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An Overview of Climate-Economy and Energy System Models

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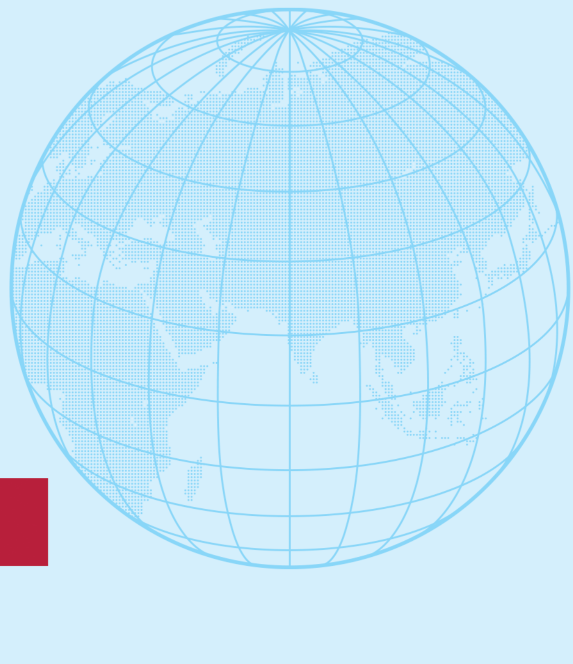

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An Overview of Climate-Economy and Energy System Models

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ADB	Asian Development Bank
API	Application Programming Interface
AFOLU	Agriculture, Forestry, and Other Land Use
BAU	Business-As-Usual
CBC	COIN-OR Branch-and-Cut
CCS	Carbon Capture and Storage
CDE	Constant Differences in Elasticity
CES	Constant Elasticity of Substitution
CET	Constant Elasticity of Transformation
CGE	Computable General Equilibrium
CNG	Compressed Natural Gas
DICE	Dynamic Integrated Climate-Economy
ENVISAGE	Environmental Impact and Sustainability Applied General Equilibrium
EPS	Energy Policy Simulator
ESTAP	Energy Technology Systems Analysis Program
EWS	Economically Weaker Section
EV	Electric Vehicle
FAIR	Framework to Assess International Regimes for the differentiation of commitments
FTT: Power	Future Technology Transformations for the Power sector
FY	Financial Year
G4M	Global Forest Model
GAINS	Greenhouse Gas and Air Pollution Interactions and Synergies
GAMS	General Algebraic Modelling System
GCAM	Global Change Analysis Model
GDP	Gross Domestic Product
GENeSYS-MOD	Global Energy System Model
GHG	Greenhouse Gas
GISMO	Global Integrated Sustainability Model
GLOBIO	Global Biodiversity Model for policy support
GLOBIOM	Global Biosphere Management Model
GLOFRIS	Global Flood Risk with IMAGE Scenarios
GTAP	Global Trade Analysis Project
GUI	Graphical User Interface
HVDC	High-Voltage Direct Current
IAM	Integrated Assessment Model
IEA	International Energy Agency
IESS	India Energy Security Scenarios
IIASA	International Institute for Applied Systems Analysis
IMAGE	Integrated Model to Assess the Global Environment
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change
ISIC	International Standard Industrial Classification
IXMP	Integrated and Crosscutting Modelling Platform

I/O	Input-Output
JGCRI	Joint Global Change Research Institute
LCOE	Levelized Costs of Electricity
LIG	Lower Income Group
LULUCF	Land Use, Land Use-Change and Forestry
MACRO	Macroeconomic model (by IIASA)
MAGICC	Model for the Assessment of GHG Induced Climate Change
MAGNET	Modular Applied GeNeral Equilibrium Tool
MAgPIE	Model of Agricultural Production and its Impact on the Environment
MANAGE	Mitigation, Adaptation and New Technologies Applied General Equilibrium
MARKAL	Market Allocation model
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental impact
MFMod	Macro-Fiscal Model
MIG	Middle Income Group
MoManI	Model Management Infrastructure
MPCE	Monthly Per Capita Expenditure
NDC	Nationally Determined Contribution
NGFS	Network for Greening the Financial System
OECD	Organisation for Economic Co-operation and Development
OSeMOSYS	Open Source energy Modelling System
O&M	Operations and Maintenance
PBL	Planbureau voor de Leefomgeving (Environmental Planning Agency)
PIER	Perspectives on Indian Energy based on Rumi
PIK	Potsdam Institute for Climate Impact Research
PV	Photo Voltaic
R&D	Research and Development
RCP	Representative Concentration Pathway
REMIND	REgional Model of INvestments and Development
RES	Reference Energy System
REST API	Representational State Transfer Application Programming Interface
RFF	Resources for the Future
PNNL	Pacific Northwest National Laboratory
SAMBA	South American Model Base
SPA	Shared Policy Assumption
SSP	Shared Socioeconomic Pathway
TEMBA	The Electricity Model Base for Africa
TIMER	The IMAGE Energy Regional model
TIMES	The Integrated MARKAL-EFOM1 System
T&D	Transmission and Distribution
UNEP	United Nations Environment Programme
VOC	Volatile Organic Compounds
WITCH	World Induced Technical Change Hybrid
WRI	World Resources Institute

Abstract

Mathematical modelling programs have become indispensable in climate science and policy research, providing projections of greenhouse gas emissions and economic output for the analysis of climate change mitigation and adaptation strategies. These programs, including Integrated Assessment Models (IAMs) and Energy System Models (ESMs), facilitate evidence-based policymaking at national and international levels. This report provides a descriptive overview of selected models, highlighting their diverse applications and accessibility. IAMs such as REMIND, GCAM, IMAGE, WITCH and MESSAGE, which have been notably used in the development of the IPCC's Shared Socioeconomic Pathways (SSPs), and ESMs such as TIMES and OSeMOSYS are discussed, along with India-specific models such as IESS 2047, Rumi/PIER and EPS India. The report 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. Inter-model comparison tables are provided to help assess the suitability of a model for a desired application. The report also acknowledges the limitations and uncertainties in the models. Recommendations include increasing transparency and accessibility to improve the usability and integration of these tools.

1. Introduction

Mathematical modelling programs, developed since the 1970s, have become a mainstay of the climate science and policy research community for making projections into the future and analysing different climate change mitigation pathways and adaptation strategies and resource requirements for different regions of the world. From the development of pathways that examine how the world would change socially, demographically, and economically over the next century, to providing an assessment of different economic outcomes under varying degrees of global warming, the programs have been essential for evidence-based policymaking at national and international levels, and for reaching a global consensus on reducing greenhouse gas emissions to net zero by various dates around mid-century.

In this report, we review some of the modelling tools and programs that have been developed and maintained by global research organisations and are used in the leading works on climate change policy by researchers around the world. We provide a descriptive overview of the different models, which are classified as Integrated Assessment Models (IAMs: GCAM, IMAGE, REMIND, WITCH, MESSAGEix) and Energy System Models (ESMs: India EPS, IESS 2047, OSeMOSYS, Rumi/PIER, TIMES). The coverage of models is not strictly systematic, and we do not undertake an exhaustive literature review given the high number of models available. We have selected the models that are either most widely used for global mitigation scenario analysis and have been featured in prominent studies (e.g., IPCC reports), or have been developed for conducting India-specific analysis.

The five IAMs reviewed in this report (all process-based)[1] have been, most notably, used in the development of the IPCC's Shared Socioeconomic Pathways (SSPs) (Riahi et al., 2017; Rogelj et al. 2018). Other examples include WITCH used by the Asian Development Bank (ADB) for the various scenarios presented in its 2023 report (ADB, 2023). TIMES is used by the International Energy Agency (IEA) for its annual International Energy Outlook reports. OSeMOSYS is used by researchers to analyse decarbonisation pathways for various regions such as Australia, South America, Africa, etc. Both models offer a high degree of customisation to define energy system structures specific to national circumstances and are widely cited. Few models reviewed are India-specific and have been developed at Indian institutions (IESS 2047 v3 and Rumi/PIER) and offer high accessibility through their web-based interfaces (India EPS and IESS 2047 v3).

The modelling paradigms and use cases of these programs differ along several attributes such as economic growth assumptions, modelling algorithms, optimisation methods, solution types, geographical resolution, temporal scales, sectoral coverage, etc. The models also vary along the dimensions of usability, scalability, transparency, flexibility, integrability, and adaptability to different policy settings. These criteria and other technical attributes of the models are described in this report, along with an inter-comparison of model features. An evaluation of the robustness of these models or a comparison of their results is beyond the scope of this report.

