All-of-Society Climate Pathway:

KEY POLICY LEVERS FOR 1.5°C-ALIGNED ACTION

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TECHNICAL APPENDIX

The *All-of-Society Climate Pathway: Key Policy Levers for 1.5°C-Aligned Action* report identifies eleven policy levers that can work better when undertaken in all-of-society partnership. It lays out how keeping 1.5°C within reach will require engagement by key countries, working on all greenhouse gasses and sectors, and integrating action across all levels.

This technical appendix documents the methods and approach used in this analysis. Section 1 outlines the modeling approach, section 2 highlights the key policies that are modeled, and section 3 provides an overview of the integrated assessment model used, the Global Change Analysis Model (GCAM), as well as the model adjustments included and a short discussion of uncertainties in section 4.

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1. OVERVIEW OF MODELING APPROACH

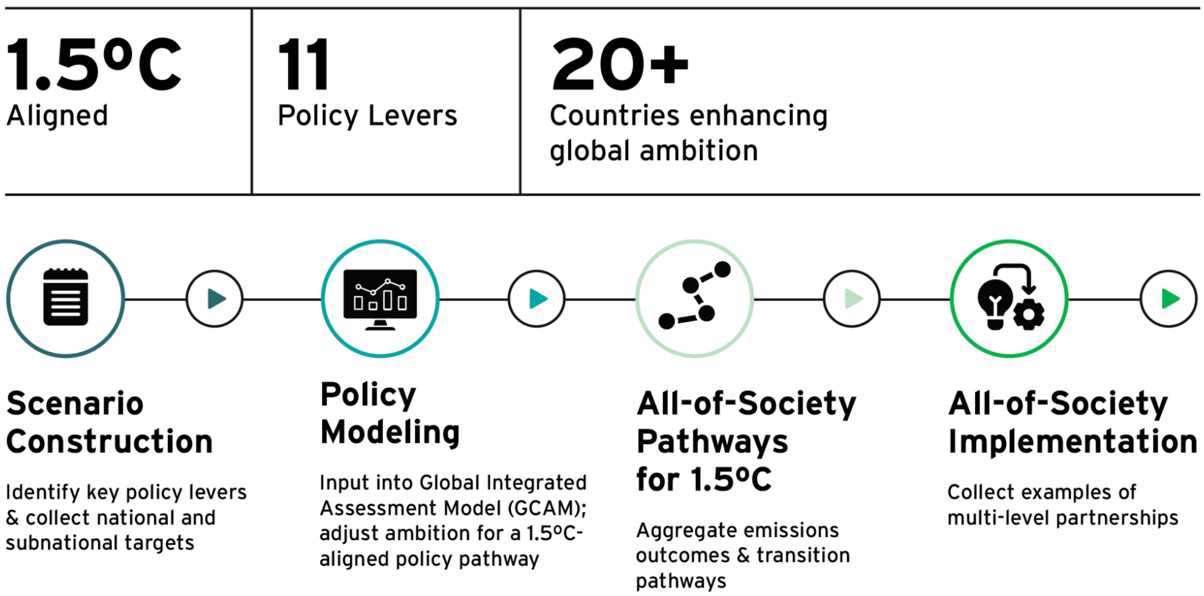

Figure A1. Research Design: Scenario Construction, Modeling Approach, and All-of-Society Implementation.

This analysis estimates the potential emissions reductions resulting from a global all-of-society strategy that leverages multi-level partnerships (Figure A1).

Key policy levers are identified based on emissions reductions potential, potential of adoption at different levels and ease of implementation in the modeling framework. National & subnational policies/targets were collected around key policy levers to develop country-specific parameters for enhanced action. We collected national and subnational policies from key countries, with over 300 national and 100 subnational policies with quantitative targets reviewed to date. Countries are categorized into one of four groupings based on their historical and current circumstances, including emissions trends and transition stages. The Group A countries (faster pace transition) are: Australia, Canada, the European Union and European Free Trade Association GCAM region, and the United States; the Group B countries (medium pace transition) are: Brazil, China, Japan, Mexico, and South Korea; and the Group C countries (slower pace transition) are: Argentina, India, Indonesia, South Africa, Russia, and the Middle East and other Non-EU European GCAM regions. In the final group, rest of the world (ROW), countries collectively achieve the Group C countries policy parameter. Most of the key emitting countries, such as the G20, are represented as a single country region in GCAM and are modeled in each of the country groupings; European Union plus the United Kingdom are covered by EU-12 and EU-15 in GCAM; and for a few countries that are not their own separate regions in GCAM, such as Turkey and Saudi Arabia, the GCAM regions containing those countries, such as “Europe_Non_EU” and

“Middle East”, respectively, are treated as G20 countries, by assignment to country Group C. Building on detailed policy review and modeling, we implement and adjust each policy lever according to country grouping contexts, aiming to represent what is possible with best practice efforts across society.

