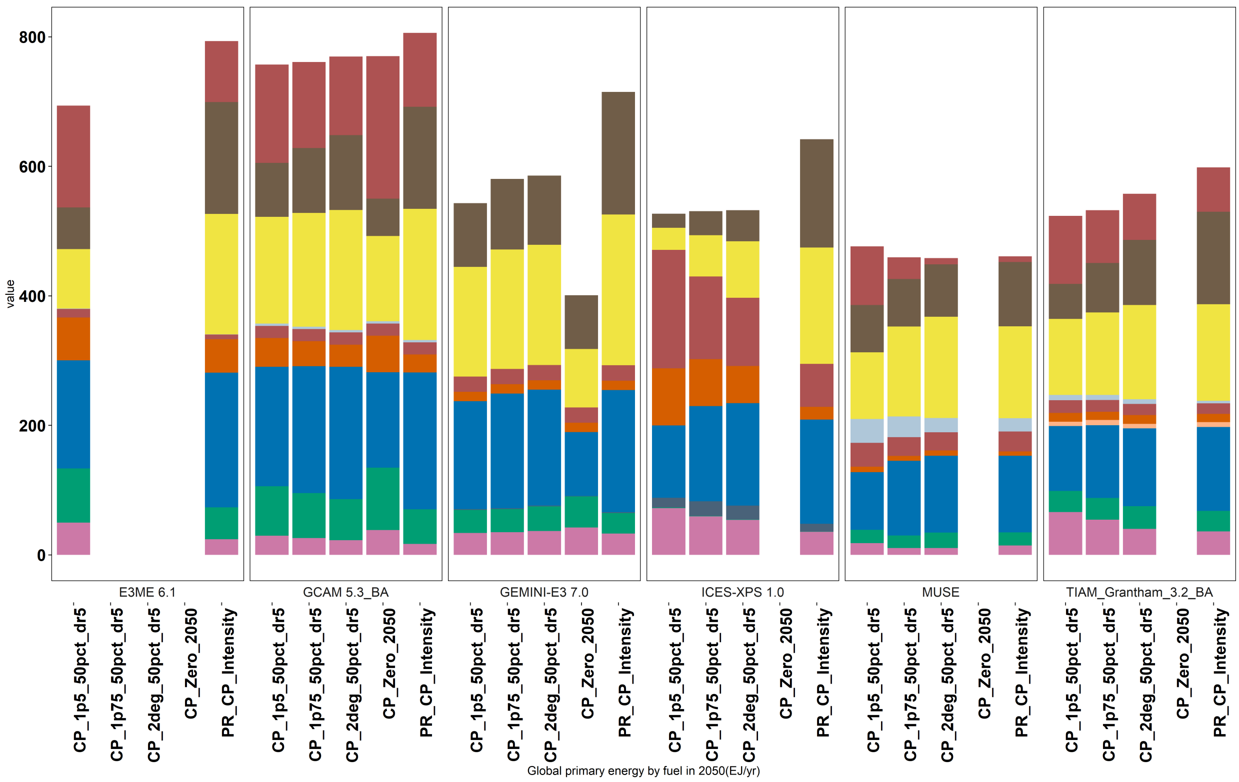


Figure 9: Global primary energy consumption in mitigation scenarios (and CP_Intensity for comparison) in 2030 and 2050 for all models

3.2.2 Final energy

3.2.2.1 Sector-wide

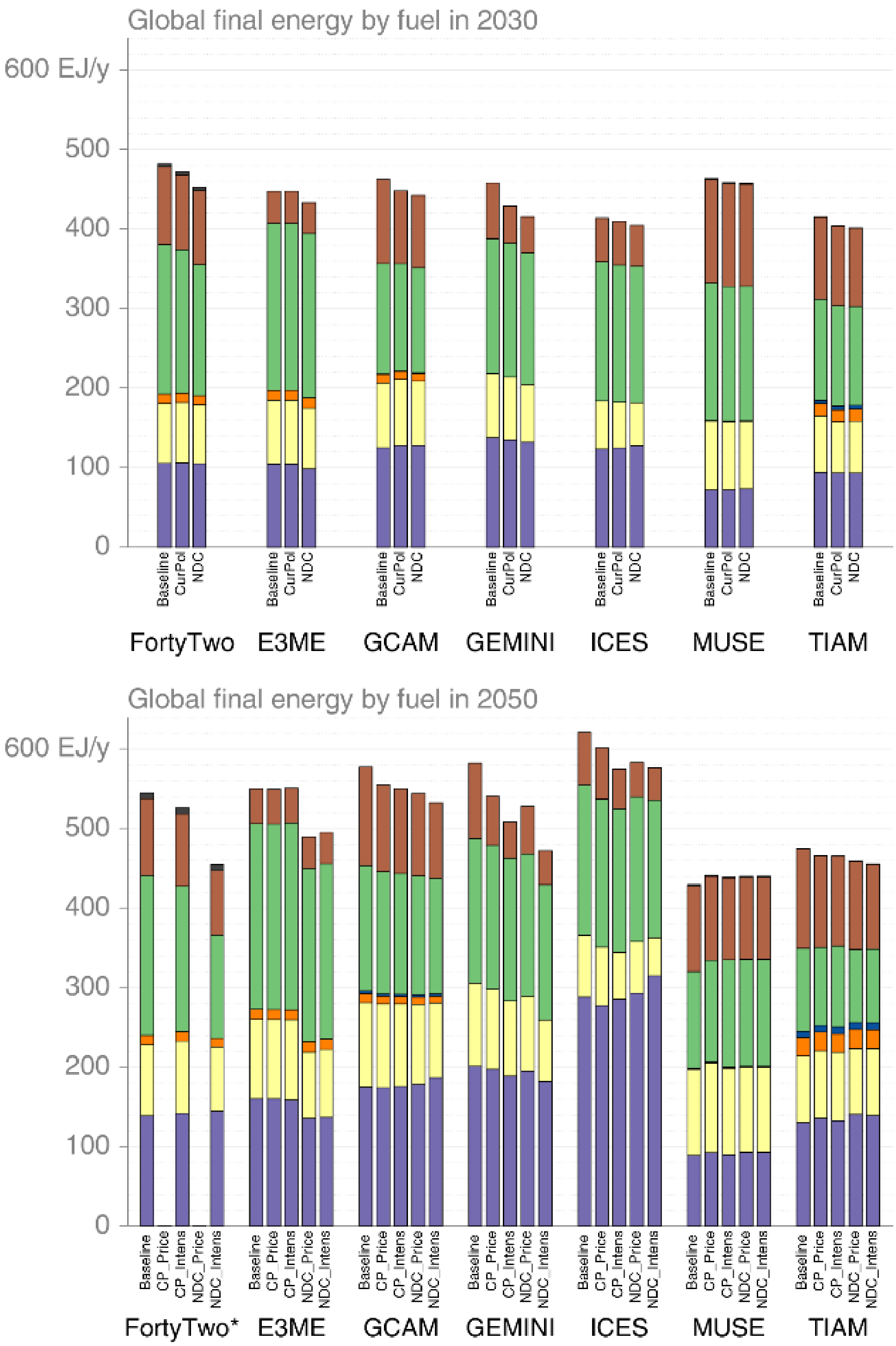


Figure 10: Global final energy consumption in reference scenarios in 2030 and 2050 for all models