While not comprehensive, this report provides a succinct descriptive overview of the selected models and is intended for readers with some background in economic and energy system modelling. Our aim is to present various state-of-the-art models and highlight their diversity, to help the reader navigate through the vast array of choices available by comparing model features, and to assess the suitability of a model for a prospective study based on the most notable and recent works that use these models.

Modelling programs in climate science and policy research have evolved from simple cost-benefit analyses to complex, multi-sectoral, process-based models that integrate with other disciplines such as economics, energy systems, atmospheric chemistry, and climatology. Over the years, the expansion of the scope of modelling programs has been accompanied by improved transparency and reliability, making these tools more comprehensive and useful for climate policy-making. However, it should be noted that these models vary widely in their features and so do their solutions, depending obviously on the formulation of the problem, the economic and technical inputs, the use cases, and scenarios.

[1] Unlike aggregated IAMs, such as DICE by Nordhaus (2013), which are used in cost-benefit frameworks to analyse the most economic level of mitigation considering the future impacts of climate change, process-based IAMs explicitly represent the drivers and processes of change, capture both biophysical and socio-economic processes across many sectors, and project optimal mitigation pathways (Wilson, et al., 2021).

To quote George E.P. Box, "All models are wrong, but some are useful," these models do not claim to accurately predict the future, and their results must therefore be interpreted carefully, as they are subject to statistical uncertainty due to various factors, including but not limited to the input parameters, assumptions and value judgements made by the user. Indeed, owing to these uncertainties, most global assessments, including by the IPCC, present the median of future outcomes from an ensemble of different model projections, with a measure of uncertainty to indicate the variation in the results of different models.

A technical summary of the main features and limitations of these models is presented in the following tables, followed by a brief discussion of each model to provide the reader with a comprehensive overview in the subsequent sections, and a final section with a discussion of the existing literature on modelling tools to conclude the report.

2. Technical summary tables

Table 1: Integrated Assessment Models (GCAM, IMAGE, MESSAGEix-GLOBIOM)

	GCAM	IMAGE	MESSAGEix-GLOBIOM
Developer(s)	PNNL; University of Maryland	PBL Environmental Assessment Agency	IIASA, Austria
Country	US	The Netherlands	Austria
Licensing	Open source	Restricted	Open source
Programming platform/language	C++, R	–	Python, R
Solution type	Recursive dynamic	Simulation	Optimisation
Solution concept	Partial equilibrium (price elastic demand)	Partial equilibrium (price elastic demand)	General equilibrium (closed economy)
Solution method	Cost minimisation	Cost minimisation	Welfare maximisation
Foresight	Myopic	Myopic	Flexible
Technological Change	Exogenous	Mixed	Exogenous
Geographic Scale	Global - 32 regions	Global	Global - 11 regions
Climate System	HECTOR	MAGICC	MAGICC
Land System	(integrated)	PJmL	GLOBIOM
Climate impacts/ Adaptation	Yes	–	–

	GCAM	IMAGE	MESSAGEix-GLOBIOM
Limitations	• Complex setup and data requirements. • Less computational detail in some sector-specific processes. • No perfect foresight.	• Extensive data collection required for detailed modelling may pose a challenge for comprehensive coverage across all regions. • The use of soft linking between components may limit interaction detail. • Access may be limited due to licensing restrictions.	• Integrating multiple models demands extensive input data from various region. • High computational requirements and analysis complexity.
Selected works	Chaturvedi and Malyan (2022), Bertram et al. (2021)	van Sluisveld et al. (2016), van Vuuren et al. (2018)	Bertram et al. (2021), Kikstra et al. (2021)

Source: JGCRI (n.d.), PBL (2021), Krey, V., et al. (2020).

Table 2: Integrated Assessment Models (REMIND, WITCH)

	REMIND	WITCH
Developer(s)	Potsdam Inst. for Climate Impact Research (PIK)	RFF-CMCC European Inst. on Economics and the Environment (EIEE)
Country	Germany	Italy
Licensing	Open source	Open source
Programming platform/ language	GAMS, R	GAMS
Solution type	Non-linear Optimisation	Optimisation
Solution concept	General equilibrium (closed economy)	General equilibrium (closed economy)
Solution method	Welfare maximisation	Welfare maximisation
Foresight	Intertemporal	Intertemporal
Technological Change	Endogenous	Endogenous
Geographic Scale	Global - 12 regions	Global
Climate System	MAGICC	DICE climate equations
Land System	MAgPIE	GLOBIOM
Climate impacts/ Adaptation	–	Yes

	REMIND	WITCH
Limitations	• Complex model structure, requiring detailed input data and significant computational resources. • Lacks detailed representation of some behavioural responses. • High level of abstraction can limit its applicability to certain region-specific policy analyses. • Requires proprietary software (GAMS) and solver.	• Assumes full information for an open-loop Nash equilibrium (non-cooperative), which may not reflect real-world conditions (may oversimplify complex geopolitical dynamics). • Climate-system model may offer limited representation of the complexity of mitigation options. • Runs on proprietary software (GAMS).
Selected works	Bertram et al. (2021), Bauer et al. (2020)	ADB (2023), Colelli et al. (2022), Reis et al. (2022)

Source: Luderer, G., et al. (2023), RFF-CMCC EIEE/WITCH Team (n.d.).

Table 3: Energy System Models (India EPS, OSeMOSYS, IESS 2047)

	India EPS	OSeMOSYS	IESS 2047
Developer(s)	Energy Innovation LLC; WRI India	(Consortium)	NITI Aayog; IIT Bombay
Country	US	UK	India
Licensing	Proprietary	Open source	Open source
Programming platform/language	Vensim	Python, GAMS, GNU MathProg	Microsoft Excel
Solution type	Simulation	Optimisation (linear)	Accounting framework
Solution method	System dynamics model/ evaluation of stocks and flows	Cost minimisation	Balancing energy supply and demand
Foresight	–	Intertemporal	–
Technological Change	Endogenous	Exogenous	Exogenous
Geographic Scale	Regional	Customisable	Regional
Emissions	Emissions of 12 pollutants/GHGs	Emissions from fuel-use	GHG emissions from the energy sector only
Land System	CO_2 emissions from LULUCF sector	N/A	Cost and quantity of land and water required are estimated

	India EPS	OSeMOSYS	IESS 2047
Limitations	• Limited by assumptions in BAU scenario and policy settings. • Reliance on system dynamics and underlying assumptions can increase output uncertainty. • Lacks detailed infrastructure modelling, might not capture full policy impacts. • Uses proprietary simulation software.	• Detailed sectoral analysis might be limited by a simplistic representation of real-world energy systems. • Additional tools necessary for a comprehensive analysis.	• Limited by assumptions regarding technological advancements and policy impacts. • Excludes certain GHG emissions; does not fully account for infrastructure costs. • Use of an Excel-based platform restricts computational capabilities for complex analyses.
Selected works	WRI/Swamy et al. (2021)	Aboumahboub et al. (2020), Barnes et al. (2022)	NITI Aayog (2023)

Source: Energy Innovation (n.d.), Howells, M., et al. (2011), NITI Aayog (2023).

Table 4: Energy System Models (Rumi/PIER, TIMES)

	Rumi/PIER	TIMES
Developer(s)	Prayas Energy Group	IEA
Country	India	France
Licensing	Open source	Open source
Programming platform/ language	Python	GAMS
Solution type	Optimisation (linear) and accounting framework	Optimisation (linear)
Solution method	Cost minimisation	Cost minimisation
Foresight	Intertemporal	Intertemporal
Technological Change	Exogenous	Flexible
Geographic Scale	Regional (25 Indian states/ territories)	Global - 16 regions
Emissions	GHG emissions (by fuel) and intensity are computed	Total global emissions by GHG
Land System	N/A	Land-use by commodity/ capacity

	Rumi/PIER	TIMES
Limitations	• Lacks macroeconomic linking between energy demand and supply, preventing assessment of energy tax impacts on demand. • Limited representation of energy carriers. • Potentially unsuitable for long-term projection analysis.	• Requires extensive and detailed input data; complexity and data intensity may limit accessibility for new users. • Runs on proprietary software: GAMS.
Selected works	Prayas (2021), Prayas (2023)	Vaillancourt et al. (2008), Kypreos et al. (2017)

Source: Prayas (2021), IEA-ETSAP (n.d.).

