

Promising climate progress from net-zero ambitions to the Paris Agreement goal

In the format provided by the
authors and unedited

Supplementary Material

Supplementary Table 1 provides an overview of main characteristics of IAMs participating in this study. Further detailed comparison across models and the IAM community can be found in the reference cards of the IAMC Wiki.

Supplementary Table 1: Main model characteristics

Model	Solution concept	Solution horizon and method	Spatial dimension	Energy technology choice/deployment
COFFEE	General equilibrium (closed economy)	Intertemporal optimization (foresight) Optimization	18 regions	Linear choice (lowest cost)
GCAM	General equilibrium (closed economy)	Recursive dynamic (myopic)	32 regions	Logit choice model
GEM-E3	General equilibrium (closed economy)	Recursive dynamic (myopic) Optimization	46 regions	Mostly high substitutability
IMAGE	Partial equilibrium (price elastic demand)	Recursive dynamic (myopic) Simulation	26 regions	Logit choice model
MESSAGEix-GLOBIOM	General equilibrium (closed economy)	Optimization	11 regions	Linear choice (lowest cost)
POLES	Partial equilibrium (price elastic demand)	Recursive dynamic (myopic) Simulation	66 regions	Logit choice model
REMIND	General equilibrium	Intertemporal optimization (foresight)	12 regions	Mostly high substitutability

	(closed economy)	Optimization		
WITCH	General equilibrium (closed economy)	Intertemporal optimization (foresight) Optimization	17 regions	No discrete technology choices

Short documentation of models

COFFEE

COFFEE is an Integrated Assessment Model (IAM) that uses intertemporal linear programming optimization and is based on a process-based approach. The model aims to depict worldwide energy, industrial, agricultural, and land-use systems. Essentially, COFFEE seeks to determine the most cost-effective arrangement of the depicted systems that meets the requirements and limitations provided as input. The model contains various input data for every geographical area, such as demographic patterns, service needs (like food, transportation, and heating), advancements in technology (like energy technologies costs and efficiency), and the availability of resources (such as biomass, coal, and oil). COFFEE is subject to various simultaneous limitations related to environmental factors (such as carbon budget), institutional factors (like current public policies), and historical factors (used for calibration). Utilizing this information and a set discount rate, COFFEE provides the optimal setup for the worldwide energy, industrial, agricultural, and land-use systems from 2010 to 2100 under the specified circumstances.

COFFEE uses a linear programming optimization technique. It considers various options for energy production, land use, and technology advancement. It then identifies the combination that minimizes overall cost while meeting specified demands and environmental limitations.

The model relies on population and economic growth data, service demands and consumer profile (e.g., diet, mobility), technological development (costs, efficiency, and other market constraints), and resource availability. It also considers environmental constraints and exogenous policy assumptions.

The model operates globally with 18 regional divisions, including major economies like BRICS.

Further information: [Model Documentation - COFFEE-TEA - IAMC-Documentation \(iamcdocumentation.eu\)](https://iamcdocumentation.eu/Model%20Documentation%20-%20COFFEE-TEA%20-%20IAMC-Documentation)

GCAM

The Global Change Analysis Model (GCAM) is an integrated assessment model (IAM) that represents the interactions among energy, water, agriculture, land use, the economy, and climate systems globally. In each modelling period, GCAM simulates the competition among various technologies and resources to meet energy and agricultural demands while accounting for environmental constraints and policies. The model aims to evaluate long-term, multi-sectoral, and multi-regional dynamics of global change, projecting from the present up to the year 2100. GCAM has been used to assess the implications of different technological, economic, and policy scenarios on future energy pathways, land-use changes, greenhouse gas emissions, and climate impacts (Calvin et al., 2019).

GCAM utilizes a market-equilibrium approach within a dynamic-recursive simulation. In each five-year time step, the model equilibrates supply and demand across energy, agriculture, and land-use sectors by adjusting prices. Agents (different energy, land, and water sectors) within the model make decisions based on costs, preferences, and policy influences. GCAM accounts for technological change, resource depletion, and environmental feedback, allowing for the evaluation of how different policies or technological advancements could influence global and regional multi-sector systems over time.

GCAM's primary drivers include exogenous assumptions about population growth, economic development (GDP projections), technological advancements (costs and efficiencies of technologies), resource availability (fossil fuels, renewables, land, water), and policy assumptions (carbon pricing, subsidies, mandates). GCAM also incorporates alternative socio-economic pathways, such as the Shared Socioeconomic Pathways (SSPs), to explore a range of future scenarios based on varying socio-economic conditions (O'Neill et al., 2014).

GCAM operates on a global scale with detailed regional disaggregation. It divides the world into 32 geopolitical regions for energy and economic analysis, 233 water basins, and 384 land-use regions to capture spatial variations in different systems.

More detailed information about GCAM can be found on the official documentation website: <https://jgcri.github.io/gcam-doc/>

IAMC Wiki: [Model Documentation - GCAM - IAMC-Documents \(iamcdocumentation.eu\)](https://www.iamcdocumentation.eu/)

Calvin, K., Clarke, L., Edmonds, J., Eom, J., Hejazi, M., et al. (2019). GCAM v5.1: representing the linkages between energy, water, land, climate, and economic systems. *Geoscientific Model Development*, 12, 677–698. <https://doi.org/10.5194/gmd-12-677-2019>

O'Neill, B. C., Kriegler, E., Riahi, K., Ebi, K. L., Hallegatte, S., et al. (2014). A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Climatic Change*, 122(3), 387–400. <https://doi.org/10.1007/s10584-013-0905-2>

GEM-E3

GEM-E3 is a large scale multi-sectoral hybrid CGE model designed to evaluate the effects of external shocks on the economy. The model provides a robust framework to capture the complex energy-economy-climate interactions and simulate the impact of climate damages or climate and energy policies on the performance of sectors, sectoral output, prices and bilateral trade, the competitiveness of regions and the welfare of communities. Results have a yearly frequency up to 2030 and 5-year time steps until 2050/2100. The model has a global coverage, with 46 regions, where the G-20 countries, EU27 Member States, and major equipment manufacturing or energy exporting countries are represented individually. All countries are linked through endogenous bilateral trade transactions. The model explicitly

represents 68 distinct economic activities, which are interlinked across the production and consumption value chain.

Focus is placed on the representation of the energy system where specialized bottom-up modules of the power generation, buildings and transport sectors have been developed. To this end, the model includes a detailed representation of the power generation system (10 power technologies) and a detailed transport module (private and public transport modes), while different technological options for energy use in buildings and industry are provided. The energy system representation includes an explicit representation of new technologies such as hydrogen, clean fuels, and bioenergy options. The GEM-E3 environment module covers all GHG emissions and a wide range of abatement options, as well as a thoroughly designed carbon market structure (e.g., grandfathering, auctioning, alternative recycling mechanisms). The model has been used extensively by the European Commission, governments and public institutions to assess the macroeconomic, distributional and employment implications of the transition to climate neutrality.

The model is based on advanced applied modelling techniques and has been further extended to allow the representation of semi-endogenous technical progress, endogenous formation of labour skills and human capital and a detailed bottom-up representation of the energy system (in particular transport and power generation), along with non-CO₂ emission abatement options and negative emissions technologies. It moves beyond the standard CGE framework as it is dynamic and features involuntary unemployment in the labour market and alternative macroeconomic closures supported by a detailed representation of the financial sector. The model is established on rigorous microeconomic theory, it is empirically estimated (substitution and trade elasticities) and is able to undertake long term analysis as opposed to econometric models that suffer from the Lucas critique. The model can be used both in a comparative and what if analysis frameworks as represents a closed and consistent accounting of resources.