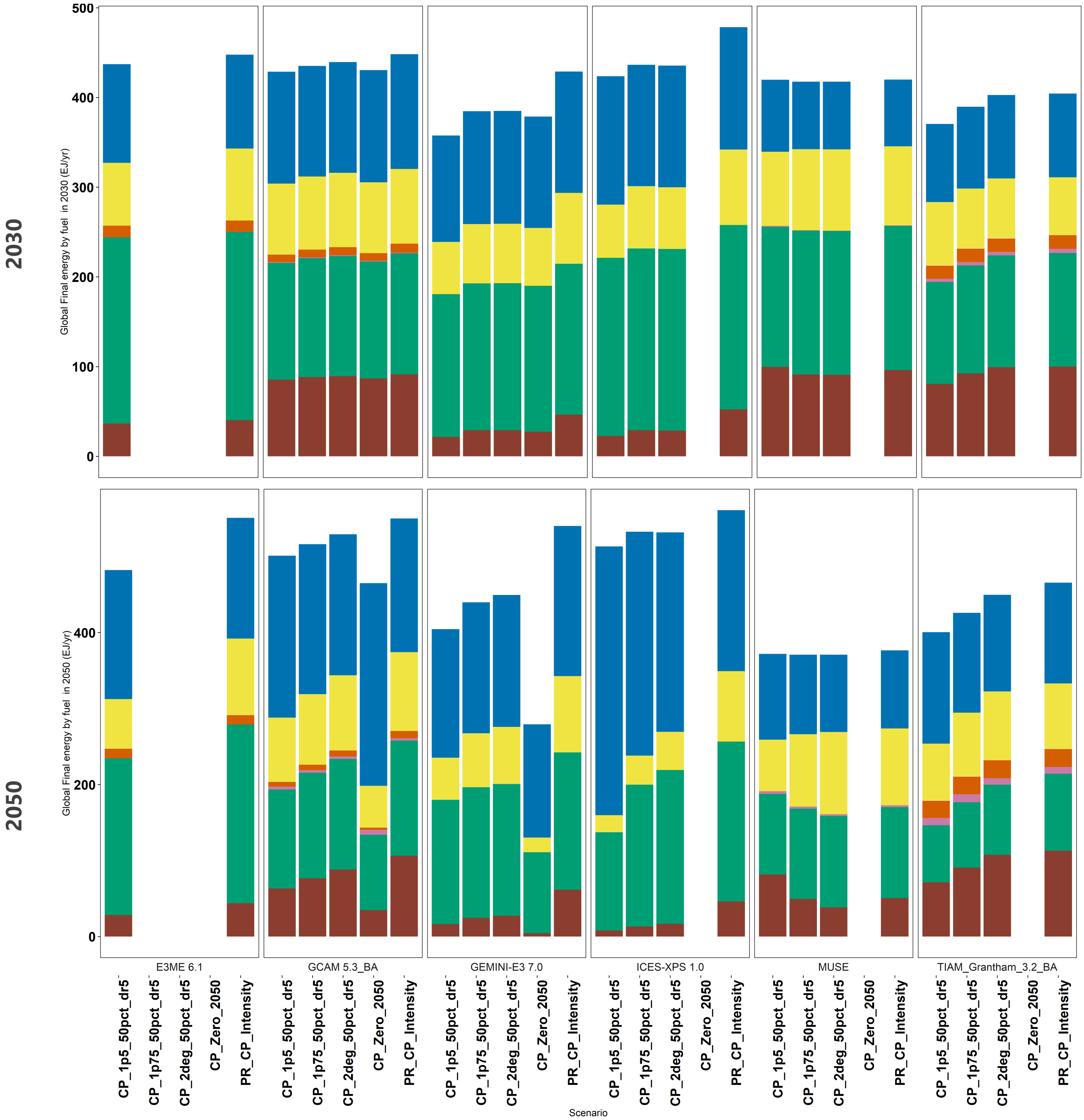


Figure 11: Global final energy consumption in mitigation scenarios (and CP_Intensity for comparison) in 2030 and 2050 for all models

3.2.2.2 Industry

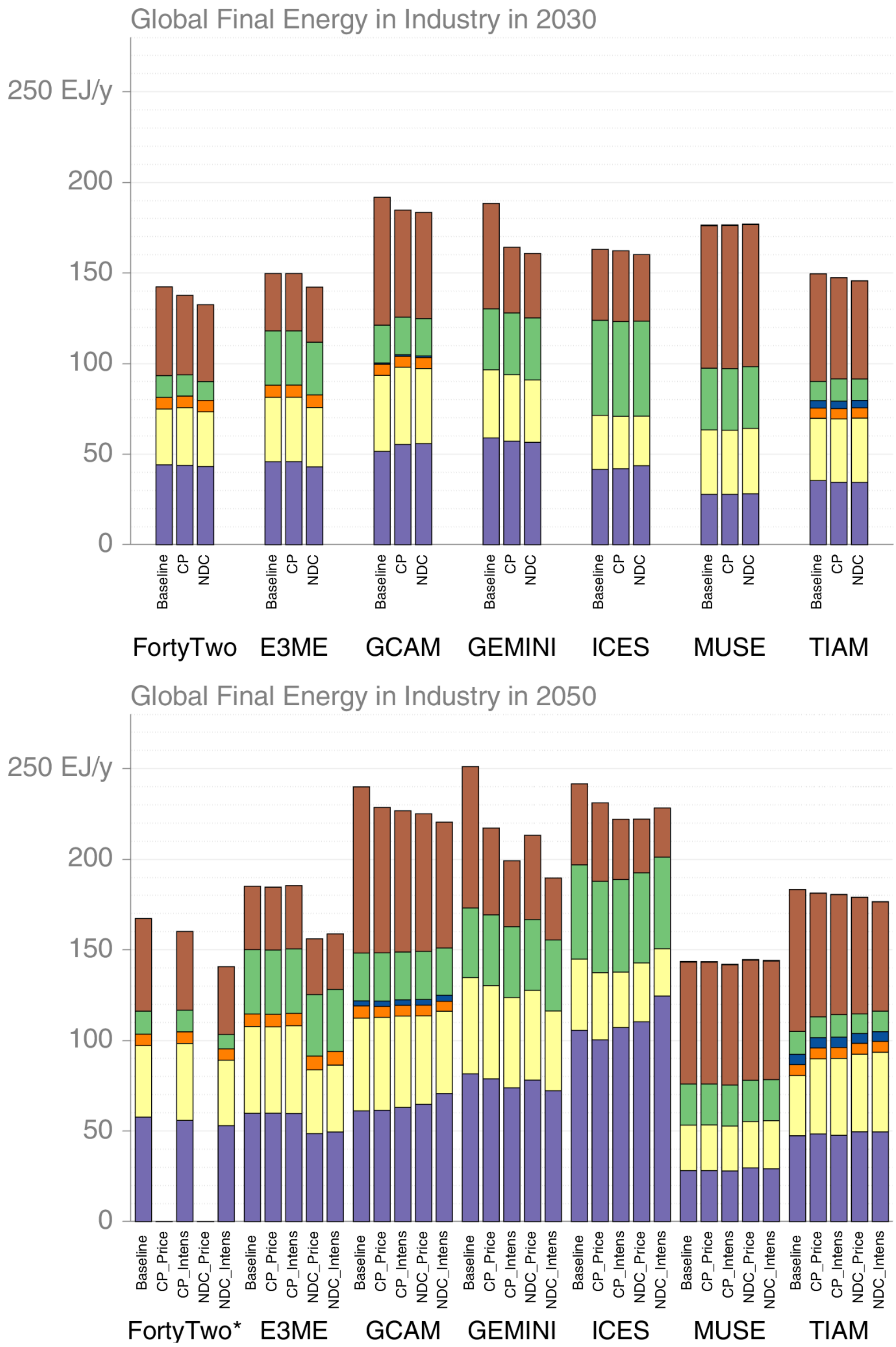


Figure 12: Global industry final energy consumption in reference scenarios in 2030 and 2050 for all models

2030

2050

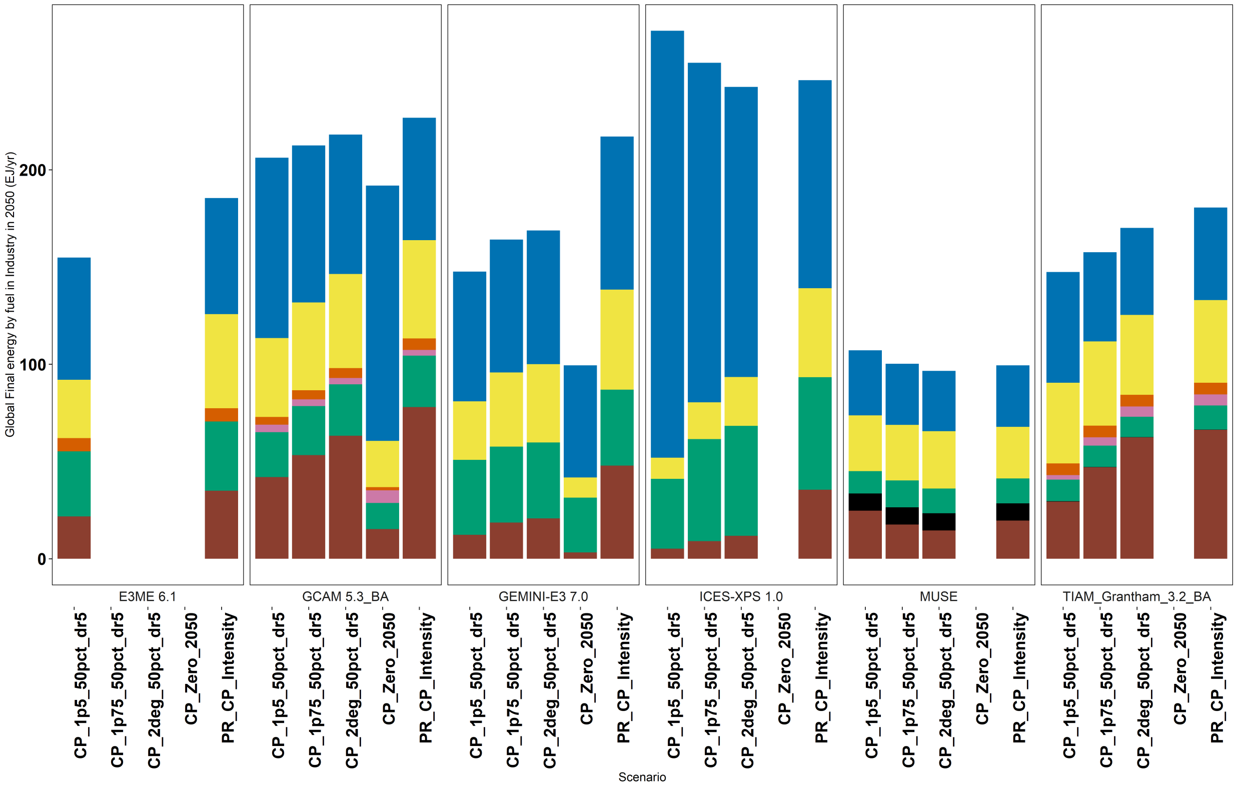


Figure 13: Global industry final energy consumption in mitigation scenarios (and CP_Intensity for comparison) in 2030 and 2050 for all models