3. GCAM

Global Change Analysis Model (GCAM)[2] is a dynamic, recursive, market-equilibrium-based IAM jointly developed by the Joint Global Change Research Institute (JGCRI), Pacific Northwest National Laboratory (PNNL), and University of Maryland, College Park. It was developed in the late 1970s under a US Department of Energy research program to evaluate the global CO_2 emissions from fossil fuel consumption and is among the first models to compute anthropogenic emissions. Over time, GCAM was expanded in its scope of evaluation by defining linkages between multiple sectors, as illustrated in Figure 1. Through such multi-sector modelling, GCAM brings both human and earth systems together to evaluate the system interactions and dynamics between them, while also allowing users to explore "what-if" scenarios. GCAM has since been used to develop various national and international assessment scenarios, including the present Shared Socioeconomic Pathways (SSPs) used in IPCC assessments.

GCAM is a global model with varied geographical granularity across different systems. It models 32 geopolitical regions in the energy and macroeconomy systems, 384 subregions in the land system, and 235 hydrologic basins in the water system.[3] Since it is largely input-driven, GCAM can be modified to be run as a regional model by increasing the resolution of input data pertaining to a specific geography. Using this flexibility, the region-specific models—GCAM-USA and GCAM-China—were developed to explore national scenarios. GCAM is usually run in 5-year time steps with the goal to perform long-term analyses on global environmental change.

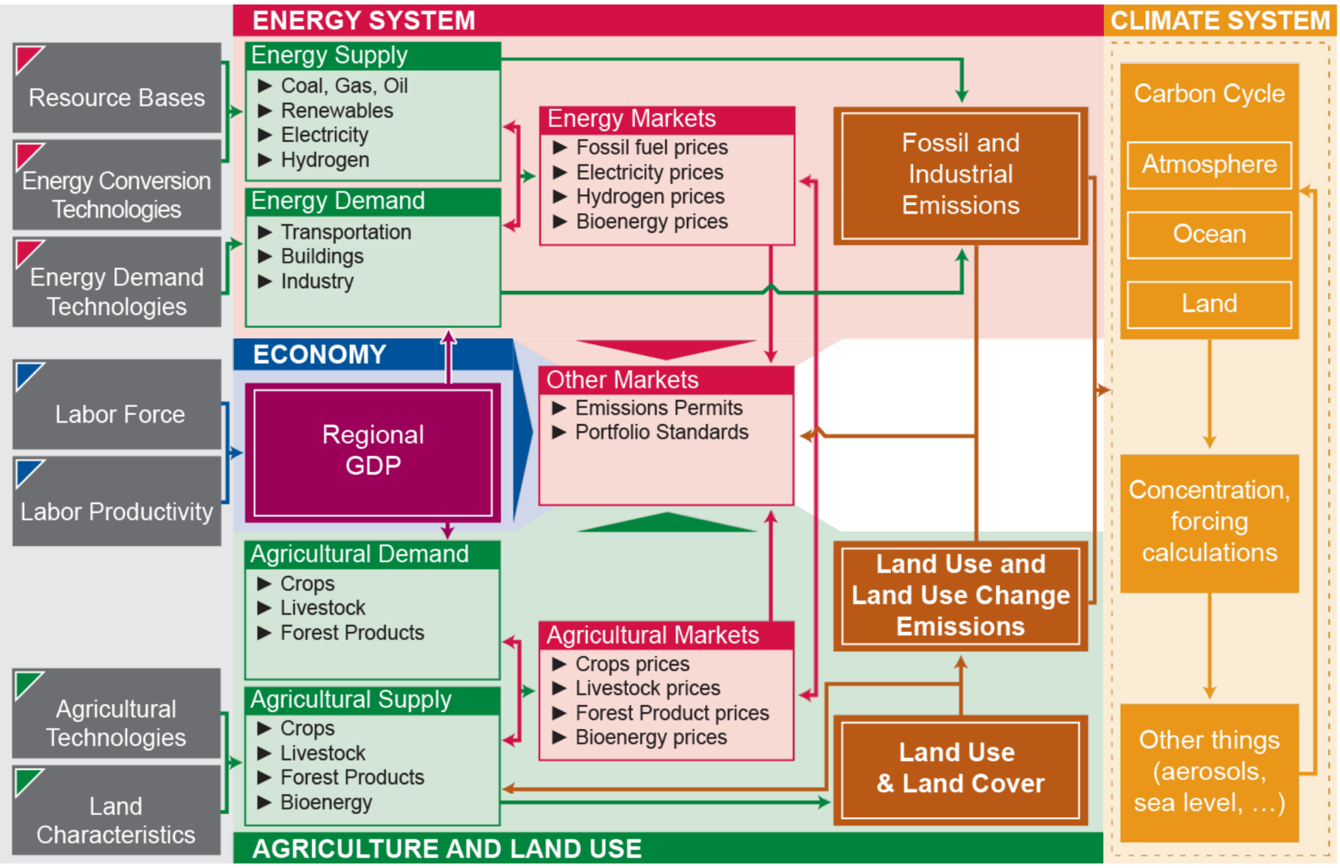
The model is available as an open-source program, developed in C++. The model implementation is data-driven and follows an object-oriented programming approach of C++. It has a modular architecture with GCAM Core at the centre, connected to other modules for data processing and visualisation. Its components are modelled to represent the underlying behaviour of the sectors. Since these components are not modelled as detailed process-scale representations, GCAM has low computational requirements for the exploration of scenarios and uncertainties. Additionally, through an application programming interface (API), GCAM Fusion, users can enable a bidirectional feedback loop between GCAM and any other model of their preference for additional analysis.

The GCAM Core is the main module that solves for the equilibrium state in the markets of various sectors. Five energy-economic systems i.e., energy, macroeconomy, agriculture and land, water, and physical earth systems, are designed as modules that are integrated within the GCAM Core. The five systems have representative agents that utilise the information on prices and other relevant data to determine the resource allocation. These agents interact with each other through markets by indicating their supply/demand for goods and

[2] Website: https://gcims.pnnl.gov/modeling/gcam-global-change-analysis-model

[3] 32 geopolitical regions, comprised of countries or groups of countries, are subdivided into land regions based on agro-ecological zones. The hydrologic basins represent the global river basins (with a few regions such as Antarctica not being modelled).

Figure 1: Structure of GCAM



Source: Global Change Intersectoral Modelling System.

services. The model optimises prices across all the markets iteratively until market equilibrium is reached. Since GCAM is a recursive-dynamic model, it is not aware of the future state before solving the current state i.e., it does not have a perfect foresight. It, therefore, iterates in 5-year intervals to project the future state of the world, facilitating scenario and sensitivity analyses, as well as Monte Carlo simulations. In this process, each representative agent aims to maximise its utility, which is not necessarily a global optimum across the model's time horizon.

The GCAM's energy module comprises energy supply, demand, and conversion technologies, emissions, and energy trading across regions. In the energy supply sub-module, the energy resources, both depletable and renewable, are modelled through resource supply curves that determine the production quantities and the status of resource or its reserve. Various energy conversion technologies that transform primary energy resources into final energy use compete for market share based on costs, which depend on various factors. For instance, in the electricity sector, the costs of generation technologies depend on an exogenously specified non-energy cost, as well as endogenously calculated factors such as fuel cost, emissions costs, and technological characteristics such as conversion efficiency. Several other conversion technologies are modelled, such as refineries that produce single refined liquid products, gasifiers that produce natural gas, coal gas, and biogas, hydrogen production and distribution technologies, etc. Energy trade in coal, gas, oil, and bioenergy is modelled using the Armington[4] approach.

The energy demand is modelled for three sectors viz., buildings (commercial and residential), industry, and transport. Buildings' energy use is characterised by floor space, and fuel and technology choices of consumers, which in turn depend on population, income, population density, etc. The industrial sector comprises six manufacturing (iron and steel, chemicals, aluminium, cement, fertiliser, and others) and three non-manufacturing industries (construction, mining, and agricultural energy use). The physical commodity flows are calibrated using historical data

[4] The Armington model is one of the standard models of international trade, where goods are differentiated by source (region).

from industrial associations. The growth of these sectors is determined using GDP, income, and price elasticities. The transport sector is subdivided into passenger air travel, freight shipping, and other freight and passenger travel, whose demand depends on the income and prices of these services. Through its linkage to other modules, the energy module exchanges data useful for its simulation. For example, linking the energy system module with agriculture and land module enables the computation of the demand for bioenergy. Emissions from final energy use are also computed and passed on to the earth system module.

The macroeconomy module in GCAM sets the scale of economic activity in terms of demand through the macro-indicators like population, per-capita GDP growth of the regions, and labour productivity. The demand for energy, agriculture, and land-use is set to be proportional to the GDP. Earlier, GDP was specified exogenously with no feedback loop from other sectors like energy that affect the GDP output in subsequent time steps. However, in recent versions, the energy output (price, quantity, etc.) affects the GDP endogenously, thereby establishing a two-way coupling between economic activity and the energy sector. The model uses solver algorithms to determine the prices and quantities of commodities, ensuring equilibrium.