The model is calibrated to a wide range of datasets comprising of IO tables, financial accounting matrices, institutional transactions, energy balances, GHG inventories, bilateral trade matrices, investment matrices and household budget surveys. All countries in the model are linked through endogenous bilateral trade transactions identifying origin and destination. The substitution elasticities of the model are not derived from the general literature but are estimated according to its dimensions and functional forms using the latest available datasets. The model is recursive dynamic through the accumulation of capital via the decision for investments and through the accumulation of knowledge stocks via R&D and human capital development. Model regions are linked through endogenous bilateral trade following the Armington assumption of imperfect substitution across domestic and imported goods. The nested production functions are differentiated by sector and follow a CES structure. For the demand side, the model simulates consumer behaviour and maximizes a Klein-Rubin utility function that results in a Linear Expenditure demand system subject to its

disposable income not used for obliged consumption (subsistence minima consumption) and after allowing for the decision on savings. The representative household decides on the allocation of its available for consumption income over different consumption categories (COICOP), distinguishing between durable and non-durable goods. The model has been calibrated to the latest statistics (GTAP 11, IEA, UN, ILO) while Eurostat statistics have been used for the EU.

The key innovations of the model relate to the explicit representation of the financial sector, semi-endogenous dynamics based on R&D induced technical progress and knowledge spillovers, the representation of multiple households, unemployment in the labour market with a representation of five labour skill levels and endogenous formation of labour skills.

The most important results, provided by GEM-E3 are: Full Input-Output tables for each country/region identified in the model, GDP and GDP components, employment by economic activity and by skill and unemployment rates, capital, interest rates and investment by country and sector, private and public consumption, bilateral trade flows, consumption matrices by product and investment matrix by ownership branch, GHG emissions by country, sector and fuel and detailed energy system projections (energy demand by sector and fuel, power generation mix, deployment of transport technologies, energy efficiency improvements).

More details here: <https://e3modelling.com/modelling-tools/gem-e3/>

IAMC Wiki: [Model Documentation - GEM-E3 - IAMC-Documentation \(iamcdocumentation.eu\)](https://iamcdocumentation.eu/Model-Documentation-GEM-E3-IAMC-Documentation)

IMAGE

IMAGE (Integrated Model to Assess the Global Environment) is an integrated assessment modelling framework that simulates the environmental consequences of human activities worldwide. It represents interactions between society, the biosphere and the climate system to assess sustainability issues such as climate change, biodiversity and human well-being. The model can be used to explore the long-term pathways for future environmental and sustainable development problems as well as possible response strategies. It has representations of the energy, agriculture, land use, and climate systems. Typical outputs include projections of energy supply and demand, agricultural production, land use and land cover change, emissions of greenhouse gasses and other pollutants, and demand for water and material resources. The model is calibrated to datasets of energy supply and demand (International Energy Agency) and Agricultural production and land cover (Food and Agricultural Organisation). IMAGE participates in multiple model intercomparison projects covering energy, agriculture, emission scenarios, and sustainable development.

IMAGE is a hybrid systems dynamics model. It employs stylized optimization techniques when meeting climate targets. The model simulates the human and natural environment from 1971 to 2100, with the 1971-2022 period acting as a calibration and spin-up period. The model works on an annual timestep.

Population, economic activity are key exogenous drivers. Assumptions (across the food and energy systems) on technology availability and development, behavioural and lifestyle choices are also inputs. The model can incorporate land protection, energy, and other quantifiable policies.

IMAGE is a global model. Biophysical and land use are represented at a 0.5x0.5 degree grid, while socioeconomic processes are modelled on 26 regions.

For more information, see: <https://www.pbl.nl/en/image/home>

IAMC Wiki: [Model Documentation - IMAGE - IAMC-Documents \(iamcdocumentation.eu\)](https://www.pbl.nl/en/image/home)

MESSAGEix-GLOBIOM

IIASA's Integrated Assessment Model (IAM), MESSAGEix-GLOBIOM, consists of multiple modules. The energy sector model MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) which sits at the core of the IAM, incorporates land-use dynamics through an emulation process, applying inputs from the land-use model GLOBIOM (Global Biosphere Management Model). Through an iterative process, MESSAGE is coupled with a single-sector macro-economic module, MACRO, providing estimates of the macro-economic demand response based on the energy system and service costs derived from MESSAGE. MESSAGEix-GLOBIOM relies on emission data from the air-pollution and GHG model GAINS and uses the simple climate model MAGICC for assessing climate related impacts. MESSAGE has a long history of contributing to major international assessments and scenario studies, such as the IPCC, RCPs, WEC, SSP, GEA and a multitude of European funded research projects.

The model covers all major GHG emission species and major air-pollutants across both the energy and the land-use sectors. Eleven regions provide a global representation, calibrated to historically up until the base-year 2015 using a wide range of private and open-source data. Population and economic drivers and techno-economic assumptions based around the Shared-Socioeconomic Pathway storylines define the scenario space up to 2110 in five-year increments until 2060 and ten-year increments thereafter.

Solution mechanism: Hybrid model (linear program optimization for the energy systems and land-use modules, non-linear program optimization for the macro-economic module) optimizing the energy system so that it can satisfy specified energy demand at the lowest

cost over a timeframe from 2020-2100. MESSAGE can be run is run with perfect foresight, while GLOBIOM runs myopically.

Main drivers/exogenous inputs: Population, economic activity are key exogenous drivers of demand, along with assumptions on techno-economic developments.

Regional aggregation: MESSAGE is a global model, differentiating globally between eleven regions. GLOBIOM differentiates globally between 37 regions.

Model documentation: <https://docs.messageix.org/projects/global/en/latest/index.html>

IAMC wiki: [Model Documentation - MESSAGE-GLOBIOM - IAMC-Documentation \(iamcdocumentation.eu\)](https://www.iamcdocumentation.eu/Model-Documentation-MESSAGE-GLOBIOM-IAMC-Documentation)

V. Krey, et al. MESSAGEix-GLOBIOM Documentation – 2020 release. Technical Report, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, 2020. URL: <https://pure.iiasa.ac.at/id/eprint/17115>, doi:10.22022/iacc/03-2021.17115.

O. Fricko, et al. The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. *Global Environmental Change*, 42:251–267, 2017. [doi:10.1016/j.gloenvcha.2016.06.004](https://doi.org/10.1016/j.gloenvcha.2016.06.004).

Petr Havlík, et al. Climate change mitigation through livestock system transitions. *Proc. Natl. Acad. Sci. Unit. States Am.*, 111 (10) (2014), pp. 3709-3714.

Georg Kindermann, et al. Global cost estimates of reducing carbon emissions through avoided deforestation. *Proc. Natl. Acad. Sci. Unit. States Am.*, 105 (30) (2008), pp. 10302-10307.

Sabine Messner, Leo Schrattenholzer. MESSAGE–MACRO: linking an energy supply model with a macroeconomic module and solving it iteratively. *Energy*, 25 (3) (2000), pp. 267-282.

Markus Amann, et al. Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications. *Environmental Modelling & Software*, 26(12):1489–1501, 12 2011. [doi:10.1016/j.envsoft.2011.07.012](https://doi.org/10.1016/j.envsoft.2011.07.012).

POLES

The POLES (Prospective Outlook on Long-term Energy Systems) model hosted by the European Commission's Joint Research Centre is a global multi-regional energy-economy partial equilibrium simulation model of the energy sector, with complete modelling from upstream production through to final user demand. It follows a year-by-year recursive modelling, with endogenous international energy prices and lagged adjustments of supply and demand by world region, which allows for describing full development pathways to 2100.

The model provides full energy and emission balances for 66 countries or regions worldwide (including an explicit representation of OECD and G20 countries), 14 fuel supply branches (including multiple production pathways for secondary carriers such as power, hydrogen and biofuels) and 15 final demand sectors (with sector-specific end-use modelling for industry, buildings, transport). Following equipment depreciation, choice across fuels or technologies is made with a logit distribution function using total costs and preference factors. CO₂ emissions from fossil fuel combustion are derived directly from the projected energy balance. Other emissions from energy and industry are simulated using activity drivers identified in the model and abatement cost curves. Emissions from agriculture and LULUCF are derived from GLOBIOM-G4M lookup tables.