3.2.2.3 Residential and Commercial

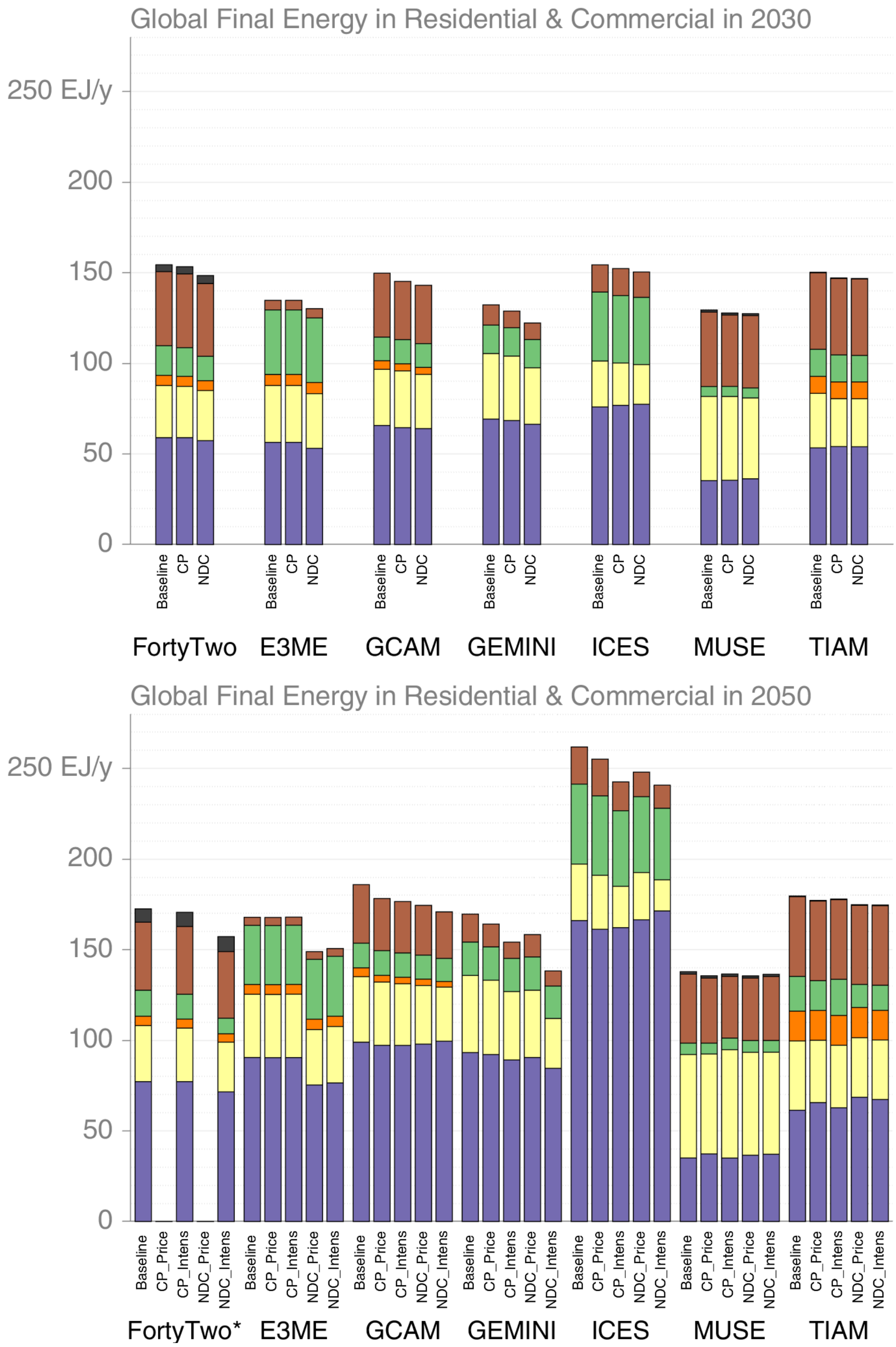


Figure 14: Global residential and commercial final energy consumption in reference scenarios in 2030 and 2050 for all models

2030

2050

Figure 15: Global residential and commercial final energy consumption in mitigation scenarios (and CP_Intensity for comparison) in 2030 and 2050 for all models

3.2.2.4 Transport

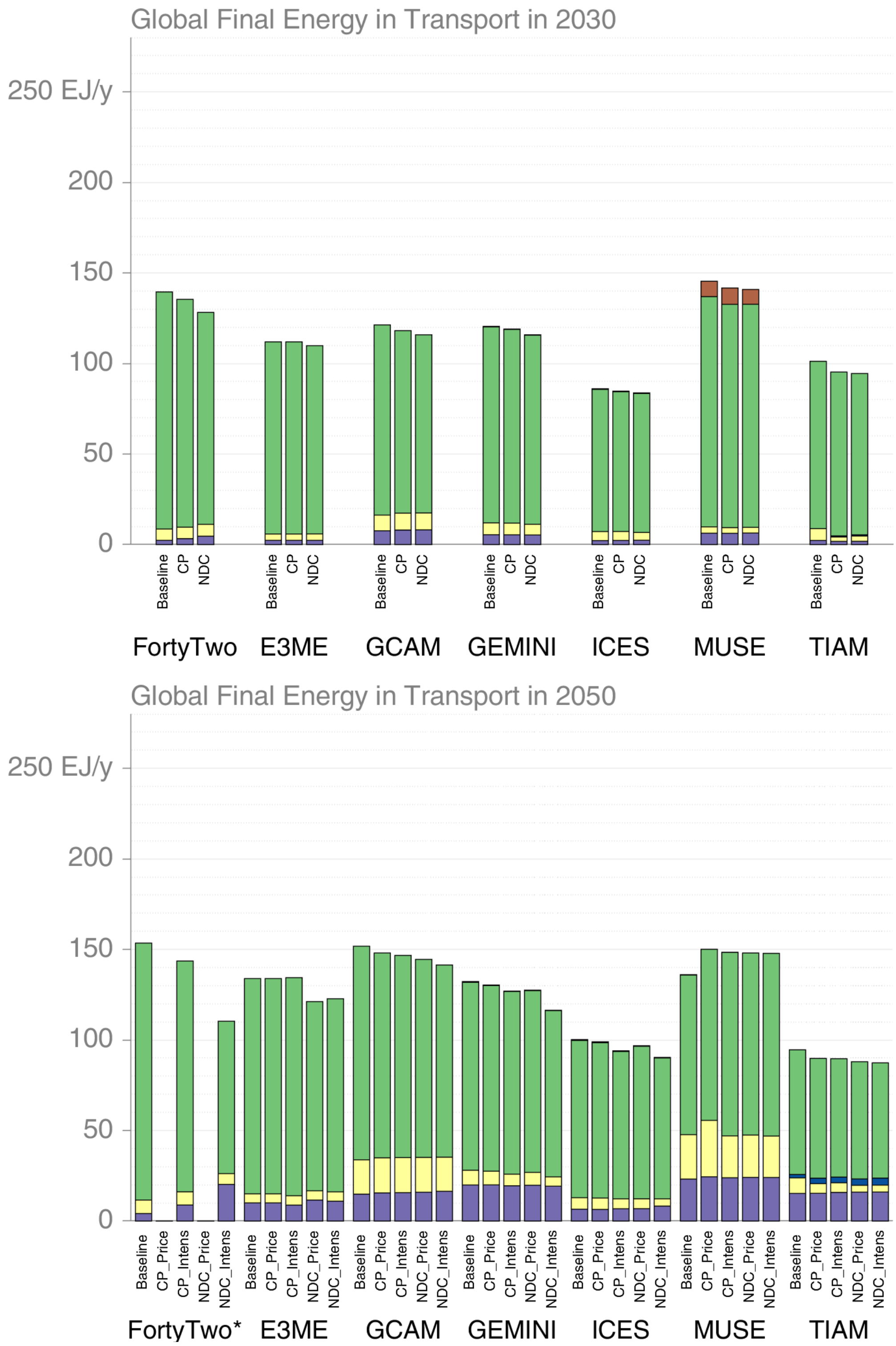


Figure 16: Global transport final energy consumption in reference scenarios in 2030 and 2050 for all models

2030

2050

Figure 17: Global transport final energy consumption in mitigation scenarios (and CP_Intensity for comparison) in 2030 and 2050 for all models

3.3 Other results

Carbon sequestration (Figure 18) has been a trivial way of mitigation in several models. Except for ICES, in all models, carbon sequestration had some contribution, although the contribution is limited in TIAM and E3ME, while in GEMINI-E3 carbon sequestration only comes in after 2030. In most models, sequestration tends to increase with mitigation efforts, with most carbon being sequestered from fossil energy, but in 2050 the share of carbon sequestered from biomass (BECCS) is also substantial. Carbon prices (Figure 19) differ strongly between models, despite aiming for the same mitigation targets, which are defined by the mix of technological options included in the model, as well as elasticities of substitution. They are highest in ICES and MUSE, and lowest in GCAM, while the other models all range around US$ 200 per ton of CO_2 by 2050 in the 1.5°C compatible scenario.