The agriculture and land system module covers land-use, forest cover and carbon stocks, land-use change emissions, food production, forest produce, bioenergy, etc. The demand for these products is determined based on population, income levels, and prices. Furthermore, the module is connected to other modules such as the energy system module (for bioenergy) and water module (to estimate water demand from the agriculture and land-use sector).

The water module determines the supply or withdrawal of water, based on its demand from other sectors, i.e., energy, and agriculture and land-use. Three sources of fresh water (at basin levels) are modelled in the module, namely: renewable water, non-renewable groundwater, and desalinated water. Water distribution is modelled by their efficiencies through conveyance losses as well as improvements in distribution.

The climate or physical earth system module is implemented through Hector, an open-source reduced-form global climate and carbon-cycle model. This model helps determine the composition of the atmosphere based on emissions from different sectors and parameters such as ocean acidity and climate. GCAM interacts with Hector through the emissions parameters. At each time step, GCAM passes on emissions to Hector, and the model computes the response of the earth's climate system (radiative forcing). These computations can then be used as constraints in further time steps.

GCAM can be used to explore the implications of various policies such as carbon prices, emissions trading, limits on energy production, land-use constraints (such as protected lands policies), and bioenergy constraints. It enables users to develop a set of scenarios based on certain assumptions and policy interventions, aiding in evaluating the corresponding outcomes. While GCAM has been widely used to conduct country-specific research on climate change mitigation, it has some limitations. Its complex setup and extensive data requirements can limit its accessibility and application in regions with limited data resources. Although GCAM provides detailed insights into many sectors, it has relatively less computational detail in some sector-specific processes. Additionally, GCAM 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. As with any IAM/ESM, the limitations of GCAM highlight the need for cautious interpretation of its results when making policy recommendations.

4. IMAGE

The Integrated Model to Assess the Global Environment (IMAGE)[5] is an integrated assessment model developed by the Environmental Assessment Agency (PBL) to study global environmental and climate change through the construction and analyses of long-term climate change scenarios. Beginning as a single-region (global) model in the late 1980s, IMAGE focused on examining the relationships

[5] Website: https://www.pbl.nl/en/image/about-image

between human activities and climate change using global total and average parameters, such as world population and average emission factors. Subsequent versions have improved spatial granularity and detailed modelling of biosphere, land cover, and land use, resulting in the development and use of sector-specific models such as The IMAGE Energy Regional model (TIMER) and the Model for the Assessment of GHG Induced Climate Change (MAGICC). IMAGE has been used in various international agencies' reports and studies, including the IPCC's Shared Socioeconomic Pathways (SSPs), the UNEP's Global Environment Outlook, the OECD's Environment Outlook, etc.

IMAGE comprises of two subsystems: the human (or socioeconomic) system and the Earth system, which are interlinked, enabling the evaluation of the impacts of anthropogenic activities on the environment and vice versa. The human system includes agriculture and land-use, and energy supply and demand modules, while the Earth system consists of land, atmosphere, and ocean modules. The human system is modelled for 26 global regions based on their environmental and geo-economic significance and relative commonalities. The Earth system is modelled at different levels of spatial granularity: a) land use related systems are modelled on a 5x5 minutes grid, and b) carbon and water cycles, and plant growth are modelled on a 30x30 minutes grid. Both systems are simulated with time steps of 1 or 5 years to capture long-term patterns and trends up to 2100, though some components, such as electricity supply, have shorter time scales. While the components in the Earth system are fully linked, those in the human system, like the TIMER energy model and MAGNET agroeconomic model, are soft-linked to the framework.

The human and Earth systems are driven by exogenous inputs across various dimensions, including demography, economy, policy and governance, technological development, culture and lifestyle, natural resource availability—these are the same drivers that influence global environmental change. These model drivers are qualitative or semi-quantitative and are made consistent by formulating future scenarios. Demographic variables are determined using UN population projections, which consider fertility, mortality, migration, and more. Population is further broken down by economic classes, gender, rural-urban, education, etc., which determine the consumption patterns. The granularity of these projections can be scaled down to the grid level. Economic activity is measured through GDP per capita, which can be further resolved into the average income of the population according to urbanisation levels, quintiles of income levels, etc. Policy and governance drivers determine the priorities of the governing entities by giving different weights to short-term monetary gains and long-term sustainable development. The technological development driver is linked to economic growth, and vice versa; however, the pace and direction of various technologies may vary. The culture and lifestyle of a region can determine the composition of demand in various sectors. And finally, the quantity of resources available in the future depends on assumed future technological capabilities to extract such resources, and policy preferences.

In the human and Earth systems, the energy module is implemented by TIMER. It is a simulation-based energy system model that determines outcomes from a set of algorithms where the future state of the system is derived from its previous state. It is used to explore scenarios and analyse long-term trends in the energy sector. It has 12 primary energy carriers in the 26 world regions, and three sub-components: energy demand, conversion, and supply.

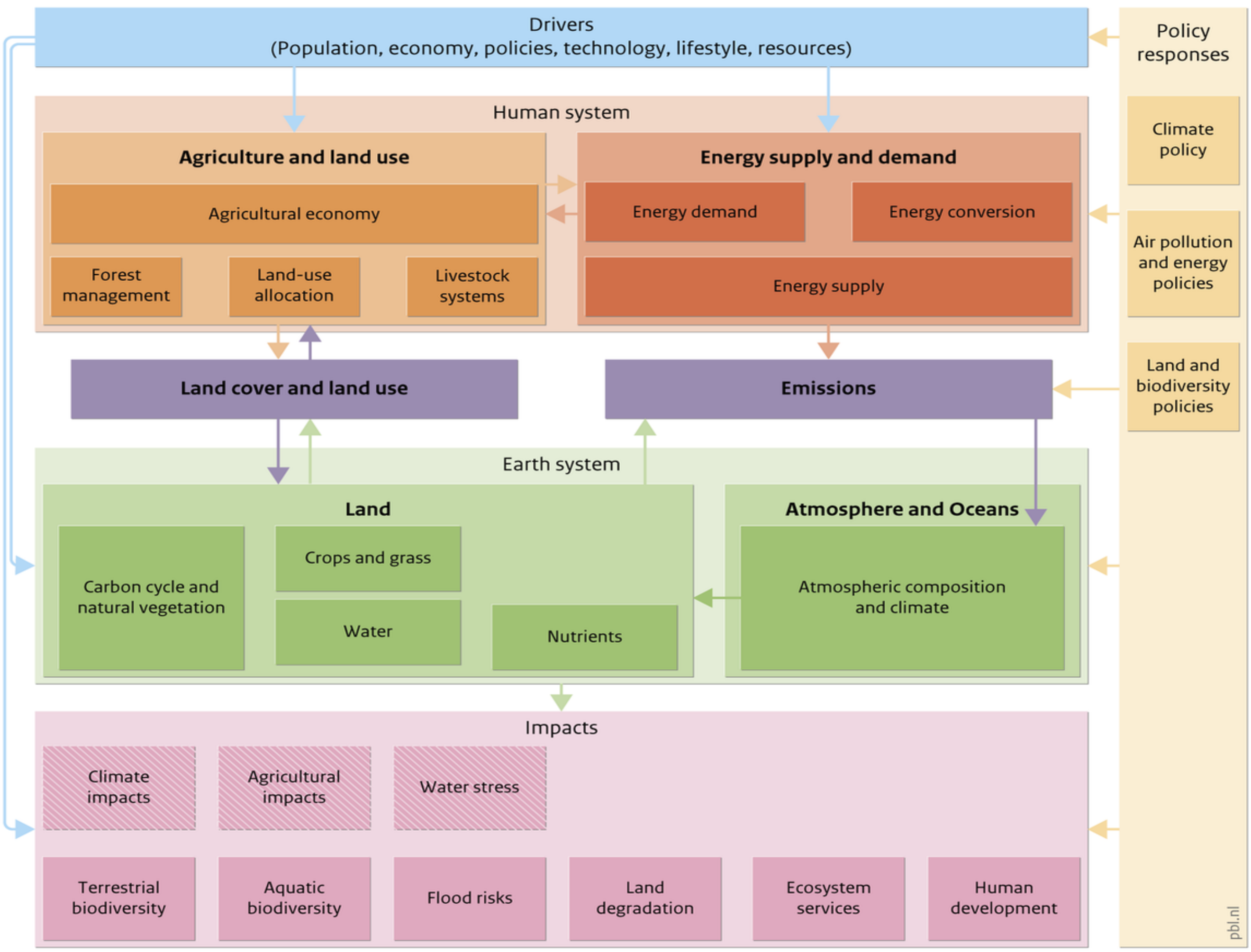
Energy demand is modelled for five sectors viz., residential, industry, transport, private and public services, and others (mainly agriculture). The final energy demand is defined as the product of population, activity per capita, a structural change factor, and energy efficiency improvements (autonomous and price-induced), divided by the weighted sum of end-use efficiency. A multinomial logit model is used to determine the market share of each fuel based on their relative prices. The prices include the cost of production, energy and carbon taxes, and premiums due to environment policies, infrastructure, etc. The transport, residential, and heavy industry sectors are modelled in detail in their respective specific modules.

