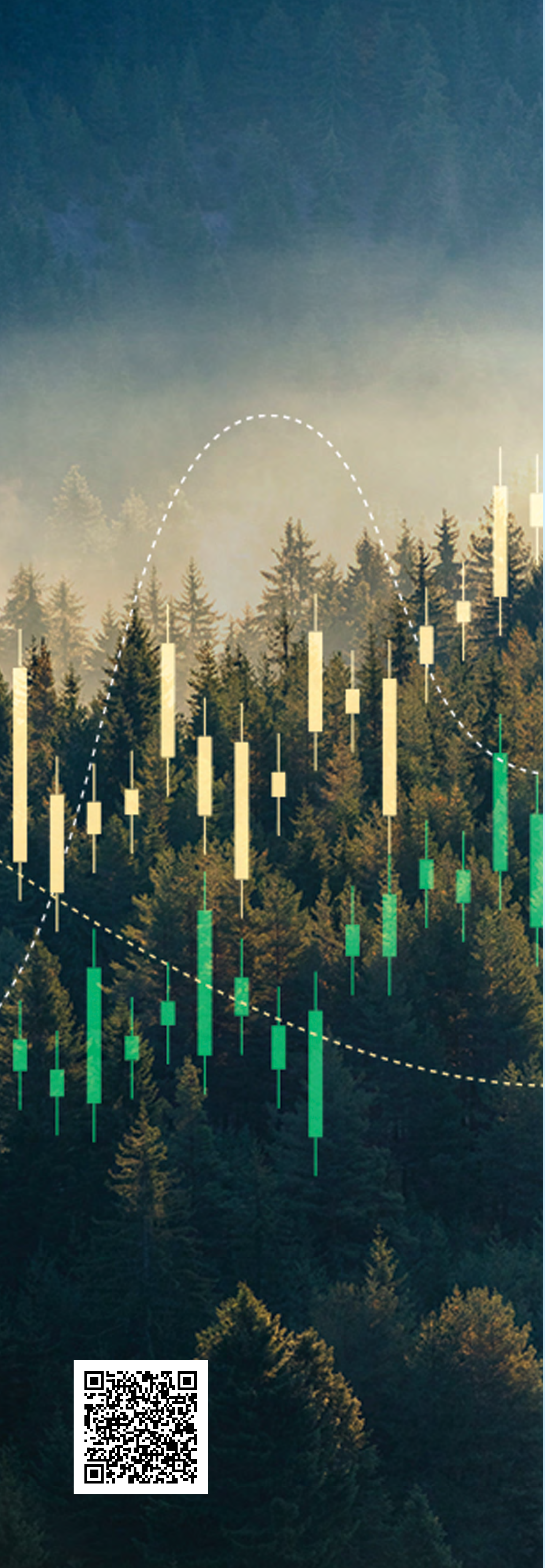

TECHNICAL PAPER | EXECUTIVE SUMMARY

An Overview of Climate-Economy and Energy System Models

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Mathematical modelling programs have become indispensable tools in climate science and policy research, enabling the projection of greenhouse gas (GHG) emissions and economic outcomes for the analysis of climate change mitigation and adaptation strategies useful for informing evidence-based policymaking at national and international levels. This paper is intended for readers with some background in economic and energy system modelling and it aims to offer a clear guide to a few Integrated Assessment Models (IAMs) and Energy System Models (ESMs) by providing a descriptive overview and highlighting the diverse applications and suitability of different models to specific research questions. The paper outlines the technical attributes and features of the models, such as sectoral coverage, economic growth assumptions, modelling algorithms, optimisation methods, etc., with an emphasis on the usability and scalability of the models. The authors stress that understanding these variations is crucial for interpreting model outputs and applying them effectively in policy and research contexts.

The paper begins with an introduction that underscores the increasing role of mathematical modelling programs in climate science and policy research since the 1970s. These programs have been used for projecting future trends in GHG emissions, their impact on global temperatures, and assessing resource needs across various regions. From the development of scenarios that depict how the world might evolve socially, demographically, and economically over the coming century, to providing detailed assessments of economic consequences under varying degrees of global warming, these models have become integral to evidence-based decision-making at both national and international levels. They have also become essential for fostering a global consensus on reducing GHG emissions to net-zero by various target dates. The paper concentrates on models that are either widely used for global mitigation scenario analysis, have been featured in significant studies like Intergovernmental Panel on Climate Change (IPCC) reports, or have been specifically developed for conducting analysis relevant to India, reflecting the technical differences and geographical focus of these modelling tools.