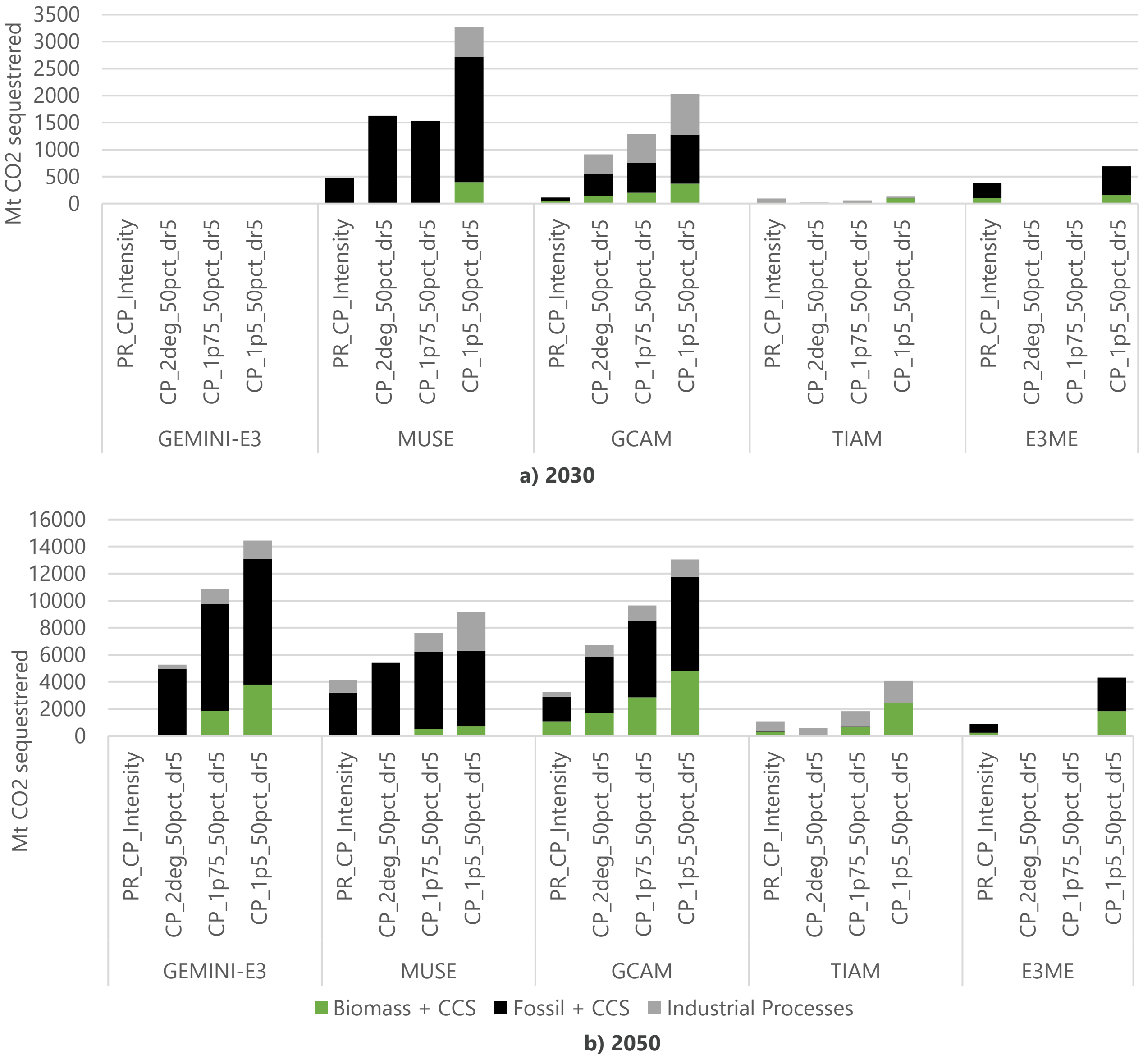


Figure 18: Carbon sequestration in 2030 and 2050 per model and scenario

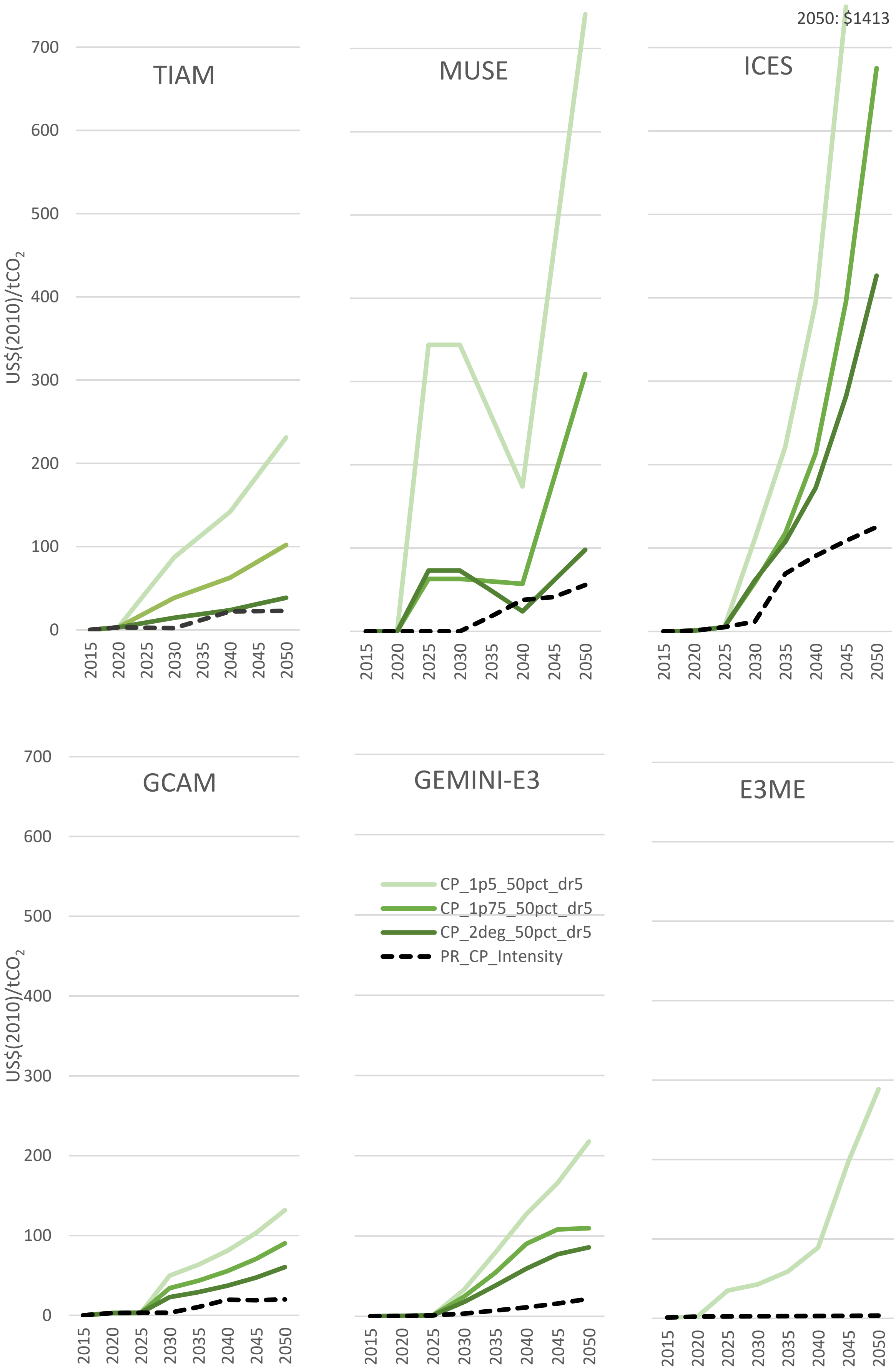


Figure 19: Carbon prices until 2050 for all models and mitigation scenarios and CP_intensity

4 Summary of regional and national modelling results

Figure 1 in the introduction shows that the 2nd iteration of global modelling is intended to be informed by the results from WPs 5 and 6. The LTS_ADV scenario (see Section 2.3.2.2) is intended to take into account deep decarbonisation pathways that are modelled with regional models in collaboration with local stakeholders. This section summarises the regional model results to be taken into account in the LTS_ADV scenario.

Table 9: List of regional models which inform the global LTS_ADV scenario

Model	Geographical focus	Model type	Online detailed documentation in I²AM PARIS
NEMESIS	EU	Macro-economic	https://www.i2am-paris.eu/detailed_model_doc/nemesis
EU-TIMES	EU	Energy-system	https://www.i2am-paris.eu/detailed_model_doc/eu_times
FORECAST	EU	Sectoral: Industry/Buildings	https://www.i2am-paris.eu/detailed_model_doc/forecast
ALADIN	EU	Sectoral: Transport	https://www.i2am-paris.eu/detailed_model_doc/aladin
CONTO	Russia	Macro-economic	https://www.i2am-paris.eu/detailed_model_doc/conto
GCAM-China	China	Partial equilibrium	https://www.i2am-paris.eu/detailed_model_doc/gcam
GCAM-USA	USA	Partial equilibrium	https://www.i2am-paris.eu/detailed_model_doc/gcam
India AIM/CGE	India	General equilibrium	https://www.nies.go.jp/media_kit/16.AIM/index.html
MAPLE	China	Energy-system	https://www.i2am-paris.eu/detailed_model_doc/maple
NATEM	Canada, USA, Mexico	Energy-system	https://www.i2am-paris.eu/detailed_model_doc/natem
MUSE-Brazil	Brazil	Energy-system	https://www.i2am-paris.eu/detailed_model_doc/muse
TIMES-CAC	Central Asia Caspian region	Energy-system	https://www.i2am-paris.eu/detailed_model_doc/times_cac

4.1 EU runs (WP5)

4.1.1 Scenario rationale

To go beyond "Where are We Headed" scenarios for Europe (Nikas et al., 2021), WP5 explored deeper climate change mitigation scenarios in the EU and, particularly, scenarios compliant with the Paris Agreement. Also, several assumptions were updated using input from D5.3, including post-COVID-19 GDP for EU countries with NEMESIS and using updated fossil fuel prices projections, resulting in some potential impacts of the COVID-19 crisis on the EU energy system and GHG emissions up to 2030. The EU revised its Long-Term Strategy (European Union, 2020) with the objective that the European economy becomes carbon-neutral in 2050 (or net-zero GHG emissions, including carbon sink from LULUCF). Furthermore, to reinforce its 2030 climate change mitigation action, the European Commission has launched the 2030 Climate Target Plan, in the framework of the European Green Deal, setting a reduction target for EU GHG emissions of at least 55% in 2030 compared to 1990 and developing a set of policy proposals (“Fit for 55” package) to adapt the EU climate policy framework to this new objective.