Energy conversion from primary fuels to electricity and hydrogen is modelled in detail, and for other processes, simple multipliers are used. Both electricity and hydrogen conversion modules include two key elements: investment strategy and operational strategy. Instead of modelling in detail, which would include ramping constraints, costs, reliance, etc., TIMER deploys meta-relationships which are relatively simple to program. New electricity generation capacity requirement, for instance, is determined based on the maximum electricity demand forecast along with a 10% reserve margin minus the existing capacity. The lifetime of generation assets is assumed to vary between 30 to 50 years. The model uses a multinomial logit function in which larger market shares are assigned to lower-cost technologies. Accounting for limitations in supply, a few constraints are endogenously added. Twenty types of power plants that use fossil fuels, nuclear energy, biomass, or renewables, are included. The costs of nuclear power and renewable energy (solar and wind) are computed using learning curves and long-term cost supply curves. Additional system integration costs include backup capacity, costs of electricity curtailment, and additional required spinning reserve.

In the energy supply subsystem, resource depletion (a function of cumulative or annual production) and technology development (learning curves) together constitute the long-term dynamics of energy supply. Energy carriers are widely traded across regions such that demand is always met. The primary fuel prices determined in this module affect the investments in the energy conversion and end-use modules. Land use for bioenergy production, emissions of GHGs, etc., is modelled through linkage with other components within IMAGE.

The agricultural economy in the agriculture and land-use subsystem is modelled through MAGNET (a CGE model) and is soft-linked to the IMAGE core. The drivers in MAGNET include changes in demographics and income levels. The agricultural sector supplies both domestic and other markets through trade in response to demand. It utilises

Figure 2: IMAGE 3.0 Framework



Source: PBL.

information from IMAGE on land availability, changes in agricultural productivity due to climate change, etc. The results of production and yield are utilised in IMAGE to determine land use, effects on the nutrient, carbon and water cycles, climate, and biodiversity. The module allows restrictions on the use of specific land-types, the imposition of taxes, or the provision of subsidies, etc., to evaluate the impact of different policies. Interactions between crop and livestock production are modelled in IMAGE's livestock systems module. Livestock production and its consequences on environment and land such as expansion of grazing land for feed crop production, increases in non-CO_2 GHG emissions from livestock rearing, land degradation, compensatory afforestation, etc., can be analysed with the help of this module.

Forest cover and forestry are also modelled in the IMAGE framework. Three forest management systems are defined viz., clear cutting or felling, selective logging, and forest plantations. Timber demand drives forest harvest. External models are used to make assumptions on the production and trade of logs and pulp, and the domestic demand for fuel wood is taken from TIMER.

The land-use allocation module determines locations for new agricultural areas which are identified based on the vegetation type removed, the amount of carbon emitted, and changes in biodiversity due to the loss of vegetation. Other factors such as the impact of agriculture on nutrient and water cycles, soil properties, composition of landscapes (biodiversity effects, wind and water erosion, hydrology, and ecosystem services), etc., also help determine land-use allocation. IMAGE uses two methods to analyse land-use allocation in detail: a simple regression-based method and a sub-model that represents land systems in greater detail.

Interaction between the human/socioeconomic system and the Earth system occurs through the emissions module and the land cover and land use module. In the land cover/land use module, crop cultivation, livestock grazing, timber production and bioenergy, shelter and housing, mining, transportation, and infrastructure are some of the examples of land use from human activities. These activities cause GHG emissions and air pollution affecting the environment and the climate. Mitigation pathways and strategies are explored using a soft-linked model, FAIR, which uses data such as baseline emissions, reforestation potential, etc., from IMAGE and feeds the results back into it.

The Earth system module represents the physical processes of the Earth. It is used to determine the carbon cycle, natural vegetation dynamics, crop, and grass production at the grid cell level, using inputs such as soil types, climate, and management. In addition to this, a hydrology module is included that simulates changes in water availability, water demand, and stress. Water demand is computed using evapotranspiration requirements, population, economic growth, electricity production, etc. To determine atmospheric composition in the climate module, an adapted version of MAGICC is used to compute changes in global mean temperature, concentration of GHGs, etc., which vary by geographic regions.

The social and ecological impacts of climate change and global environmental change are computed in IMAGE either endogenously or through external models developed by PBL, such as GLOBIO (to assess biodiversity loss), GISMO (impact on human development), and GLOFRIS (to assess water stress, flood risk). The impact on human development is evaluated using indicators such as hunger, disease burden (based on age and gender), millennium development goals, etc. A nutrients model is used to determine the nutrient surplus in fresh water and topsoil from key drivers such as nitrogen fixation, use of fertilisers, the availability of proper sanitation systems, wastewater treatment, etc.

The IMAGE model is adept at modelling the interplay between human and Earth systems but is not without limitations. Its extensive data requirements pose a challenge in providing uniform, detailed results across all geographical areas, particularly when data for certain regions are scant. The soft linking of components within the model can limit the resolution of interaction details, resulting in simplified representations of complex systems and interdependencies. Additionally, restrictive licensing may impede its accessibility and further development, limiting its widespread use. Despite these limitations, owing to the broad range of its sub-models, IMAGE is extensively applied in policy impact evaluation, not only for climate and energy but also across fields such as land use, biodiversity, human development, and ecology.

5. REMIND

The REgional Model of INvestments and Development (REMIND)[6] is an open-source mathematical model of the energy-economy system developed and maintained by the Potsdam Institute for Climate Impact Research (PIK) in Germany. It is a modular, multi-regional model of the world that incorporates the economy, the climate system, and the energy sector. It can also be integrated with a land-use model, MAgPIE,[7] to incorporate the land use, land use-change, and forestry (LULUCF) sector. REMIND provides an integrated assessment of the human and earth systems and explores self-consistent transition scenarios spanning from 2005 to 2150.

REMIND is a general equilibrium model, linking a macroeconomic growth model (Ramsey-type) with a bottom-up energy system model. The General Algebraic Modelling System (GAMS) serves as its implementation platform. The model identifies an intertemporal Pareto-optimal solution in economic and energy investments across the 12 regions defined in the model. It describes different fuels and energy conversion technologies and represents the trends of economic growth, cross-border trade in final goods, primary energy, and emissions credits.

The macroeconomic core of REMIND is an optimal growth model with perfect foresight of economic agents and the internalisation of external effects. The model non-linearly optimises intertemporal global welfare to derive region-specific transformation pathways, subject to market-clearing and sustainability constraints. A decentralised market outcome is obtained through iterative solutions by the model. This approach is suitable for describing long-term economic growth patterns, which are the primary drivers of energy demand and emissions. The model projects growth, incomes, savings and investments, and commodity demand.

The model's macroeconomic production factors comprise capital, labour, and final energy. Final energy demand is determined by a nested production function with customisable constant elasticity of substitution (CES). REMIND uses GDP for investments in the creation of capital stock as well as for consumption, imports, and energy system expenses.

The welfare module enables the implementation of different social welfare functions, while the optimisation module allows selecting between different solution algorithms.

The macroeconomic core and the energy system modules are interlinked by the demand for final energy and the costs of the energy system. Final energy demand (electric and non-electric) is generated by economic activity in different sectors, viz., transport (where transport demand composition is calculated based on the CES function), industry, and buildings (residential and commercial). The power module (for electricity as the energy carrier) determines the operational production decisions related to electricity supply.

The primary energy system representation describes fossil fuels (and nuclear fuels) and renewables (including bioenergy) separately. The cost of extracting a specific quantity of fossil fuel is calculated by the fossil module. The model consists of over 50 technologies that transform energy and distribute secondary energy carriers.

All anthropogenic greenhouse gases (long- and short-lived) and air pollutants (aerosols) are described by type and origin in the model. They are linked to anthropogenic activities in the global system: CO_2 to fossil fuel use, CH_4 to the extraction of fossil fuels and domestic energy consumption, and N_2O to source-specific energy supply. F-gases and land-use change emissions are exogenously specified based on SSP scenario and global warming targets.