At the core of the paper is a review of various IAMs, namely Global Change Analysis Model (GCAM), Integrated Model to Assess the Global Environment (IMAGE), Regional

Model of INvestments and Development (REMIND), World Induced Technical Change Hybrid (WITCH), and Model for Energy Supply Strategy Alternatives and their General Environmental impact (MESSAGEix), while the ESMs include India Energy Policy Simulator (India EPS), India Energy Security Scenarios (IESS 2047), Open Source energy Modelling System (OSEMOSYS), Rumi/Perspectives on Indian Energy based on Rumi (Rumi/PIER), and the Integrated MARKAL-EFOM1 System (TIMES). A technical summary is provided to compare the models' key features and limitations. These include the developer, country of origin, licensing terms, programming language, solution type, underlying concepts, solution method, approach to foresight, treatment of technological change, geographic scope, representation of the climate system and land system, and handling of climate impacts and adaptation. The summary helps in determining the suitability of each model and provides a practical resource for researchers and policymakers seeking to understand and apply these tools to a specific problem.

GCAM is described as a dynamic, recursive model rooted in market equilibrium. It is jointly developed by the Joint Global Change Research Institute (JGCRI), Pacific Northwest National Laboratory (PNNL), and the University of Maryland. GCAM integrates five interconnected systems: energy, macroeconomy, agriculture and land use, water, and the Earth system. It models 32 geopolitical regions for energy and the macroeconomy, 384 subregions for land use, and 235 hydrological basins for water resources. The model finds equilibrium prices across markets iteratively and projects future global states in five-year increments. Available as open-source software in C++, GCAM has helped create various assessment scenarios at both national and international levels, including the Shared Socioeconomic Pathways (SSPs) used in IPCC reports. The model's easy accessibility, and capacity to integrate diverse systems and provide detailed regional analyses makes it a valuable tool for examining the complex interactions between human activities and the Earth's climate. GCAM has relatively less computational detail in some sector-specific processes. Additionally, it assumes imperfect foresight, i.e., uncertainty in future technological developments increases over time, which needs to be mitigated by sensitivity analyses and multiple scenario simulations to explore a range of possible outcomes and corresponding policy responses.

IMAGE is an integrated assessment model created by the Netherlands Environmental Assessment Agency (PBL) to study global long-term climate change scenarios. IMAGE has two main parts: the human (or socioeconomic) system and the Earth system, linked to assess how human actions affect the environment and vice versa. The human system is modelled across 26 global regions based on their environmental and economic importance. The Earth system is modelled with varying spatial detail. The energy part of IMAGE uses TIMER, a simulation-based energy system model that determines outcomes through a series of algorithms, to project the system's future state from its current state. This approach allows for a comprehensive assessment of the long-term impacts of various policies and technological developments on the global environment. IMAGE's extensive data requirements pose a challenge in providing uniform, detailed results across all geographical areas, particularly when data for certain regions are scant. Additionally, the model's restrictive licensing may impede its accessibility and further development, limiting its widespread use.

REMIND is an open-source mathematical model of the energy-economy system, developed and maintained by the Potsdam Institute for Climate Impact Research (PIK). REMIND is a general equilibrium model, connecting a Ramsey-type macroeconomic growth model with a bottom-up energy system model. The model determines an intertemporal Pareto-optimal solution for economic and energy investments across its 12 defined regions. REMIND is programmed in GAMS as a set of modules interlinked through defined input and output variables. This modular structure allows for detailed analysis of individual model components and enables researchers to adapt the model to address specific research questions. This also makes REMIND's modelling structure complex, requiring detailed input data and substantial computational resources, making it challenging to implement and maintain, particularly in resource-constrained settings. It also lacks a detailed representation of certain behavioural responses, leading to oversimplified outcomes in some scenarios. Additionally, REMIND's implementation using GAMS and CONOPT, both proprietary software, may limit its use among researchers.

WITCH is developed and maintained by the RFF-CMCC European Institute on Economics and the Environment. WITCH is a dynamic optimisation model that combines an intertemporal optimal growth model of the economy, an energy sector representation, land-use change model, and a climate model. The model analyses the best strategies for mitigating GHG emissions adapting to climate change, based on a region's vulnerability to climate damage and external limits on emissions, GHG levels and temperature. The model has a game-theoretic approach to technological change and allows for endogenous depiction of R&D diffusion and innovation processes, which means that it can assess the impact of R&D investments on mitigation. Although its assumption of full information for an open-loop Nash equilibrium (non-cooperative) may be an oversimplification of the real-world geopolitical dynamics which may undermine the model's ability to capture complex dynamics.