Based on these new developments as well as stakeholder inputs from workshops performed in Switzerland, France and the Netherlands, three new core scenarios have been designed:

Table 10: New EU Core Scenarios

Scenario name	Description
WWH21	A scenario similar to the previous WWH scenario, with updated post-COVID19 socio-economic parameters: GDP and fossil fuel prices, and still considering the current set of policies (*i.e.* not including ‘Fit for 55’ policy package and NZE target)
NZE Benchmark	Explorative EU “least-cost” scenario towards NZE in EU
NZE – EU Policy standard	Explorative NZE scenario aligned with the new EU climate policy framework

As not all models deal with non-CO_2 emissions and/or LULUCF emissions, three sets of assumptions for the “NZE Benchmark” scenario were defined according to the extent of the non-CO_2 and LULUCF emissions contribution to all GHG mitigation targets, with a high (NZE Benchmark - High), medium (NZE Benchmark - Medium) and a low contribution (NZE Benchmark – Low). For the “NZE EU policy standard” scenario, the medium case has been used. Not all scenarios have been run by all models, depending on their capabilities. The sector models (ALADIN and FORECAST) ran the WWH21 and NZE EU Policy standard scenarios. ICES-XPS only ran the high case of the “NZE Benchmark” scenarios, due to limited mitigation options. GCAM ran the “NZE Benchmark - Medium” scenario because it models non-CO_2 and LULUCF emissions.

More policy-specific scenarios are to follow beyond the Core scenarios mentioned above, but their design and implementation have not been completed at the timing of this deliverable (intended for D5.5 and D7.7). Tables 11 and 12 shows the details of the core scenarios ran in WP5, and which results will be used in the global models for the LTS_ADV scenarios.

Table 11: Synthesis of main GHG emissions reduction targets in the EU27 in the EU core scenarios

<table>
<tr><th></th><th colspan="2">WWH21*</th><th colspan="2">NZE Benchmark**</th><th colspan="2">NZE EU Policy standard**</th></tr>
<tr><th></th><th>2030</th><th>2050</th><th>2030</th><th>2050</th><th>2030</th><th>2050</th></tr>
<tr><td>GHG emissions reduction (w.r.t 1990)</td><td>-40%</td><td rowspan="3">carbon price equivalent</td><td>-55%</td><td>Net Zero Emission</td><td>-55%</td><td>Net Zero Emissions</td></tr>
<tr><td>EU-ETS GHG emissions reduction (w.r.t. 2005)</td><td>-43%</td><td colspan="2" rowspan="2"></td><td>-61%</td><td>Adjusted to reach NZE EU-level target</td></tr>
<tr><td>ESR GHG emissions reduction (w.r.t. 2005)</td><td>-30% (w. national targets)</td><td>-40% (wo. national targets)</td><td>-80%</td></tr>
<tr><td colspan="7">*: GHG emissions scope excludes LULUCF and includes intra-EU aviation in EU-ETS; **: GHG emissions scope includes LULUCF and international transports.</td></tr>
</table>

Table 12: Synthesis of main GHG emissions reduction targets in the UK in the EU core scenarios

	WWH21		NZE			
	2030	**2050**	**2025**	**2030**	**2035**	**2050**
GHG emissions reduction (w.r.t 1990)	-58% (wo LULUCF & in't transports)	carbon price equivalent	-55% (w LULUCF & wo in't transports)	-68% (w LULUCF & wo in't transports)	-78% (w LULUCF & w in't transports)	NZE
EU-ETS GHG emissions	2021-2025: 736 $MtCO_2eq$. 2026-2030: 630 $MtCO_2eq$.					
ESR GHG emissions reduction	-37% (w.r.t. 2005)					

4.1.2 Results

The summary results presented below are extracted from Deliverable 5.5, thus refer to D5.5 for more details and the comprehensive analysis.

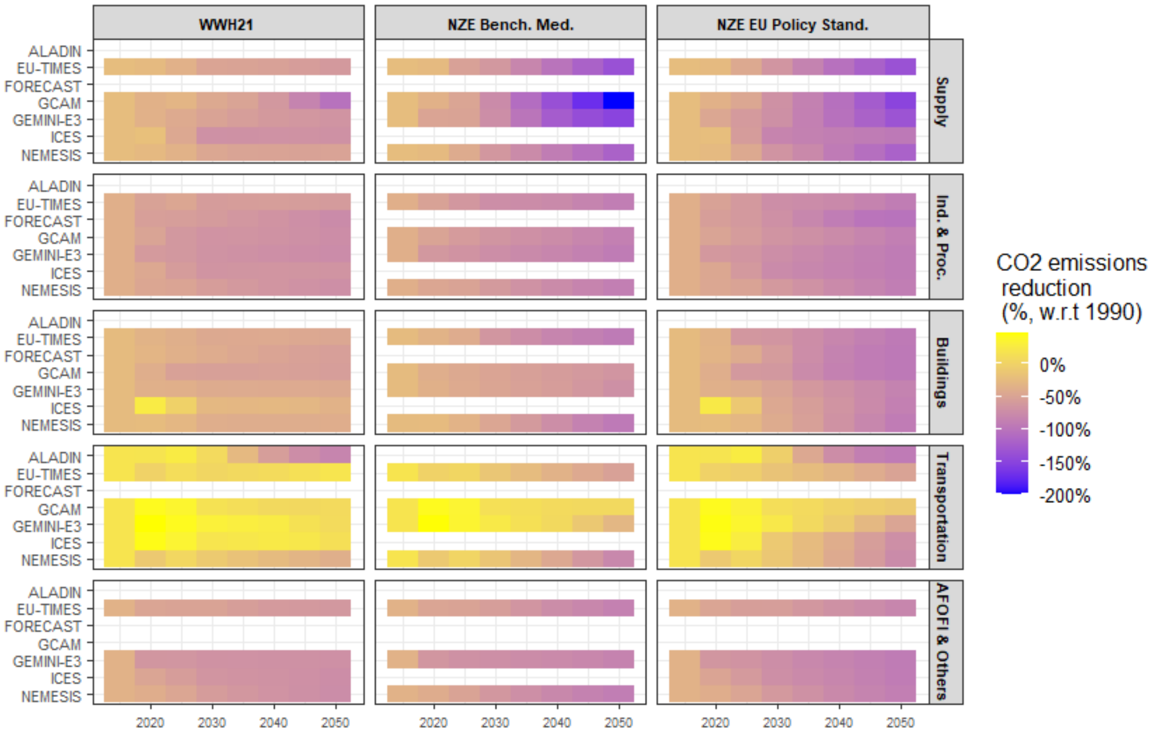


Figure 20: EU sector reduction of CO_2 emissions from energy and industrial processes (w.r.t. 1990) in the EU Core scenario.

Note: Only results from EU regional models (ALADIN, EU-TIMES, FORECAST, NEMESIS) are relevant for LTS_ADV. AFOFI: Agriculture, Forestry and Fisheries (only energy related emissions).