Model documentation: <https://dx.doi.org/10.2760/814959>

IAMC wiki: [Model Documentation - POLES - IAMC-Documentation \(iamcdocumentation.eu\)](http://iamcdocumentation.eu/Model%20Documentation%20-%20POLES%20-%20IAMC-Documentation)

Further information: https://joint-research-centre.ec.europa.eu/poles_en

REMIND

The **Regional Model of Investment and Development** hosted by PIK is an energy-economy general equilibrium model which links a macro-economic growth model with a bottom-up engineering-based energy system model. It covers twelve world regions, differentiates between various energy carriers and technologies, and represents the dynamics of economic growth and international trade. It is an inter-temporal optimization model, solving for the perfect-foresight equilibrium of the global economy between the years 2005-2150, with flexible time steps. The default time step is 5 years from 2005 (base year) to 2060, then 10-year time-steps out to 2100, followed by 20-year time-steps. The model treats energy as a factor input, with different final energy types contributing to GDP calculations in a nested CES production function, as shown in Figure SI 3.2-3. The model also accounts for crucial drivers of energy system inertia and path dependencies by representing full capacity vintage structure, technological learning of emergent new technologies, as well as adjustment costs for rapidly expanding technologies. The emissions of greenhouse gases (GHGs) and air pollutants are largely represented by source and linked to activities in the energy-economic system. Several energy sector policies are represented explicitly, including energy-sector fuel taxes and consumer subsidies. The model also represents trade in energy resources.

More information about the REMIND-MAGPIE model is available:

Model documentation: <https://rse.pik-potsdam.de/doc/remind/2.1.0/> and <https://www.pik-potsdam.de/en/institute/departments/transformation-pathways/models/remind>

IAMC wiki: [Model Documentation - REMIND-MAgPIE - IAMC-Documentation \(iamcdocumentation.eu\)](https://iamcdocumentation.eu/Model-Documentation-REMIND-MAgPIE-IAMC-Documentation)

GitHub: <https://github.com/remindmodel/remind>

WITCH

WITCH (World Induced Technical Change Hybrid) is an optimal growth model of the world economy that integrates the sources and consequences of climate change into a unified framework. A climate module links GHG emissions, produced by economic activities, to their accumulation in the atmosphere and the oceans. The effect of these GHG concentrations on global mean temperature is derived. A damage function explicitly accounts for the consequences of temperature increases on the economic system.

Regions interact with each other due to the presence of economic (technology, exhaustible natural resources) and global environmental externalities. In each region, a forward-looking agent maximizes its inter-temporal social welfare function, strategically and simultaneously with other regions. The inter-temporal equilibrium is calculated as an open-loop Nash equilibrium. Alternatively, a cooperative solution can be derived by aggregating the welfare of each region. More precisely, the Nash equilibrium results from a non-cooperative, simultaneous, open membership game with full information. Through the optimization process, regions choose the optimal dynamic path of a set of control variables, namely investments in the main economic variables.

WITCH is a hard-link hybrid model because the energy sector is fully integrated with the rest of the economy, and therefore, investments and the quantity of resources for energy generation are chosen optimally, along with other macroeconomic variables. The model is termed hybrid because the energy sector features a bottom-up characterization. A broad range of different fuels and technologies can be used in energy generation. The energy sector endogenously accounts for technological change, considering the positive externalities stemming from Learning-By-Doing and Learning-By-Researching. Overall, the economy of each region consists of eight sectors: one final good, which can be used for consumption or investments, and seven energy sectors (or technologies): coal, oil, gas, wind & solar, nuclear, electricity, and biofuels.

Model documentation is available at <http://doc.witchmodel.org>

IAMC Wiki: [Model Documentation - WITCH - IAMC-Documentation \(iamcdocumentation.eu\)](https://iamcdocumentation.eu/Model-Documentation-WITCH-IAMC-Documentation)

NDCs: conditional and unconditional

Quantification of targets for NDCs that are included in the NDC scenario can be found in the CPMP: <https://doi.org/10.5281/zenodo.10009463>

Supplementary Table 2: Unconditional NDC updates and conditional NDC for selected countries/regions.

European Union (EU-27)	Greenhouse gas emission target for 2030 of at least 55% below 1990 levels.
United Kingdom	Reduce GHG emissions by at least 68% from 1990 levels.
Ukraine	Greenhouse gas emissions 65% below 1990 levels in 2030.
Australia	The unconditional NDC is based on a reduction in emissions of 27% by 2030 (average of the range 26% to 28%).
Brazil	Reduce greenhouse gas emissions by 37%, below 2005 levels, by 2025 (50% below 2005 by 2030).
Canada	Greenhouse gas emission reduction target of at least 40% to 45% below 2005 levels by 2030.
Japan	Reduce greenhouse gas emissions to 46% below 2013 levels, by 2030.
New Zealand	50% of GHG emissions below 2005 level.
South Korea	Reduce emissions to 40% below 2018 levels, by 2030.
Kazakhstan	25% of GHG emissions below 1990 (conditional).
Argentina	Net emissions cap at 359 MtCO ₂ eq in 2030 (unconditional).
China	To achieve the peaking of CO ₂ emissions before 2030. Reduction in CO ₂ emissions intensity (emissions per unit of GDP) over 65% by 2030, compared to 2005 levels. Increase in the share of non-fossil fuel in primary energy to around 25% by 2030. New renewable wind and solar installed

	capacity target of 1,200 GW by 2030. Increase in forest stock volume by 6 billion m3 by 2030, relative to 2005 levels.
India	33-35% of CO ₂ emission intensity of GDP below 2005 level.
Indonesia	29% of GHG emissions below BAU (equals a 40% increase above 2016 level by 2030).
Russia	Limit 2030 emissions to 70% of 1990 level.
South Africa	By 2025 and 2030, emissions will be in a range between 398 and 510 Mt CO ₂ e, and between 350 and 420 Mt CO ₂ e, respectively.
USA	Reduce greenhouse gas emissions to between 50% and 52% below 2005 levels, by 2030.

Long-term strategies and status of net-zero pledges

Supplementary Table 3 provides an overview of net-zero pledges by countries, which were included in the LTS scenario.

Supplementary Table 3: Net-zero GHG or CO₂ target year based on official submissions

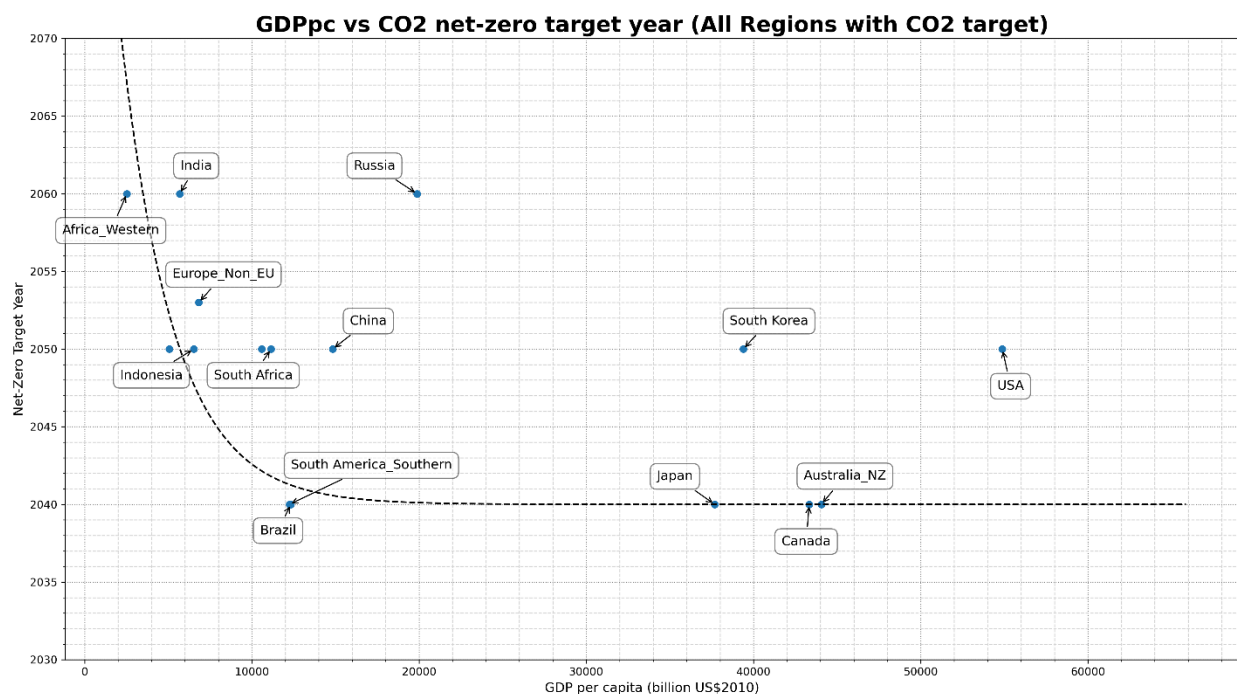
Country	Official net-zero target year	Emission type	Net-zero status
Canada	2050	GHG	In law
USA	2050	GHG	In policy document
Costa Rica	2050	GHG	In policy document
Panama	2050	GHG	In policy document
Brazil	2050	GHG	In policy document
Chile	2050	GHG	In policy document
Ecuador	2050	GHG	In policy document