MESSAGEix-GLOBIOM is a global framework for integrated assessment, developed by the International Institute for Applied Systems Analysis (IIASA). It combines sector-specific models like MESSAGE (for energy systems), MACRO (for macroeconomics), GAINS (for emissions), MAGICC (for climate), GLOBIOM (for land use), and G4M (for forestry). MESSAGEix-GLOBIOM has aided in creating various scenarios, including the Shared Socioeconomic Pathways (SSPs) used by the IPCC. It is a global model divided into 11 geographic regions, with a timeline from 2010 to 2100 in five-year steps. The model's integrated structure allows for a comprehensive assessment of the interactions between different sectors and their impacts on climate change, albeit with some challenges, such as extensive input data requirements across regions and high computational requirements to perform analyses.

India EPS is a system dynamics model originally developed by Energy Innovation LLC, which was adapted for India by the World Resources Institute (WRI) India. India EPS allows simulation of different energy and climate policy scenarios within the Indian national context, enabling policymakers and researchers to assess their cost-effectiveness and emissions reduction potential. The system dynamics model driving India EPS maintains variables or 'stocks' that vary with time steps according to 'flows' into and out of the variables. This interplay of stocks and flows captures the interactions and feedbacks between the variables over time. The model's focus on the Indian context makes it a valuable tool for informing national policy decisions. Limited to the baseline scenario and policy settings, and lacking detailed infrastructure parameters, the India EPS model may not be able to capture the full impact of polices. Further, since it relies on system dynamics, assumptions may compound uncertainty in the output. On balance, the India EPS model is particularly useful for performing simulation analysis under different policy targets.

IESS 2047 v3 is an Excel-based energy calculator, developed in collaboration with IIT Bombay by NITI Aayog. It models energy supply and demand scenarios for India up to 2047. The model allows users to create scenarios based on different assumptions about economic growth, industry shares, population, urbanisation, energy demand, energy efficiency, and technology adoption. It helps assess the impact of the energy transition on emissions, investments, water, and land use. The model's accessibility and ease of use make it a valuable tool for policymakers and researchers seeking to explore different energy futures for India, but on the other hand it restricts the computational capabilities of the model, which would require additional validation using other models.

OSeMOSYS is a free and open-source tool for energy systems modelling, developed by M. Howells et al. It is an optimisation framework with perfect foresight that solves for an optimal energy mix in terms of generation capacity and energy supply of a region while minimising the total discounted costs, subject to various constraints. It models an abstract energy system containing various types of technologies that transform one form of fuel/energy into another, such as power plants, transmission lines, and final demand entities such as EVs and heating appliances. Although the model lacks in sectoral analysis, its open-source nature and relatively simple structure have fostered its widespread adoption and use in energy planning studies around the world.

Rumi/PIER is an open-source platform for modelling energy systems, designed to evaluate long-term energy scenarios and policies. It is developed by Prayas Energy Group (India). It consists of two components: Rumi supply, an optimisation-based model that evaluates the least cost supply, and Rumi demand, an accounting framework that estimates the energy demand and provides inputs to the energy supply module. Rumi allows users to define any energy system of their choice in terms of spatial granularity, types of energy carriers, consumer types, etc. The model's focus on demand-side dynamics and its Indian context, with 25 sub-national regions, make it a valuable tool for exploring energy policy options in India. The first version of the model had several limitations (e.g. missing feedback loops between the demand and supply modules and between the energy sector and the macroeconomy), some of which have been addressed in the subsequent versions.

TIMES is an advanced energy systems model designed to analyse energy dynamics on local, national, multi-regional, or global scales across different timeframes. TIMES, like MARket ALlocation (MARKAL) model, has explicit technology definitions and uses a dynamic partial equilibrium framework. Both models aim to minimise the total cost of the energy system by maximising the surplus for consumers and suppliers through linear programming. TIMES is structured around components that blend economic, energy, temporal, and data features to explore possible energy futures. The model's comprehensive representation of the energy system and its ability to analyse a wide range of policy scenarios at regional scale have made it a widely used tool for energy planning and policy analysis, although the detailed input data requirement and use of proprietary software limit its accessibility.

Key Takeaways

The paper concludes by recognising that modelling tools have evolved significantly over time, becoming more sophisticated and integrated, and have gained importance in climate policy research. It also notes concerns about the transparency of assumptions, methods, and data used in these models. Addressing these concerns is essential for ensuring the credibility and usefulness of model outputs. The paper suggests that future development should focus on better integrating modelling tools, improving transparency and communication among modellers, and enhancing accessibility by making the tools more user-friendly. This will ensure that these models continue to be valuable resources for informing climate policy and guiding sustainable energy transitions.

About the authors

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