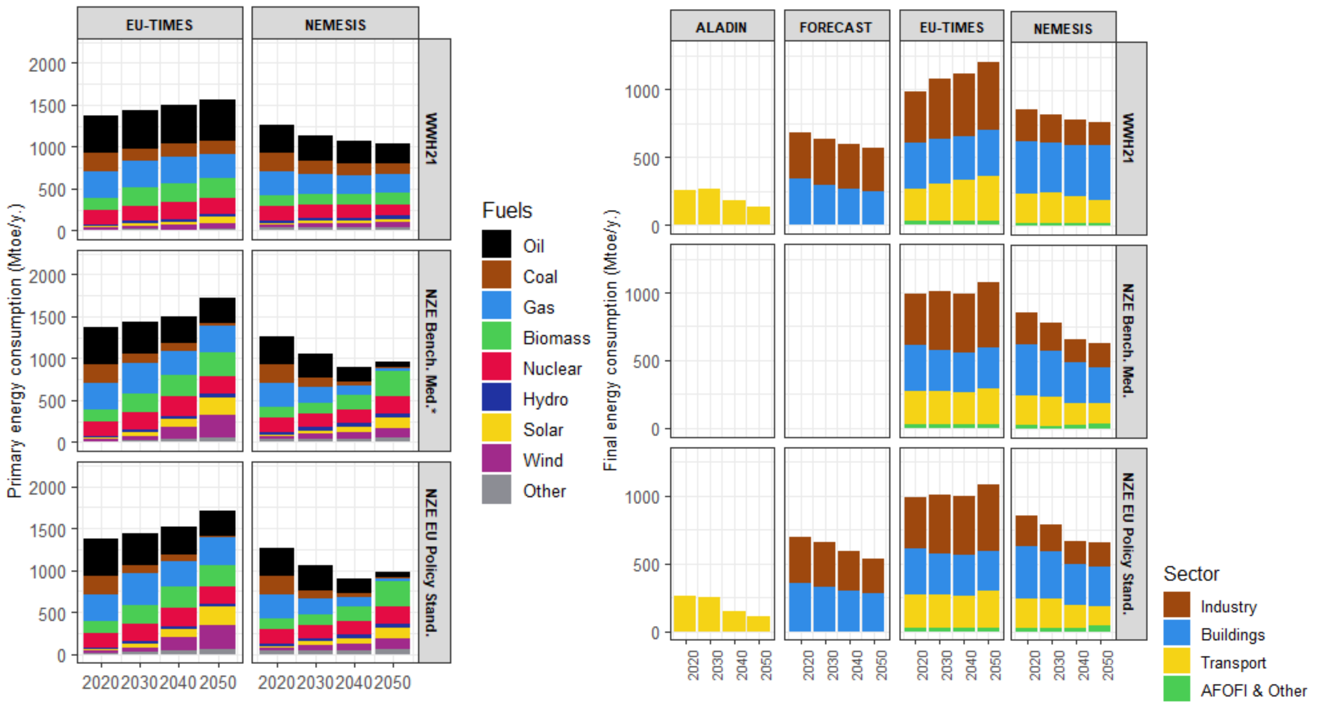
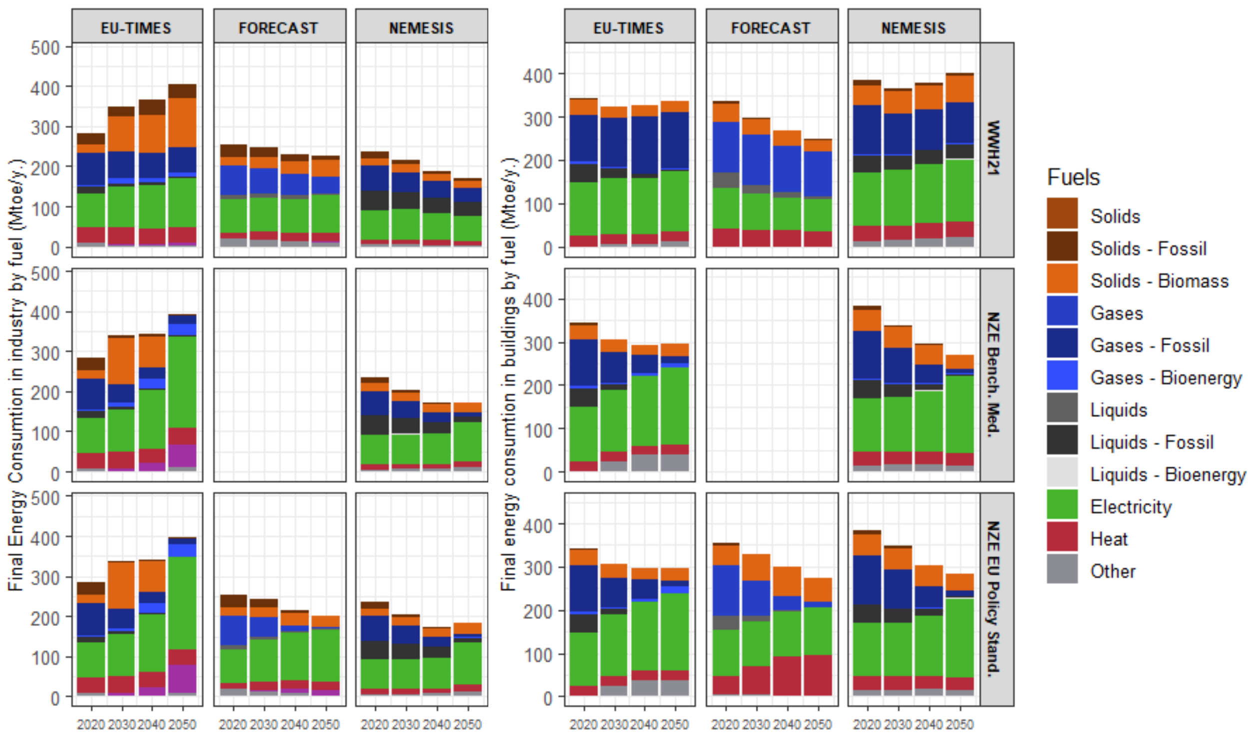


Figure 21: EU primary and final energy consumption by fuel in the EU core scenarios (in Mtoe/y.).

Note: Nuclear is harmonised among models and accounted as nuclear heat like in Eurostat, with an efficiency factor of 33%..



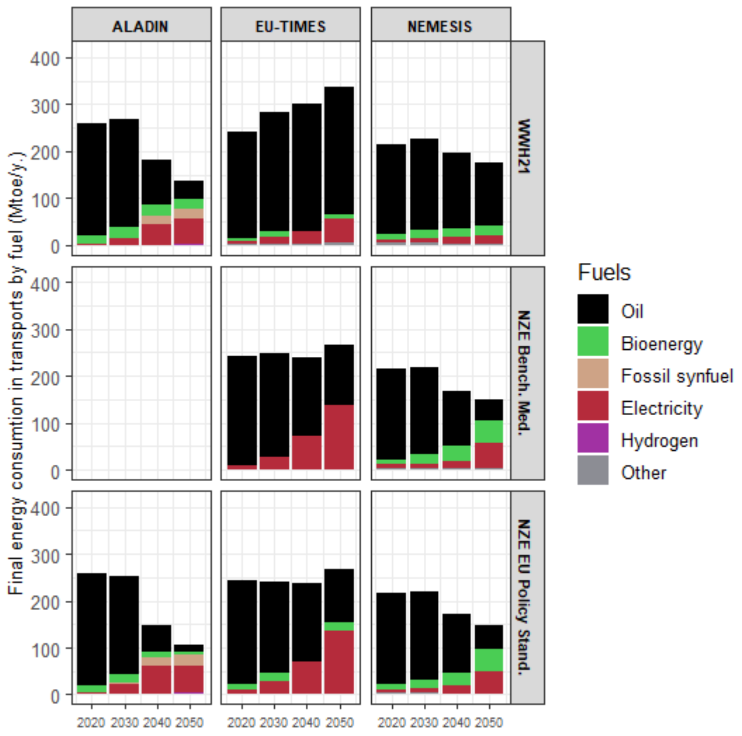


Figure 22: EU industry, buildings and transport final energy consumption by fuel in the EU Core scenarios (in Mtoe/y.).

Note: For EU-TIMES, FORECAST and NEMESIS final energy consumption excludes feedstocks. For models allowing the split between fossil fuels and bioenergy, their sum equals the respective aggregate (Solids, Gases or Liquids).

4.2 Non-EU national runs (WP6)

4.2.1 Scenario rationale

Based on either quantitative or qualitative stakeholder inputs from workshops held in the different countries represented in WP6, as well as information outside the stakeholder sphere, scenarios were designed to display likely pathways towards deep decarbonisation targets. Different approaches were taken for each country depending on regional relevance and the timing of the workshops:

Table 13: Non-EU Scenarios

Scenario Type	Regions
Scenario based on quantitative stakeholder inputs	China, India, Russia
Scenario based on qualitative stakeholder inputs	USA, Central Asia Caspian region
Scenario based on non-stakeholder information	Brazil, Canada, Mexico

More information on the specific scenario inputs can be found in D6.3.

Although the results in D6.3 were provided for both reference and deep mitigation scenarios, only the latter will be taken into account for the global model LTS_ADV scenario.