REMIND considers important factors that contribute to the inertia and path dependencies of the energy system, such as capacity vintage structure, technical learning curve for new technologies, and the costs associated with fast technology deployment. The focus on high technological detail is especially useful in depicting large-scale adoption and integration of new technologies and in exploring cost-effective approaches to attaining an exogenously prescribed climate target. It allows analyses of policy measures and technology choices for abating GHG emissions, with several energy sector policies modelled explicitly, such as fuel taxes and energy subsidies.

[6] Website: https://www.pik-potsdam.de/en/institute/departments/transformation-pathways/models/remind
[7] Model of AGricultural Production and its Impact on the Environment

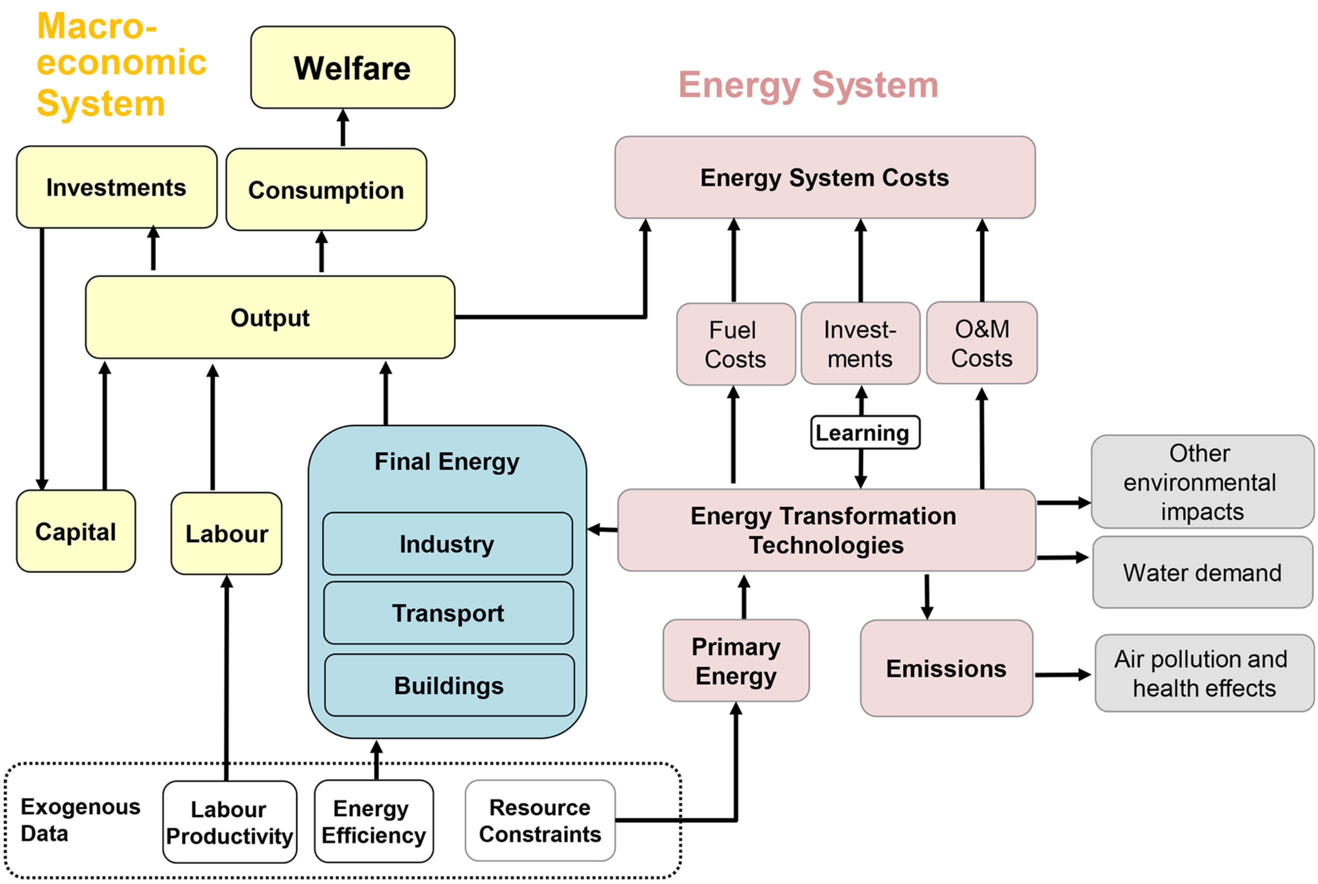
The model, featuring perfect foresight, allows identifying first-best mitigation strategies that can serve as reference scenarios and can be compared against second-best scenarios influenced by regional/sectoral fragmentation or technology limitations.

REMIND is programmed as a collection of modules that collect subject-specific code, with explicit data exchange between modules through well-defined input and output variables. Each module is customisable, facilitating versatile configuration and expansion.

REMIND's spatial resolution is determined by the resolution of the input data, allowing users to conduct region- or country-specific modelling studies. Additionally, its modular structure enables detailed analysis of individual model sections as per the research question. The model's framework can thus be adapted for multiple applications, balancing detail with overall computational runtime and numerical complexity.

REMIND has contributed to the development of the Shared Socioeconomic Pathways (SSPs) used, for example, by the IPCC. Recently, the Network for Greening the Financial System (NGFS)[8] utilised REMIND in conjunction with two other IAMs to construct climate scenarios intended to sensitise central banks to the possible outcomes of global warming, the associated transition risks, and their repercussions on the financial system and the global economy. Similarly, in 2019, the UNEP Finance Initiative published a guide for investors on climate risk assessment using scenario-based methods based on REMIND and two other models.

Figure 3: Structure of REMIND



Source: Baumstark et al. (2021).

[8] Comprising 127 central banks and 20 multilateral institutions and international organisations. Website: https://www.ngfs.net/en

While REMIND is a useful tool for exploring complex socio-economic and environmental interactions, it has some limitations. Its complex model structure requires 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. Furthermore, the high level of abstraction in REMIND's modelling approach may limit its applicability to region-specific policy analysis unless the program is extensively reconfigured to reflect the conditions of the region in question. Additionally, REMIND's implementation using GAMS and CONOPT, both proprietary software, may restrict its use among researchers. These limitations highlight the importance of improving accessibility and critical evaluation when using IAMs for policy analysis and long-term planning.

6. WITCH

The World Induced Technical Change Hybrid (WITCH) model[9] is developed and maintained by RFF-CMCC European Institute on Economics and the Environment. WITCH is a dynamic optimisation model that integrates an intertemporal optimal growth model of the economy, an energy sector representation, a land-use change model, and a climate model to mimic the dynamics of climate change at the global and regional levels.

The model operates by analysing optimal strategies for climate change adaptation and mitigation depending on a region's vulnerability to climate damage and external constraints on emissions, GHG concentrations, or temperature. These optimal strategies, entailing investment profiles, are arrived at by calculating the welfare for each region through a maximisation process that accounts for externalities from other regions. The model uses a Game Theory-based setup consisting of a non-cooperative, simultaneous, open membership game with full information that iteratively produces the open-loop Nash equilibrium. Further, WITCH allows for endogenous depiction of R&D diffusion and innovation processes, which means the model can assess the impact of R&D investments on mitigation.