Using a global integrated assessment model, the Global Change Analysis Model (GCAM 6.0, jgcri.github.io/gcam-doc/), we model an All-of-Society 1.5°C pathway from integrated national and subnational actions around each of the 11 key policy levers identified based on emissions reduction potential, ability to integrate into modeling framework, and possibility of adoption at different governance levels/actors. The levers are chosen to represent actionable and easily quantifiable mitigation options, and so the key role of overall efficiency improvements is represented via the sectoral electrification targets. This analysis develops a “bottom-up” scenario through 2030, setting parameters around key policy levers with varying ambition across countries. This is then complemented from 2035 onward with a backstop emission constraint, similar to, but updated and refined from prior research.[1,2] Please see section 3 for additional information on GCAM.

We then quantify the aggregate emissions and temperature outcomes, and so develop plausible 1.5°C-aligned pathways that achieve global net-zero fossil fuel and industrial CO_2 emissions in 2050 and globally through 2030 and beyond. Parameters are adjusted based on aggregate emissions reduction and comparison to 1.5°C pathways from the AR6 database.[3] The overall modeling approach was consistent with previous analysis.[1,2] but with further country detail and differentiation across country groupings.

Then, examples of all-of-society actions are collected and integrated into the analysis. Highlighted examples are chosen based on policy collection, expert and partner recommendation and diversity of countries and actor types included in analysis.

2. KEY POLICIES MODELED

As discussed in Section 1, policy levers are identified, and parameters are developed by country grouping to implement into GCAM. For additional information on key policy levers and implementation approach, please see Table A1 below. Unless otherwise specified, all values for ROW are set equal to Group C, but achieved collectively.

The implementation approach in GCAM varies across the policy levers. For many policies, the target is achieved by specifying the share of goods and services provided by certain technologies and fuels, which is called a market share constraint. The share, for example, of car transportation provided by electric vehicles, is specified either for the new sales or for the total service provided. Based on this specification, GCAM then endogenously subsidizes the technologies relative to the other options, if needed, until the share was achieved. Other methods of implementation include shortening the lifetimes and half-life for accelerated retirement, increasing the assumed efficiency values to a higher rate, and/or adding in a new technology into GCAM.

Table A1. Key Policy Levers and Implementation Process.

Sector	Key Policy Lever through 2030	Implementation
Power	Increasing renewable energy deployment	• Renewable energy portfolio standards are set for country groupings based on individual country targets and relative ambition across groupings. Solar and wind generation share targets for 2030 are set at 50%, 45% and 40% in Groups A, B, and C, respectively.
	Phasing down coal	• New unabated coal power installations are stopped starting in 2025, based on policy targets in key countries. • Retirement is accelerated to cause no unabated coal power in Groups A, B, and C by 2030, 2035, and 2045, respectively, reflecting recent trends and policies.
Transportation	Increasing electric vehicle deployment	• Electric vehicle market shares for light duty vehicles (including fuel cell based options) are set for each of the country groupings, based on the announced near-term targets for key regions within those groupings. For example, 60% of new sales in Group A,[4] 50% in Group B (increased by 10% over China's goal, based on expert judgment and current analysis) and 40% in Group C are targeted to be from electric vehicles in 2030. • In the absence of explicit market share goals for freight transport, these are set with a delay of 5-10 years for each country group, relative to the targets for passenger transport. • Retirement of internal combustion engine vehicles is accelerated by changes to specified lifetimes (15 years), in line with proposals in certain countries.[5]
	Shifting travel mode to various low-carbon options	• Multipliers for the value of time in transit (to promote a shift to public transport) and vehicle miles traveled (indicating the shift to remote work) are edited in line with more sustainable scenarios in the literature.[6]