Uruguay	2050	CO ₂	In policy document
Nigeria	2060	CO ₂	Declaration/pledge
South Africa	2050	CO ₂	Declaration/pledge
EU	2050	GHG	In law
UK	2050	GHG	In law
Turkey	2053	CO ₂	In policy document
Ukraine	2060	GHG	In policy document
Kazakhstan	2060	CO ₂	Declaration/pledge
Russia	2060	CO ₂	Declaration/pledge
Saudi Arabia	2060	CO ₂	Declaration/pledge
Israel	2050	CO ₂	Declaration/pledge
UAE	2050	GHG	Declaration/pledge
India	2070	GHG	Declaration/pledge
South Korea	2050	CO ₂	In law
China	2060	GHG	In policy document
Thailand	2050	CO ₂	In policy document
Viet Nam	2050	CO ₂	In policy document
Malaysia	2050	CO ₂	In policy document
Indonesia	2060	GHG	Proposed/in discussion

Japan	2050	GHG	In law
Australia	2050	GHG	Declaration/pledge
New Zealand	2050	GHG	In law
Sri Lanka	2060	GHG	In policy document

Sources: <https://www.zerotracker.net/> ; <https://www.climatewatchdata.org/net-zero-tracker>

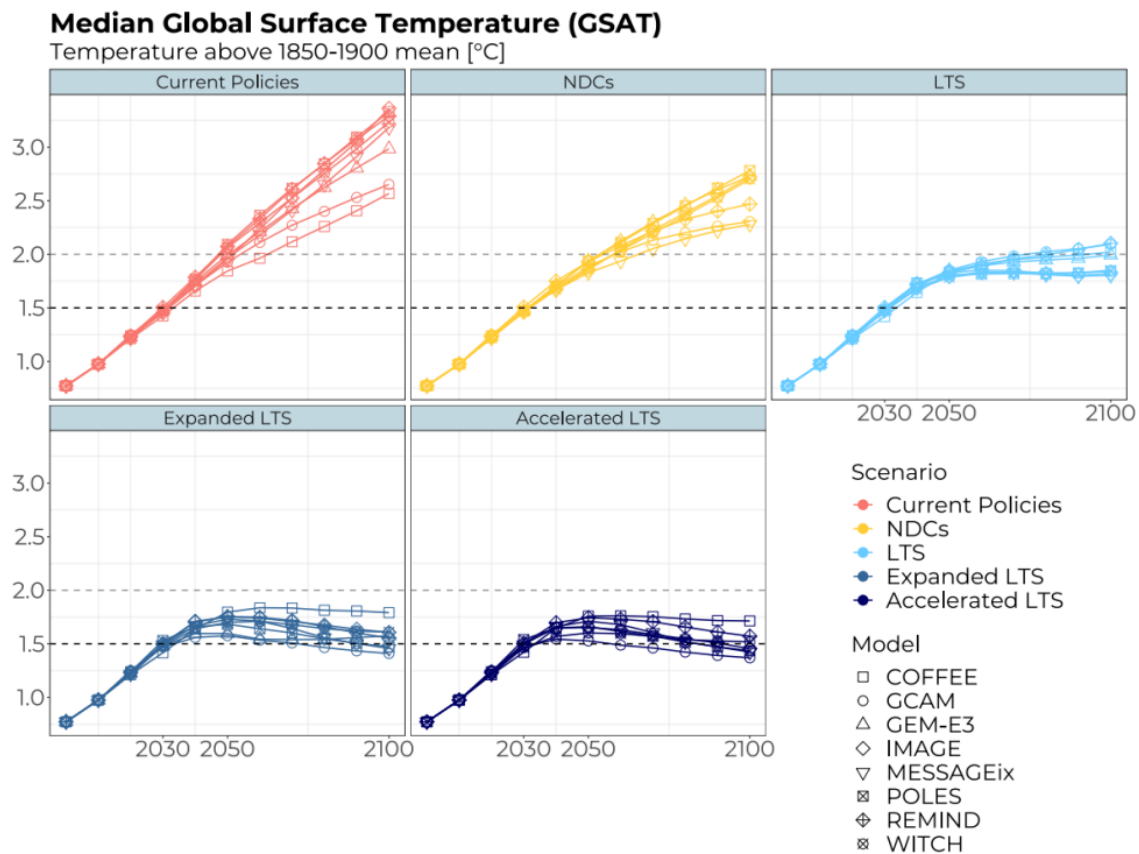
For the estimation of net-zero years for countries that do not yet have a net-zero year announced, a correlation between GDP, population and the net-zero was used, as presented in Supplementary Figure 1.



Supplementary Figure 1: GDP/capita vs net-zero target year. Income along the x-axis; net-zero year along the y-axis. Note that net-zero target years were translated from GHG to CO₂ (with a 10-year gap).