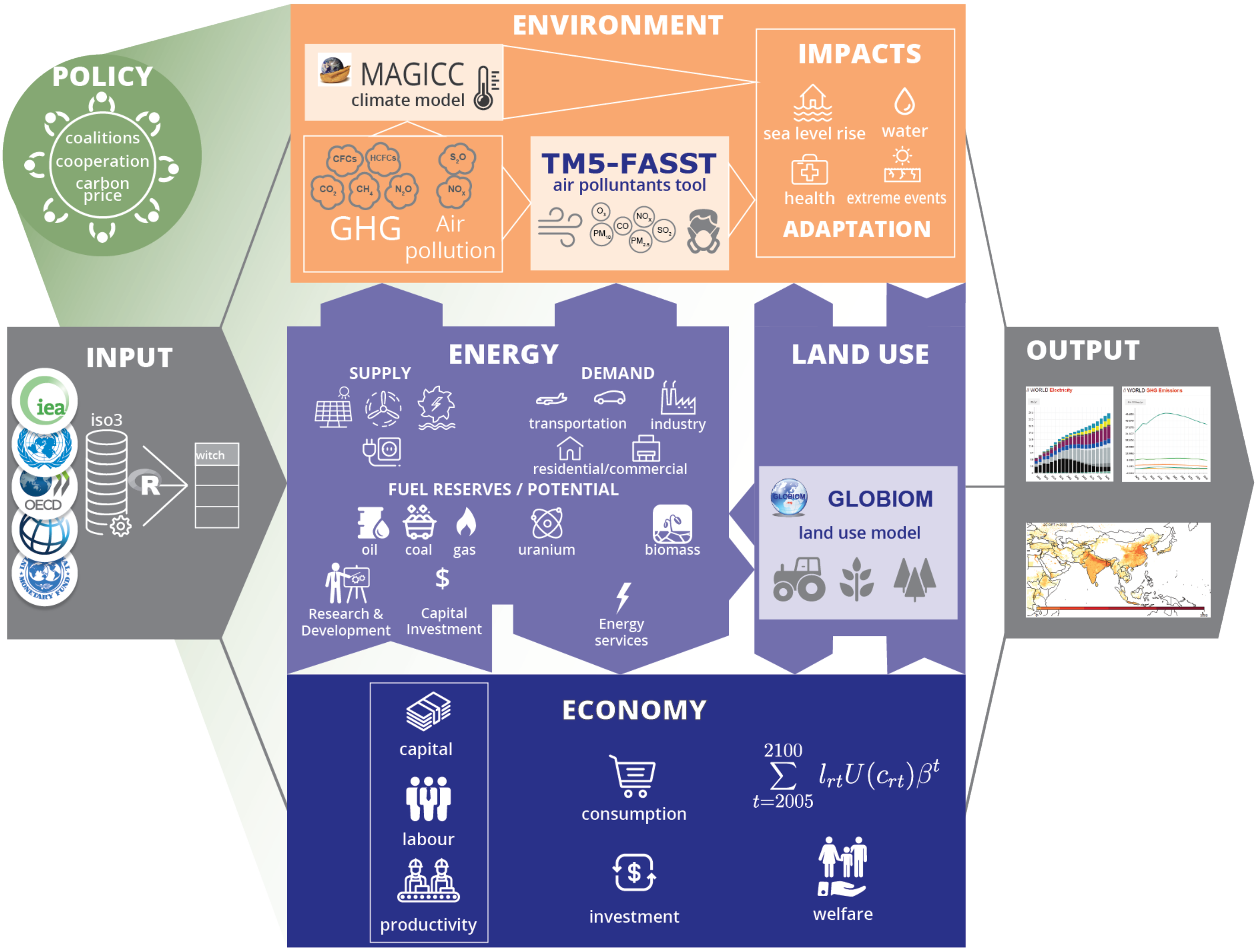
The scope of the WITCH model covers the following components: the energy sector, land-use sector, greenhouse gas emissions and air pollution, regions, coalitions, and time horizon. The energy sector includes coal, oil, gas, uranium, and bioenergy as primary sources of energy, while electricity is a secondary source. The GLOBIOM model is linked with WITCH to emulate the land use and forestry sector. There is either endogenous or exogenous modelling of many emission types such as CO_2, CH_4, N_2O, F-gases, SO_2, VOC, etc. WITCH also includes provisions for emissions mitigation like energy efficiency improvements, substitution of fossil fuels, CCS, etc.

WITCH has global coverage and is represented by 13 regions, which are categorised depending on geography, income, and structure of energy demand. By default, each region is empowered to solve its own optimisation program; however, regions can cooperate to form coalitions and maximise their joint welfare. Coalitions states can exist anywhere from no cooperation to full cooperation. The intertemporal social welfare is solved based on the game-theoretic setting described above, resulting in optimal investment profiles for various technologies when Nash equilibrium is achieved. The time horizon of WITCH spans 150 years, divided into 30 periods of 5-year time steps, with the base year starting in 2005 and economic values expressed in 2005 US dollars. The years 2005, 2010, and 2015 have been calibrated with historical statistics for energy and economic factors.

The WITCH economy is driven by the classic concept of a social planner maximising the sum of discounted utility for each of the coalitions modelled. This is either done in a non-cooperative setting using a regional intertemporal utility function that incorporates a degree of risk aversion, or in a cooperative setting in which aggregate welfare for all coalition members is maximised while accounting for inequality aversion. In WITCH, the utility function is based on per-capita consumption of the regional representative agent, and total consumption incorporates net output, investments, and operation and maintenance costs. Each region produces a single commodity for either consumption or investment. Nested CES functions, which integrate factors such as capital, labour, and energy services, then determine net output and economic costs, including those related to climate change impacts and mitigation efforts.

9 Website: https://www.witchmodel.org/

Figure 4: Components of the WITCH Model



Source: RFF-CMCC European Institute on Economics and the Environment.

In WITCH, endogenous enhancements in energy efficiency are permitted because energy services depend on the physical energy input and a stock of energy efficiency knowledge. To align the model's projections with real-world scenarios, the calibration relies on population forecasts, GDP projections, income elasticity, etc. WITCH's dynamic calibration module then iteratively calibrates total factor productivity, GDP, and total primary energy demand, as these factors change over time.

An energy sector model is at the core of WITCH, featuring techno-economic features such as annual utilisation factors, fuel efficiencies, investment, O&M costs, and capital depreciation. Energy is derived either from electricity (using some technology options) or from non-electric fuel sources. The technologies covered in the power sector include traditional thermal technologies like natural gas combined cycle power plants and coal power plants, as well as carbon-free/non-fossil options like nuclear and hydro, etc. Non-electric technologies also modelled include biomass/biofuels, oil, gas, and coal. This sector encompasses transportation, industrial, and residential and commercial energy use sectors.

A crucial aspect of the modelling paradigm of WITCH is its treatment of endogenous technological change. It dissociates economic activity from environmental degradation through technological innovation and diffusion, induced via R&D investments in energy efficiency and low-carbon technologies. Returns on R&D investment are evaluated using the stock of accumulated knowledge, which is influenced by international knowledge spillovers. The higher the stock of accumulated knowledge, the greater the innovation in energy efficiency. In WITCH, cost reductions in technologies are modelled using a two-factor learning curve that considers both knowledge accumulation (learning-by-researching) and experience (learning-by-doing) through R&D investments and the global cumulated installed capacity, for example, of backstop technologies. However, in certain cases such as wind, solar, vehicle batteries, etc., a one-factor learning curve considers either learning-by-doing or learning-by-researching, with cost reductions driven by technology deployment.

Fossil fuel resources, such as oil, coal, and gas are modelled separately in WITCH. Oil production requires the availability of extractive capital amassed through investments, which decrease exponentially. There are limitations placed on the production of oil based on available regional extraction capacity, which accumulates over time but is depreciative in nature. The extraction of coal and gas is governed by curves depicting the relationship between cumulative extraction and the cost of producing these fuels, called fossil fuel availability curves. These curves balance the global production and consumption of fossil fuels to facilitate trading. Lastly, the model only considers emissions from oil extraction and not from that of coal and gas.

To account for land-use change emissions, WITCH uses a partial equilibrium model named Global Biosphere Management Model (GLOBIOM). It assesses the interplay between agriculture, biomass energy, and forestry using mean response functions. GLOBIOM divides the world into 30 economic regions and solves economic optimisation problem using regional price-quantity equilibrium. It simulates land use scenarios by modelling consumer behaviour, agricultural and forestry production systems, livestock production activities, types of land and their transformations, crop yields, the use of fertilisers, pasture productivity, and food waste and agricultural losses. The WITCH model interacts with GLOBIOM mainly through supply curves, linking the production of woody biomass levels to production cost while incorporating the price of land-use related CO_2 emissions.

In WITCH, GHG emissions (CO_2, CH_4, N_2O, and short- and long-lived F-gases) and their impact on climate are addressed through a climate module which accounts for emissions from fossil-fuel combustion in the power sector, transport, heavy industries, from land-use change. The cost of emissions is modelled either using a carbon tax or permit prices or using marginal abatement curves in the case of non-CO_2 GHGs. The climate module converts regional emissions to changes in atmospheric concentrations of GHGs and global temperature using DICE climate equations (Nordhaus and Sztorc 2013). Additionally, an air quality module maps pollution-causing economic activities to emission levels of major air pollutants through emission factors aggregated over the WITCH regions. Emissions from non-energy-related pollution are mapped exogenously.