Buildings	Increasing electrification and heat pump deployment	• Electric technologies in all building services are subsidized via a market share floor based on high ambition countries within a group. Goals are set at 70% for Groups A and B in 2030 (based on the range of ambition of countries in the groupings), with lower and phased increase in ambition for Group C and ROW countries, to maintain recent rates of electrification through 2030. Heat pumps are given strong preference relative to other technologies within heating and cooling.
	Phasing -down gas and solid fuels	• Gas-powered heating and cooling technologies are taxed via a ceiling constraint in order to phase them out by 2040, 2045, 2050, and 2055 for Groups A, B, C, and ROW, respectively. • Direct use of coal in buildings is phased out worldwide by 2030, and traditional biomass burning in households is phased out by 2030 for Groups A and B, and by 2035 for Groups C and ROW, all via ceiling constraints, in line with current progress and sustainable development goals set by countries.[7]
Industry	Increasing electrification and fuel switching	• Electrification rates for other industrial energy use are set to increase from modeled 2020 levels by 7.5% every 5-year timestep via a market share constraint.
	Setting peaking and net-zero targets for key industrial sectors	• Net-zero emission targets are set for key subsectors in industry, such as iron and steel[8,9] and aluminum,[10] via an emissions constraint and in line with targets of major industry groups and associations. Similar accelerated reductions are expected in other sectors like chemicals where major companies have ambitious 2030 reduction targets.
Land use	Halting deforestation	• A shadow price is applied to land use change emissions that is 10% of fossil-fuel combustion and industrial (FFI) CO_2, with an increasing percentage post 2030.
NonCO_2s	Targeted methane emissions reduction	• Modeled via shadow price that achieves close to the Global Methane Pledge (GMP) target, for final trajectory assuming additional abatement in line with full achievement of GMP.[11]
	Targeted HFC emissions reduction	• A phaseout of hydrofluorocarbons (HFCs) in line with the Kigali Amendment to the Montreal protocol,[12] with different country groupings starting at different levels of ambition, and achieving 85% reduction by mid-century. See more details in Table A3.

3. OVERVIEW OF GCAM

The Global Change Analysis Model (GCAM) is a global market equilibrium model that combines economic, energy, land use, and climate systems to analyze the interactions between human activities and global environmental changes. It is designed to assess the impacts of various policy scenarios and technology options on energy use, land use change, greenhouse gas emissions and climate change.[13]

GCAM is a dynamic recursive model, meaning that decision-makers do not know the future when planning today. After it solves each period, the model then uses the resulting state of the world, including the consequences of decisions made in that period – such as resource depletion, capital stock retirements and installations, and changes to the landscape – and then moves to the next time step and performs the same exercise. GCAM operates in 5-year time-increments, with each new period starting from the conditions that emerged in the last. GCAM has previously been used to examine impacts of mitigation policies and technology deployment on greenhouse gas emissions.[14,15]

GCAM tracks emissions of 16 different species of GHGs and air pollutants from energy, agriculture, land use, and other industrial systems. In GCAM, the world is disaggregated into 32 economic regions, the resolution at which socioeconomics, energy, and market processes (including global trade) are modeled. Water flows and land use are modeled in more than 200 and 300 regions, respectively. The Earth system model (i.e., carbon-cycle climate module) Hector is the climate model within GCAM.[16]

The energy system formulation in GCAM consists of detailed representations of depletable primary sources such as coal, gas, oil, and uranium, in addition to renewable resources such as bioenergy, hydropower, wind, and geothermal. These energy resources are processed and consumed by end users in the buildings, transportation, and industrial sectors. GCAM is a hierarchical market equilibrium model. The equilibrium in each period is solved by finding a set of market prices such that supplies and demands are equal in all simulated markets.

The edition of GCAM (version 6.0) used for this study includes a number of updates: a new residential floorspace expansion model; bio-energy updates; splitting out six detailed industrial sectors from the aggregate industry sector; updated hydrogen production, distribution, and end-use technologies; a new protected lands definition.

4. OTHER MODELING ADJUSTMENTS

Emissions

In addition to the key policies that are modeled, a variety of adjustments are made in the All-of-Society 1.5°C pathway to align it with recent data and global commitments.

Emissions are calibrated in 2020, since the base year is currently 2015 in GCAM. We use an emissions constraint to act as a 2020 calibration for FFI CO_2. Given the COVID 19 pandemic and its effects on the world's energy systems, we calibrated to the average of 2019-2021. To account for differences in data sets, we took the difference of 2015 and averaged 2019-2021 from historical data[17] and added that difference to GCAM's base year 2015. Regions in country groupings A and B are all given their own separate markets to match their calibration values, all other regions are put into an aggregated market to meet their collective calibration values.

For the purposes of providing the most actionable and clear results to the policy-making audience, quantities are calculated relative to 2022, which requires post-processing as GCAM runs in five year time periods which don't include the year 2022. The historical value of net GHG emissions in 2022 is used as GCAM 2022 net GHG emissions. All emissions in 2023-2024 are interpolated between the 2022 historical data, and the 2025 model results values. Historical GHG data is from the Emissions Database for Global Atmospheric Research (EDGAR) dataset for fossil and industrial processes CO_2, N_2O and F-gas emissions[18] with CH_4 from the Community Emissions Data System (CEDS),[19] adjusted with International Energy Agency (IEA) estimates for oil and gas CH_4 emissions, and Climate Watch for LULUCF CO_2 estimates.[20]

To account for continued action, and to prevent an emissions bounce back, we keep the shadow carbon price created by the 2020 calibration as a constant carbon tax through 2030, except in regions where the price is excessive (Japan, China, Mexico, Brazil), where we reduce the carbon price by 50% for 2025 and 2030.