Temperature change outcomes from policy pathways

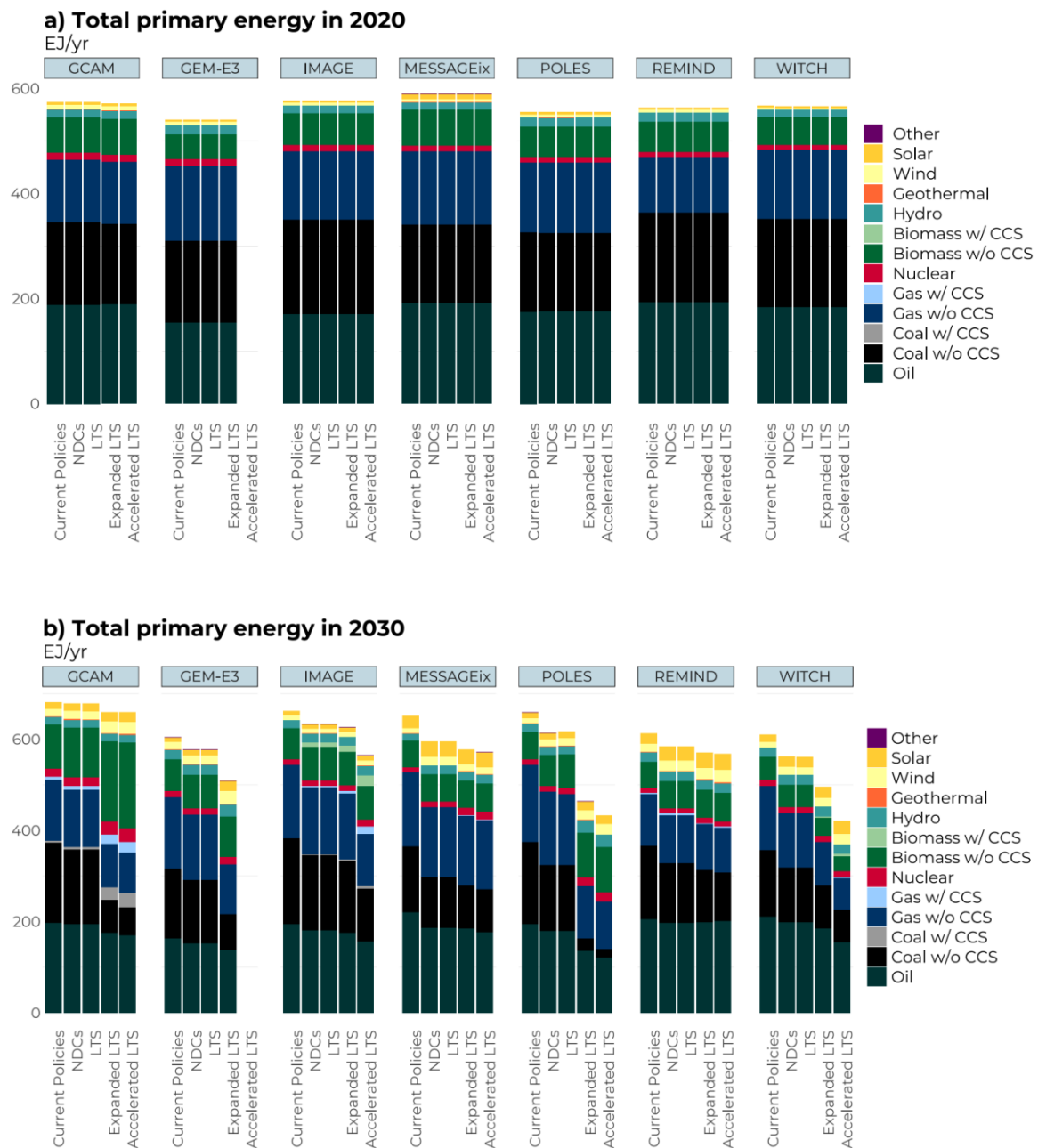
Supplementary Figure 2 presents the mean global surface temperature change (50th percentile), relative to pre-industrial levels, for all scenarios, for all models, until 2100. Probabilistic temperature simulations are performed using the MAGICC (Model for the Assessment of Greenhouse Gas Induced Climate Change) model, version 7.5.3, covering all the most important greenhouse gas emissions and short-lived climate forcers (Kikstra et al., 2022).



Supplementary Figure 2. Temperature change (50th percentile), per scenario, per model

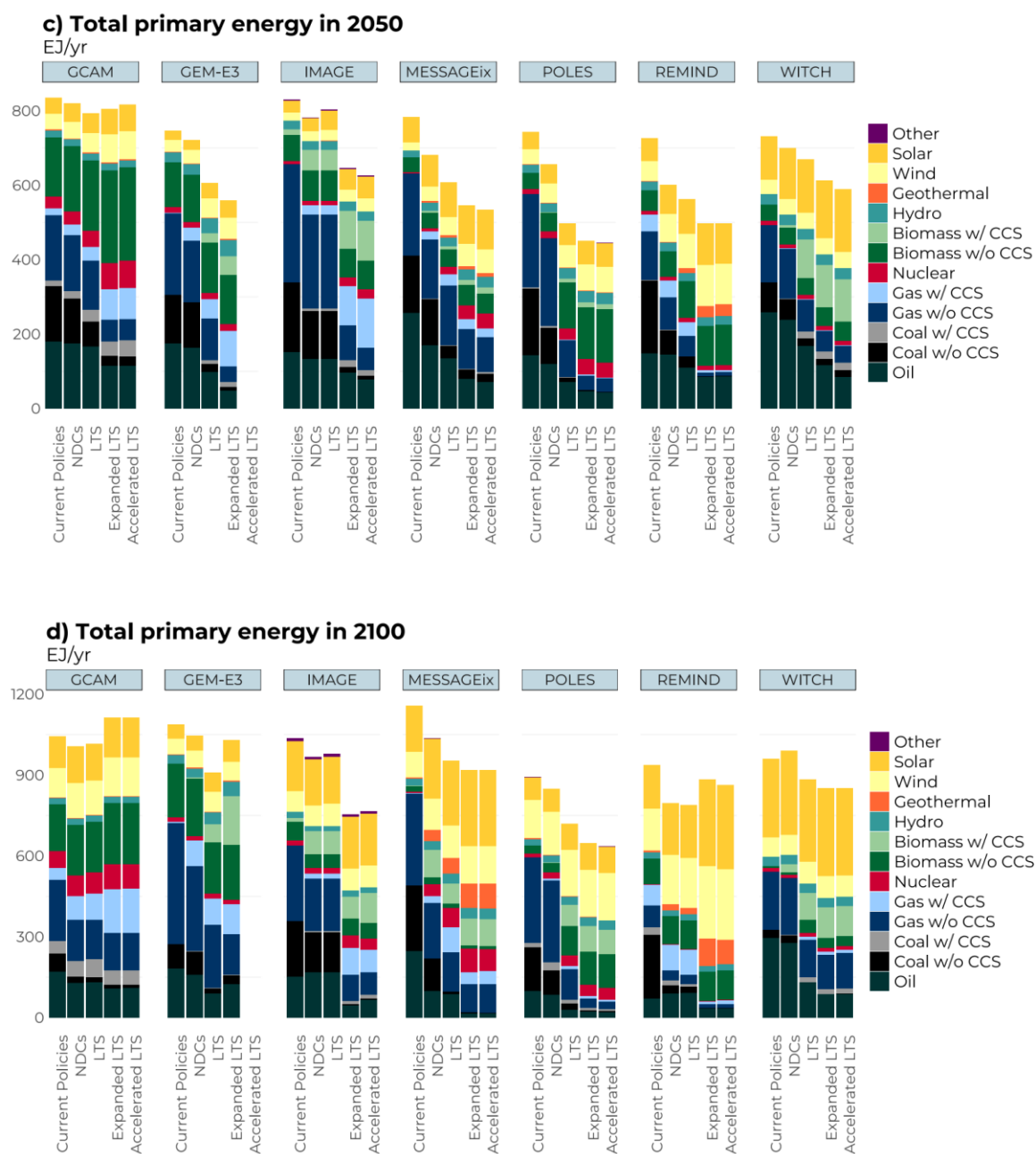
Primary energy

Supplementary Figure 3 complements the overview of primary energy at the global level, providing results for 2020 and 2100, for all scenarios, for all models¹.



Supplementary Figure 3. Global primary energy, per scenario, per model, in: a) 2020; b) 2030; c) 2050; and d) 2100

¹ Except COFFEE.