4.2.2 Results

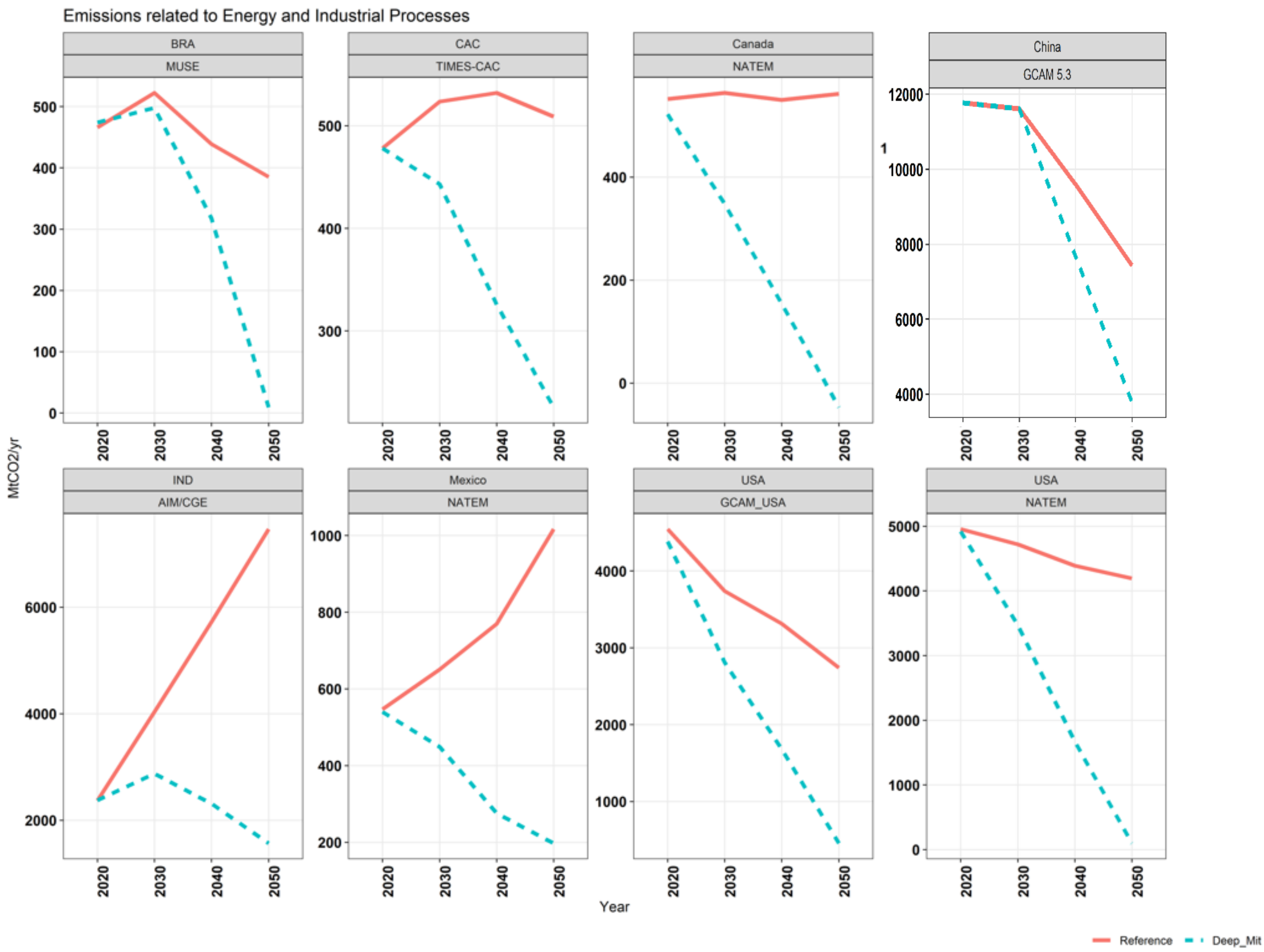


Figure 23: CO_2 emissions in reference and deep mitigation scenarios from WP6 scenarios

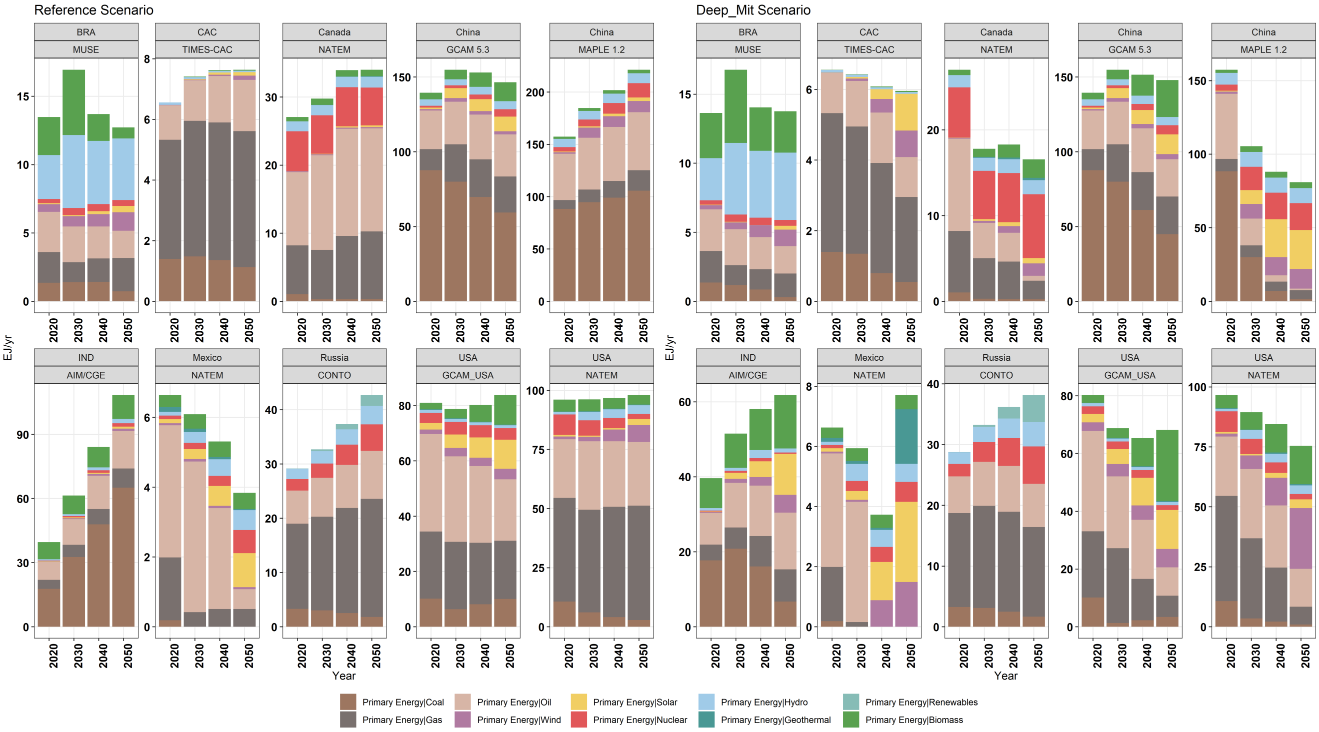


Figure 24: Primary energy consumption in EJ/yr for reference and deep mitigation scenarios from WP6

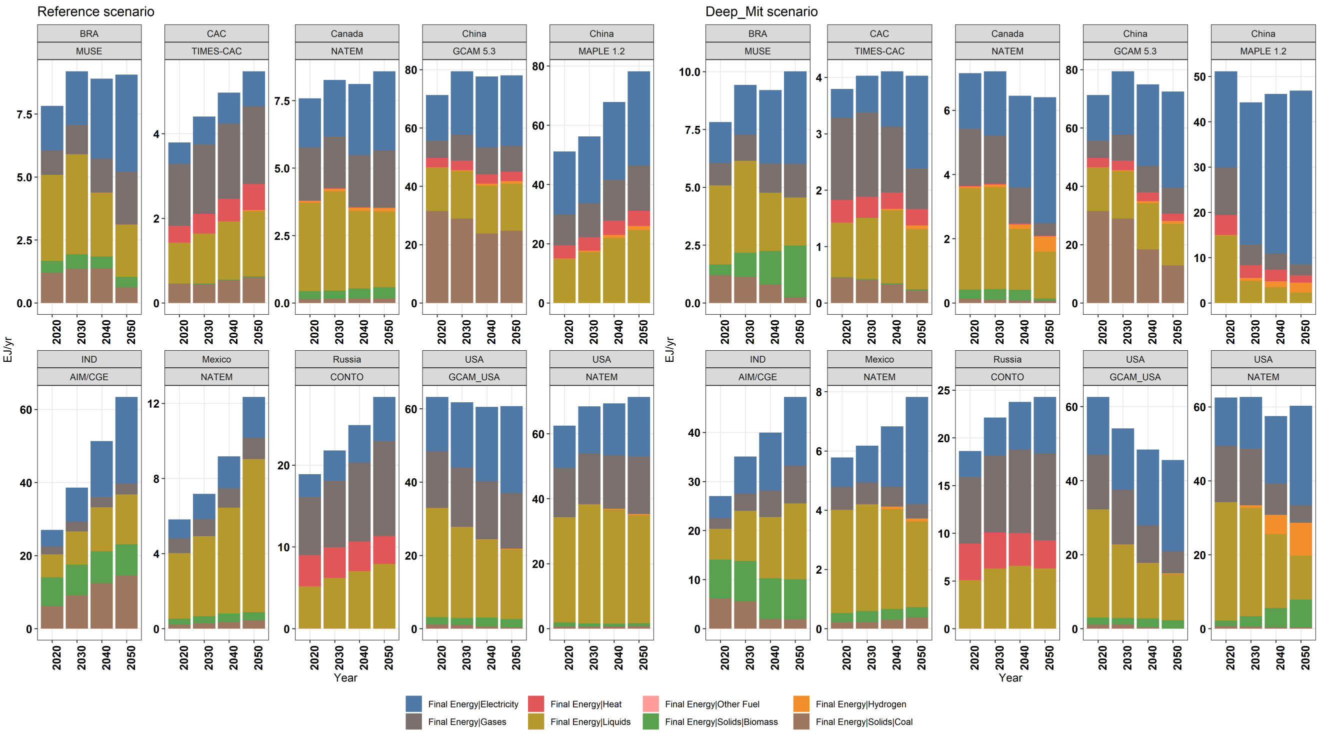


Figure 25: Final energy consumption in EJ/yr for reference and deep mitigation scenarios from WP6