Post 2030, an emissions cap is implemented and the regions stay in the same market as for the 2020 calibration and meet the targets specified in Table A3. Targets are met with a linear interpolation between the 2030 modeled value based on the approach outlined above and their net-zero target year (Table A3).

Table A2. Net-Zero CO_2 Targets Implemented across Country Grouping.

Country Grouping	Target
A	Net-Zero FFI CO_2 in 2045
B	Net-Zero FFI CO_2 in 2050
C, ROW	Net-Zero FFI CO_2 in 2060

Land use change emissions, HFC emissions, and N_2O emissions are processed partially outside of the model. Land use, land use change, and forestry (LULUCF) CO_2 emissions are calculated based on GCAM results, with some adjustments based on historical data. The 2015 and 2020 values are replaced with historical data from Climate Watch,[20] on a regional basis. Then, emissions are smoothed into a linear trajectory, approximating the total cumulative emissions in the 2015-2050 time range to be the same as they are in the GCAM modeled output. For HFC emissions, start dates and ambition levels are differentiated by country, based on Article 5 parties to the protocol.[21] Country emissions reduction pathways are based on explicit groupings in the Kigali Agreement, rather than the country groupings used in the rest of this analysis (Table A3). N_2O emissions values are constant at the 2022 values from the EDGAR dataset through 2030, and then change according to the rate of N_2O emissions from the All-of-Society 1.5°C pathway scenario post 2030. Methane emissions in the 2020-2030 time range are consistent with a deep dive analysis on methane emissions and mitigation potential.[11] Post 2030 values are calculated using the growth rate of CH_4 emissions from the All-of-Society 1.5°C pathway.

Table A3. HFC Reduction Targets Implemented.

Regions modeled	Implementation start year	2030 HFC reduction goal	2050 HFC reduction goal
Developed countries	2019	70%	85%
Russia, Central Asia, Eastern Europe	2028	10%	80%
China, Brazil and other developing regions	2024	15%	80%
India, Pakistan, Middle East	2028	5%	80%

Energy

Similarly to emissions, we also calibrate electrical power generation from coal and natural gas electricity in 2020. We use a similar approach where we take the difference between generation from each technology in 2015 and the average of 2019-2021, this time using the EMBER dataset.[22] This difference is added to GCAM's 2015 value to set the 2020 values.

Regarding energy carriers, specifically hydrogen, all new centralized or forecourt production of hydrogen after 2030 is modeled as "green", in that it is produced from solar or wind energy. This was implemented via an emissions constraint on all hydrogen technologies.

Within the industry and buildings sectors, specific scenario adjustments are made to cement and heat pumps, respectively. An accelerated retirement of older cement plants is modeled, to enable the faster installation of cement plants with carbon capture technologies to meet the ambitious emission reduction targets of the cement industry associations. This leads to a stabilization of emissions in the near term (2030) and then a linear reduction to 2050. We also implemented a conservative energy efficiency improvement in some industry subsectors over the baseline, and will explore more in the future. To more accurately reflect in GCAM the efficient technologies that are available for heating and cooling buildings, heat pumps are added as a technology option to this version of GCAM, with values for the costs, lifetime, efficiency, and unit energy output from available technology data.[23]

Areas of Uncertainty and Future Research

This analysis provides an illustrative pathway that sits within a range of other possible 1.5°C futures. Our current analysis focuses on developing a global scenario, with variation across country groupings. While individual country policies are collected and considered, country pathways are not evaluated in significant detail and may vary from other analyses or country policy targets. Additional analysis should assess country level pathways and their role in meeting the global goal. Secondly, in this analysis, we assume the same parameter across country groupings. There is significant variation within country groupings based on the progress countries have currently made, and this varies across policy levers. Future analysis can evaluate the impact of individual country level parameterization. Thirdly, ROW countries reach their targets collectively, whereas all other country groupings reach parameters individually. This is intended to require higher ambition in country groupings A, B and C, but may result in varying ambition across ROW countries, which are not evaluated in detail. Future research can assess the impact of ROW countries on global policy pathways. Finally, post-2030, we adopt an emissions constraint, rather than set specific policy parameters for most key policy levers, in part due to the uncertainty in long-term technology choices for reaching net-zero. Other analyses may vary significantly after 2030, such as in the extent of carbon dioxide removal deployment, and hydrogen use in industry and transportation.

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