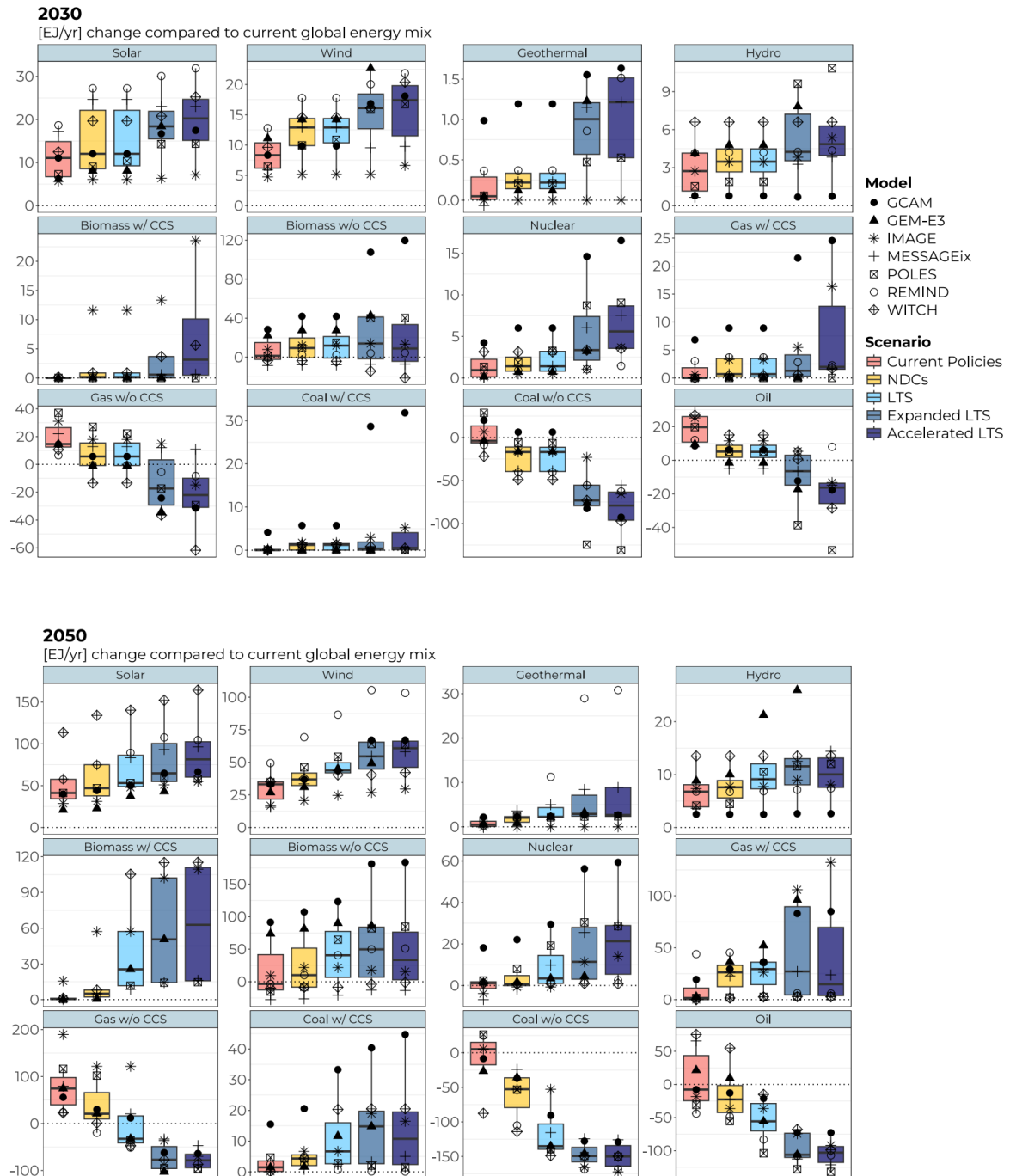
Supplementary Figure 3 (cont.). Global primary energy, per scenario, per model, in: a) 2020; b) 2030; c) 2050; and d) 2100

Results for 2020 are in line with IEA/IRENA/IAEA² data, to which all models are calibrated. The figure highlights the changes in the energy system towards the end of the century and provides an insight into model differences.

² IEA (energy balances) data used to calibrate fuel use, electricity production and capacity investments, IRENA data used to calibrate solar, wind, biomass capacity, and IAEA data used to calibrate nuclear capacity. Current capacities help models estimate future projections, with the transition happening slower or faster depending on e.g. carbon prices.

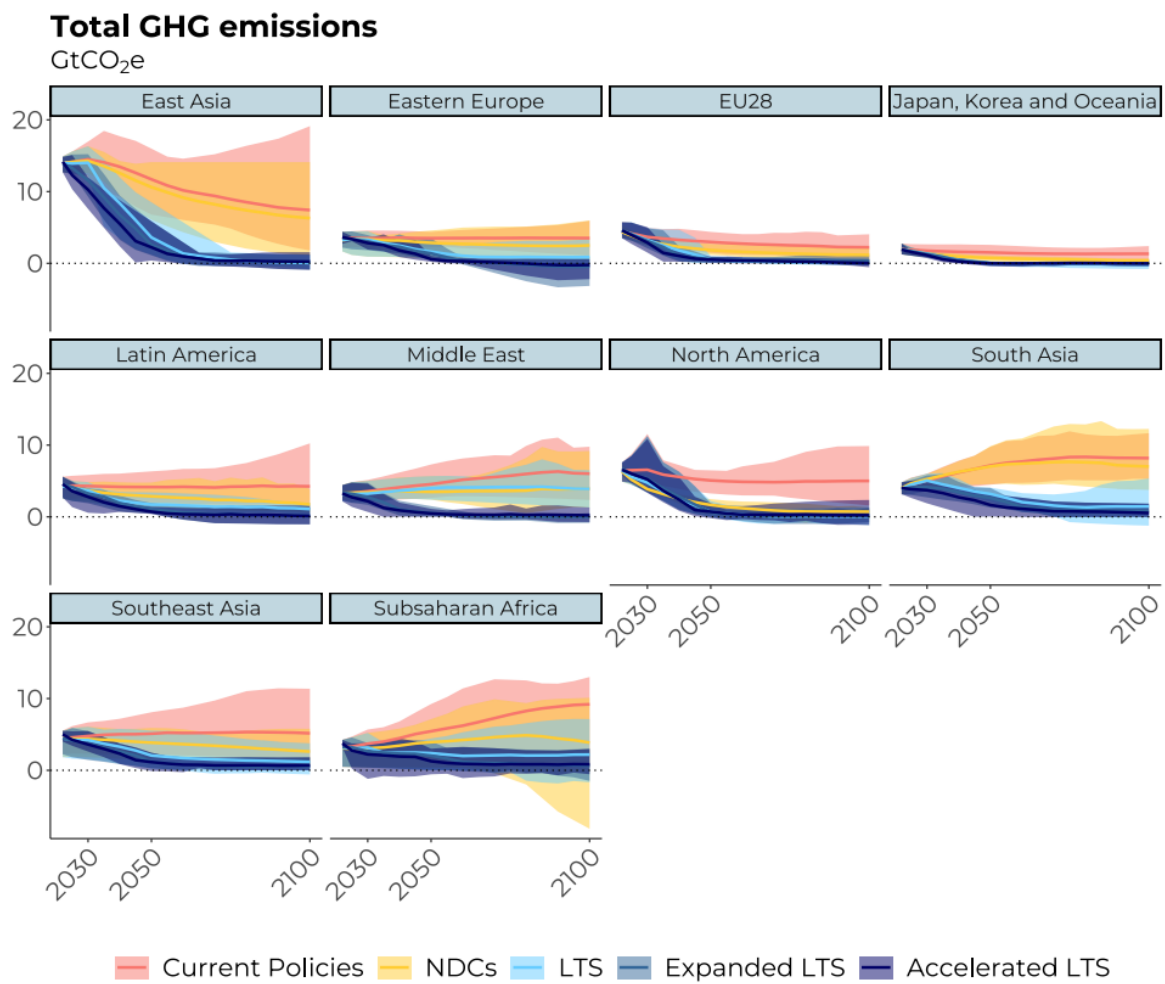
GEM-E3 is a model with a bottom-up representation of power generation technologies, showing the lowest shares on non-biomass renewables and a relatively higher preference for natural gas. Due to its recursive dynamic nature, GCAM's decision making relies on resource availability/depletion, capital stock retirements and installations, with a detailed representation of the land system, which solves simultaneously to the energy and water markets, resulting in higher preference for bioenergy use. IMAGE is also a recursive dynamic model but relies more on energy intensity reductions and carbon capture. Relatively lower values of solar/wind and nuclear energy use, especially in the shorter-term, are compensated by higher use of biomass and natural gas, which in mitigation scenarios are mostly coupled with CCS. MESSAGEix-GLOBIOM is a model that provides demand responses to energy prices, and in mitigation scenarios this results in higher amounts of carbon capture, solar and nuclear, while most of the biomass use is associated with CCS. POLES economic decisions (investments and utilization) are based on a myopic anticipation of future costs (higher inertia) and shows lower deployment of solar but higher than average wind energy use. REMIND, on the other hand, shows a faster reaction to carbon pricing, which limits fossil fuel use and ramps up the use of non-biomass renewables, with high electrification rates in transport, buildings and industry. Finally, WITCH is a model with a compact representation of the energy sector, with higher solar and lower wind shares in primary energy, and high demand shifts in the end-use sectors.