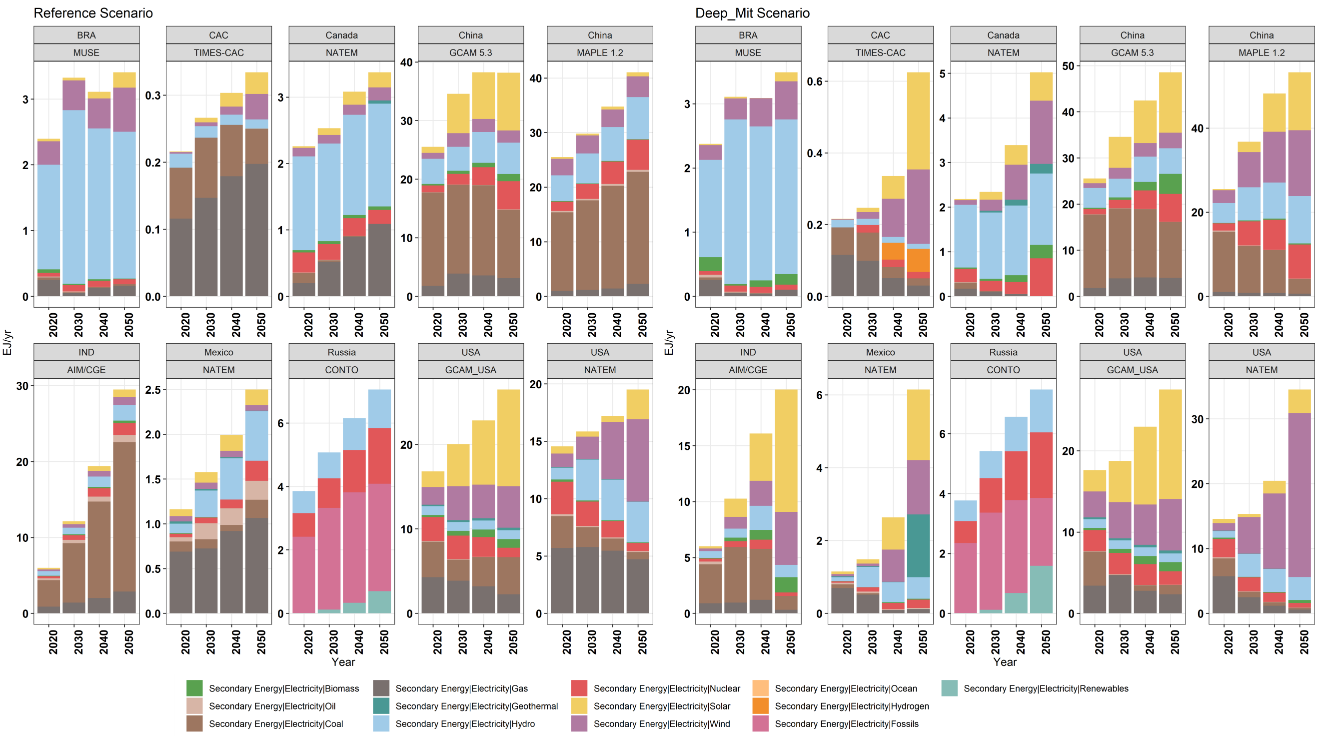


Figure 26: Mix of electricity generation in EJ/yr for reference and deep mitigation scenarios from WP6

5 Conclusions

In order to measure the gap between current global climate ambitions and the transformation that is required for achieving Paris-compliant temperature targets, the global scenarios in PARIS REINFORCE have been designed to first forecast the impact of current ambitions (policies and NDCs) on global emissions and temperature change, and second to run backcasting scenarios that switch from national/regional policies until 2025 to deep global mitigation required to keep end-of-century temperature change below 1.5-2ºC by 2100.

Seven IAMs were used that span a diverse set of approaches. In the forecasting runs, current policies and NDCs until 2030 were extended until 2050/2100 using two different methods, and even the most optimistic scenario is insufficient to meet the Paris Agreement goal of limiting global warming to "well below 2°C". To achieve this goal, global mitigation efforts will most likely have to be strengthened, and new pledges will need to be followed up by concrete policies. However, we also find that the model used has a larger impact on results than the method used to extend mitigation effort forward, which in turn has a larger impact on results than whether current policies or NDCs are assumed in 2030. The question of where emissions are headed—which is a critical question to inform policymakers about how much ambition needs to be raised to reach climate targets—might therefore depend more on the choice of models used and the post-2030 assumptions than on the 2030 target assumed. This renders estimates of temperature consequences of NDCs and current policies sensitive to study design and highlights the importance of using a diversity of models and extension methods to capture this uncertainty.

When in backcasting mode, model differences are clearly visible in the way mitigation is achieved as different models prefer different technologies, but the tendency away from fossil fuels (mainly coal) and towards both biomass and non-biomass renewables, in combination with higher electrification and lower final energy use, is visible in all models. The sectoral divide of transformation efforts however differs strongly between models. In half of the models, carbon sequestration is an important pillar of the mitigation portfolio by 2050, sequestering around 10Gt of CO_2. Nevertheless, for the other half of the models, carbon sequestration is quite a marginal technology. Carbon prices increase with mitigation for all models, but the levels can differ strongly. Most models achieve 1.5ºC compatible pathways at around $150-300 per ton of CO_2 by 2050.

Many countries released updated mitigation ambitions during the run-up to the COP26 in Glasgow, including many net-zero pledges for 2050-2070, which should, at least partly, close the gap between required efforts and actual ambitions. Therefore, the second modelling iteration takes these updated policies and pledges into account in another forecasting exercise. In the meantime, co-created mitigation scenarios in many major countries lay out "desirable" pathways in national or regional models, which clearly differ from scenarios in global models. Therefore, in addition to the updated forecasting runs, this information of co-created scenarios in WPs 5 and 6 is used in global models in WP7 to develop a better-informed global mitigation scenario compatible with Paris targets.

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Appendix

Temperature outcomes

Since the main objective was to maximise model diversity, there was a limitation by the emissions covered by each model. All models provided fossil energy CO_2 emissions, some models provided all GHGs, and only GCAM had forcing and temperature data (based on MAGICC 5.3 (Wigley, 2008)). To estimate the temperature, therefore the transient climate response to cumulative carbon emissions (TCRE) was applied with the temperature contribution from non-CO_2 based on GCAM. This assumes linearity in line with the carbon budget (Matthews et al., 2020) and was calculated using insights from Peters (2016)

$T_{model}(t) = T_{GCAM}(2020) + TCRE \times (1+\Delta n) \times (\sum C(t) - \sum C(2020))$

where:

$T_{GCAM}(2020)$=1.24°C estimated from MAGICC 5.3 (Wigley, 2008),
TCRE = 0.4503°C/1000GtCO_2,
Δn is the contribution of non-CO_2 components to temperature,
C are fossil energy CO_2 emissions.

The method assumes that the non-CO_2 emissions in every model behave like GCAM. The non-CO_2 contribution, Δn, was back-calculated from GCAM. First, the median non-CO_2 forcing relative to total forcing was estimated across all GCAM scenarios to be 19.5% (standard deviation of 0.9%), in line with other scenario datasets (such as the SSP database (Riahi et al., 2017)). Second, this was converted into a scaling factor relative to CO_2, $\Delta n = s/(1-s)$ where s is the non-CO_2 share, leading to a value of Δn=0.24. These assumptions gave the reported range of the median temperature response of each scenario of 2.2-2.9°C.

Several uncertainties were assessed in the proposed approach. For the non-CO_2 contribution, values of Δn ranging from 0 to 0.33 (which assumes a range from zero non-CO_2 contribution to a share of 33%, the latter which is an outlier value in the SSP database) were tested, and these assumptions changed the minimum temperature outcome to 2.0°C with zero non-CO_2 contribution (down from 2.2°C) and the maximum temperature outcome to 3.0°C with maximum non-CO_2 contribution (up from 2.9°C). This small variation due to non-CO_2 assumptions shows that cumulative CO_2 emissions (and associated TCRE assumptions) dominate at these temperature levels. To assess the uncertainty in the climate system, the likely range of the TCRE (IPCC) from 0.2183°C/1000GtCO_2 to 0.6824 °C/1000GtCO_2 was applied. This changes the temperature range down to 1.7°C (instead of 2.2°C) and up to 3.8°C (instead of 2.9°C), indicating the uncertainty in the TCRE is much larger than the uncertainty in the impact of non-CO_2 emissions.

Extrapolation of emissions intensity scenarios to 2100. For those models with a 2100 time horizon (TIAM, MUSE, GCAM) all scenarios were run to 2100 to get the temperature estimates. For the remaining models (E3ME, FortyTwo, ICES, GEMINI), emissions in all emissions intensity scenarios were extrapolated to 2100. This was done by continuing the rates of emissions intensity reductions implied by current policies and NDCs in 2030 in each of the native regions in these models to 2100 (instead of just to 2050 (2045 for FortyTwo)). Carbon price scenarios could not be extrapolated in the same way for models with a 2050 time horizon (ICES, GEMINI, E3ME) because emissions in these scenarios are solved endogenously post-2030. This means that the demonstrated temperature range includes all emissions intensity scenarios and three (out of six) carbon price scenarios. Since the former is more optimistic, the low end of the temperature range is more robust than the high end, which does not, for instance, include the high GEMINI current policy constrained carbon price scenario.