Supplementary Figure 4 presents the changes in primary energy output per energy source, compared to the current levels in the global energy mix. In general, unabated fossil fuels remain relevant in all models throughout the century for low mitigation scenarios such as current policies and NDCs, strongly reducing their shares in higher mitigation scenarios such as the various LTS scenarios. Carbon capture and storage has a role in dealing with fossil-fuel dependency, either by coupling with natural gas (e.g. IMAGE, GCAM, GEM-E3) or with bioenergy (e.g. WITCH, IMAGE, GEM-E3), and to a lower extent, with coal (e.g. GCAM). The role of nuclear energy use is highly model-driven, with some models showing strong constraints against nuclear (GEM-E3, REMIND and WITCH), while other models slightly expand nuclear energy use to deal with higher mitigation requirements of the LTS scenarios. Finally, non-biomass renewable energy sources increase their role in the energy system over time, for all scenarios. REMIND sees the biggest expansions in solar and wind energy in 2030, with solar reaching 855-1014 GW and wind reaching 570-697 GW in the LTS scenarios. The model ensemble (median) results show a relatively smaller expansion, with solar and wind reaching around 634 GW and 570 GW, respectively, in 2030. Solar results are in line with the estimation by IEA's net-zero scenario (630 GW in 2030), while our scenarios are more optimistic for the development of wind power (compared to 390 GW in 2030, in IEA's net-zero scenario).



Supplementary Figure 4. Change in the primary energy mix, compared to current levels, per energy source, for all scenarios (model-specific output indicated in points), in 2030 (top) and 2050 (bottom). Box plots centre-line = median; box limits = upper and lower quartiles; $n=8$.

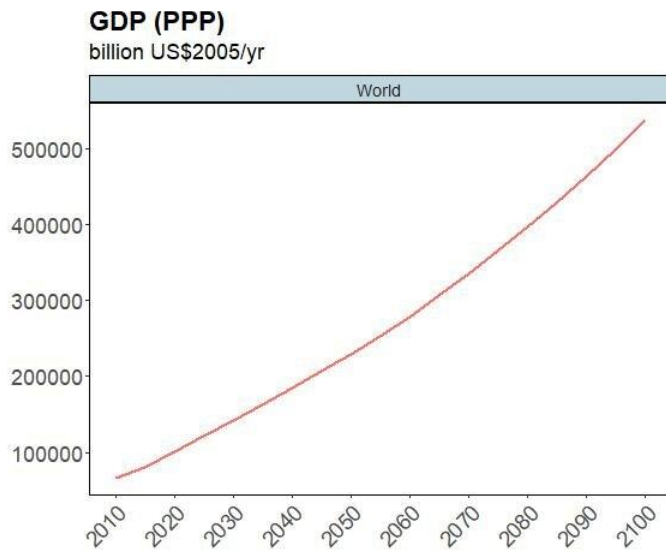
Regional pathways



Supplementary Figure 5. Regional emission pathways, per scenario. The shaded areas show the spread of models, while the lines show model mean.

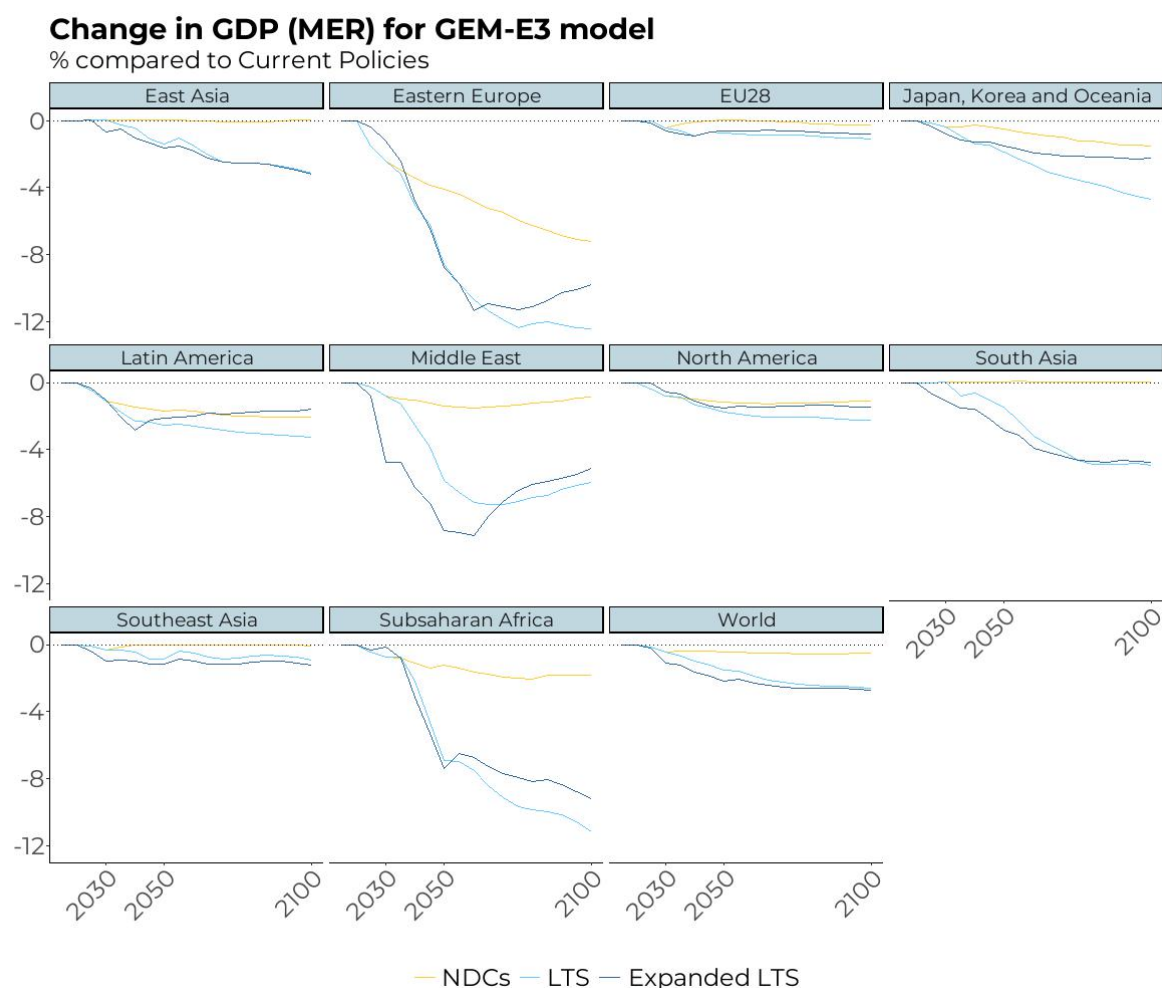
GDP growth

GDP growth projections follow the middle-of-the-road Shared Socioeconomic Pathways (SSP2), as presented in Supplementary Figure 6.



Supplementary Figure 6. GDP projections for middle-of-the-road Shared Socioeconomic Pathway (SSP2). From the SSP Public Database (DOI: 110.1016/j.gloenvcha.2016.05.009).

Impacts on GDP

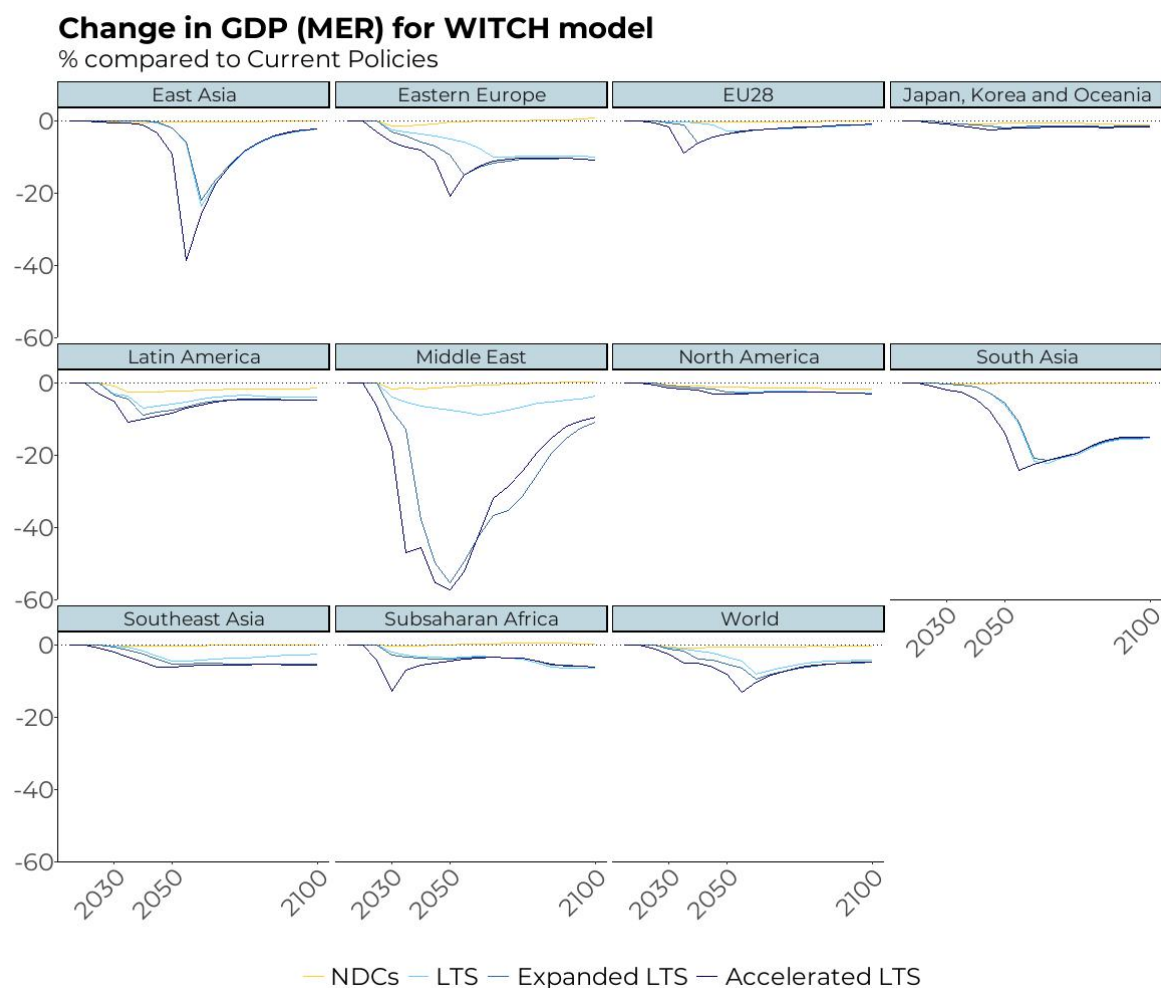


Supplementary Figure 7. Change in GDP compared to current policies (GEM-E3)

In the GEM-E3 model runs we note that the economic impacts of the NDC (Nationally Determined Contributions) and LTS (Long-Term Strategies) scenarios vary significantly across regions. Under both LTS pathways, global GDP declines modestly — by approximately 3% relative to the Current Policies scenario — from 2050 through the end of the century. However, fossil fuel-exporting and carbon-intensive regions experience substantially higher economic costs, with GDP losses reaching up to 10% compared to reference levels. In contrast, extending the implementation of NDCs through 2100 results in considerably lower global economic costs — less than 0.5% of reference GDP — reflecting the limited emissions reductions and less ambitious nature of the transition.

Across all regions in GEM-E3 model, the economic impacts under the NDC scenarios are consistently lower than those under the corresponding LTS pathways. However, the magnitude of this difference varies by region, depending on the ambition of the NDC and its

alignment with the LTS targets. For instance, the gap in GDP outcomes between the NDC and LTS scenarios is relatively small in the EU27, Japan, South Korea, and the United States. In contrast, the disparity is much more pronounced in East Asia and fossil fuel-exporting countries, which are more vulnerable to the climate policies of their trading partners.



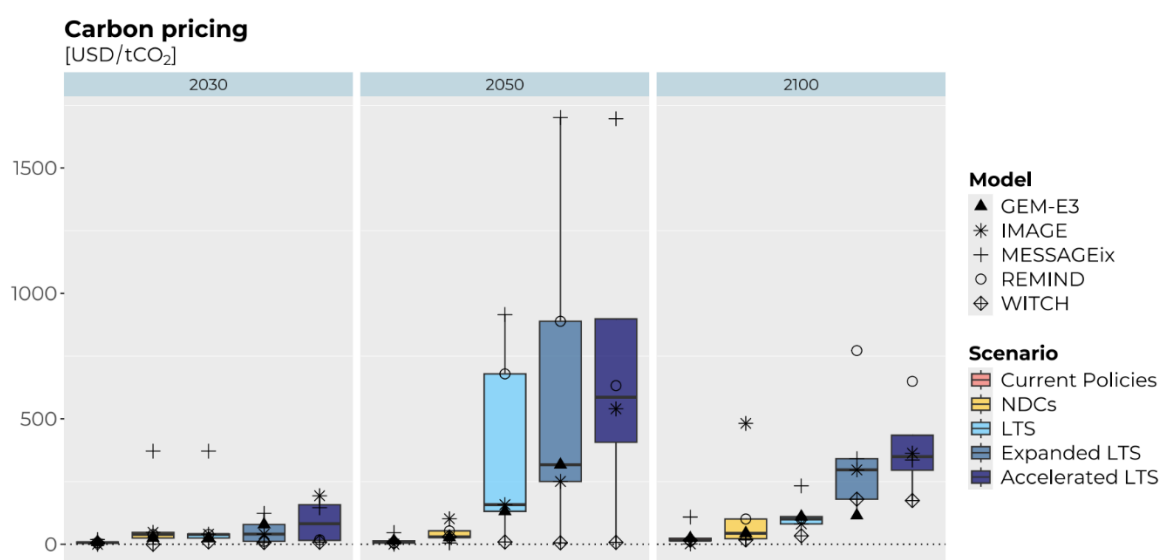
Supplementary Figure 8. Change in GDP compared to current policies (WITCH)

The regional GDP, expressed in GDP (MER) changes relative to current policies, show very contrasting responses across regions and scenarios. The NDCs scenario results in very small reductions in GDP across all regions. Conversely, LTS and LTS-variant scenarios lead to a pronounced GDP decrease by 2050, with a sustained lower GDP through the end of the century. While the GDP reductions in the LTS scenario are significant in all regions, the magnitude is substantially greater in the other LTS-variant scenarios (expanded LTS and accelerated LTS). Notably, Middle East, East Asia and South Asia experience substantial GDP declines between 2030 and 2050. This outcome is primarily driven by reduced fossil fuel

exports and the limited capacity of these economies to mitigate without compensation. That is also reflecting the fact that these regions did not voluntarily commit to the LTS pledges.

Carbon pricing

Supplementary Figure 9 presents the carbon pricing results for the different climate policy scenarios in this study. Higher carbon prices in the LTS scenarios in 2050 reflect the higher mitigation effort needed in the short to mid-term.



Supplementary Figure 9. Carbon pricing in 2030, 2050 and 2100, for all scenarios. GCAM, COFFEE and POLES did not report carbon pricing. Box plots centre-line = median; box limits = upper and lower quartiles; $n=5$.