The economic impacts of climate change are modelled in WITCH using regional reduced-form damage functions. These damage functions connect the rise in global mean temperature above pre-industrial levels to shifts in regional GDP. This method allows for the computation of economic damages as a percentage of GDP and employs adaptation as a measure that reduces the extent of damage caused by a temperature increase. The model includes various impact categories such as agriculture, coastal impacts, health, settlements and ecosystems, other vulnerable markets (energy), and catastrophic events. The adaptation module calibrates adaptation costs by gathering regional data on the costs and benefits of adaptation actions in each impact category. Costs are categorised as proactive, reactive, or specific to capacity expenditures. Proactive adaptation measures are considered for agriculture, settlements and ecosystems, and coastal impacts, meaning that defensive capital should be in place before damage occurs. For other vulnerable markets (such as energy) and health, reactive adaptation is assumed to address residual damages from climate impacts that adaptation/mitigation measures failed to address. However, catastrophic events have very low adaptation potential. Lastly, building specific capacity includes investments in infrastructure, education, early warning systems, and R&D expenditure in the agriculture sector. The effectiveness of adaptation measures varies by region and category. Considering these factors, the model estimates adaptation costs, protection levels, and net damages.

The WITCH model has some limitations. Its assumption of full information for an open-loop Nash equilibrium (non-cooperative) may be an oversimplification of the real-world geopolitical dynamics. This could lead to unrealistic outcomes and undermine the model's ability to capture complex dynamics. Additionally, the model's reliance on the Nordhaus and Sztorc (2013) climate system may provide limited representation of mitigation options and their interactions with broader socio-economic systems. The use of proprietary software (GAMS) also limits its use to a few researchers.

Through its game-theoretic foundations and endogenous technological change modelling, the WITCH model provides a novel method to assess climate policies. For example, using this model, one can conduct a non-cooperative simulation of tradeable market permits or systematically model a carbon tax schedule. Similarly, by leveraging the coalition setting in this model, one can simulate a cost-benefit analysis of endogenous policy implementation that accounts for damage feedback and externalities across a group of countries. The model was used to implement the five Shared Socioeconomic Pathways (SSPs) of the IPCC, which form the foundation for a baseline, and four scenarios aligned with the previously-used Representative Concentration Pathways (RCPs), indicating four different radiative forcing outcomes at the end of the century. Policy architecture called Shared Policy Assumptions (SPAs) incorporates different approaches to policy implementation, such as immediate global action versus delayed action, which can vary across regions and SSPs. The SSP implementation results reveal differences in primary energy supply, emissions, and policy costs across different scenarios.

7. MESSAGEix-GLOBIOM

MESSAGEix-GLOBIOM[10] is a global integrated assessment framework developed by the International Institute for Applied Systems Analysis (IIASA) in Austria. It consists of various sector-specific standalone models such as the energy systems model called Model for Energy Supply Strategy Alternatives and their General Environmental impact (MESSAGE), the macroeconomy model named MACRO, the emissions model named GAINS, the climate model named MAGICC, the land-use model called GLObal BIOsphere Management (GLOBIOM), and the forestry model named G4M. These models are linked with one another and interact throughout the simulation period. MESSAGE was developed as an energy systems model in the early 1980s and later other modules were integrated with it through IIASA's ix modelling platform (ixmp). The MESSAGEix-GLOBIOM framework has been used in developing various scenarios, including the recent Shared Socioeconomic Pathways (SSPs) of the IPCC (Dellink et al., 2017; Samir and Lutz, 2017; McCollum et al., 2018). It is a global model with 11 geographic regions and has a multi-year time horizon from 2010 to 2100, with 5-year time steps. It can operate with either perfect or limited foresight, and optimisation is carried out for one period at a time.

MESSAGEix-GLOBIOM is an open-source model developed in several programming languages such as GAMS, R, and Python. Tools such as ORACLE and REST API are used for scenario data management through database architecture, and for standardised data exchange using web services, respectively. It also has a web-accessible user interface[11] for scenario management and data analysis of the results.

MESSAGE is a deterministic linear optimisation-based energy systems model used for scenario simulations, policy analyses, and planning. It solves a least-cost optimisation problem i.e., minimising total system costs, which include capital costs, fixed costs, operating costs, penalties, etc., of various technologies and resources while subjecting it to physical, economical, and environmental constraints. It models various components of the energy system such as primary resources, generation technologies, conversion technologies, transmission and distribution systems, imports and exports, and various sectors of energy demand such as households, industry, and transport.

The resources submodule of MESSAGE consists of resources such as fossil fuels (coal, petroleum, and natural gas), nuclear, renewables, and biomass. These are modelled through assumptions based on exogenous inputs from various public sources. The availability of these resources, which vary by regions and socioeconomic conditions, is aligned with the SSP framework. In addition to primary resources, fuel blending is modelled to better reflect the emissions and sector- and end-use-specific constraints on the blended fuel.

The conversion technologies in MESSAGE are modelled using mathematical representations of economic, technical, environmental, and socio-political characteristics, such as capital costs, conversion efficiency, emissions rates, and limits on activity. Various types of conversion technologies, including heat and electricity generation and hydrogen, are considered in the module. Add-ons to technologies can be modelled to include additional functionalities (e.g., combined heat and power plant, CCS).

[10] Website: https://iiasa.ac.at/models-tools-data/messageix
[11] Accessible at: https://data.ene.iiasa.ac.at/engage/

Grid infrastructure in MESSAGE is modelled by region, accounting for costs (capital stock and turnover) and losses. In the case of gases that need to be liquified, the liquefaction and regasification processes are also modelled, in addition to the transport infrastructure. To maintain system reliability, reserve capacity is modelled as a function of the average load. To ensure sufficient reserve dispatch, dynamic shadow prices are applied to renewable generation capacity investments. These prices are determined based on the total installed renewable generation capacity, the conventional power that can be used as a reserve, and demand-side reliability requirements.

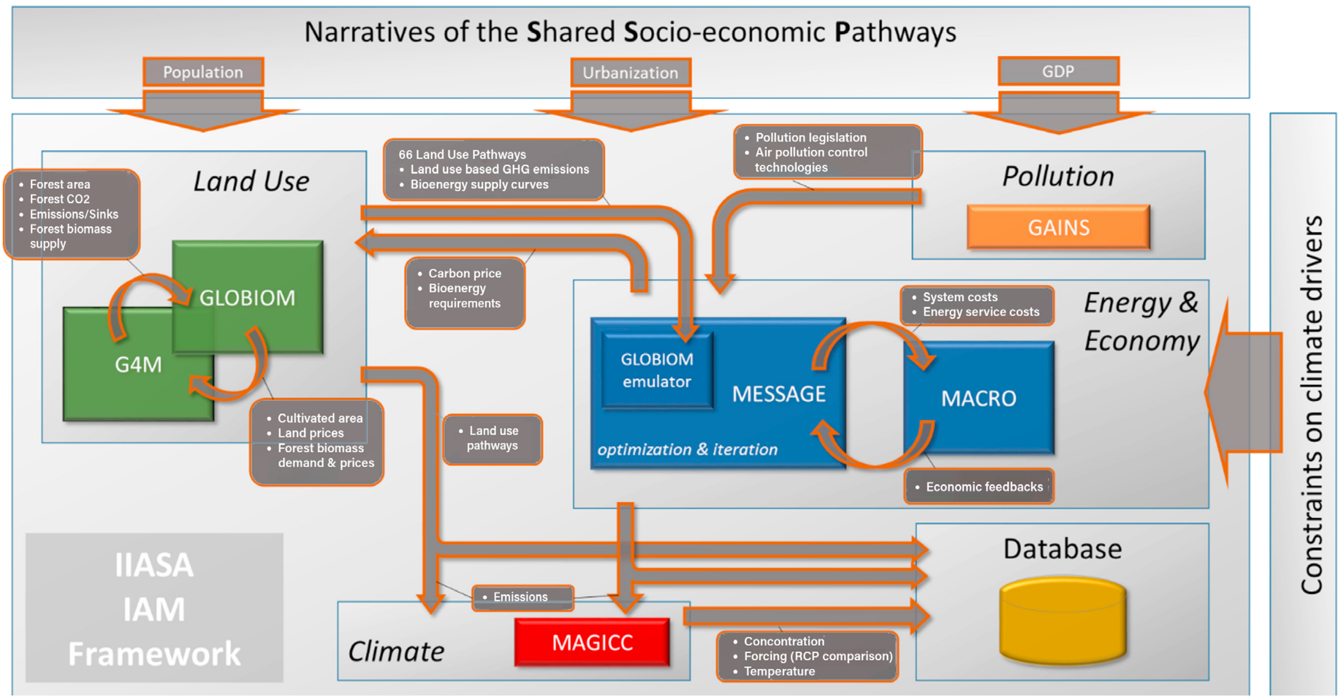
The energy end-use module contains various sectors such as residential and commercial buildings, industry, and transport, where end-use is categorised into thermal and specific (electricity) energy. Demand changes iteratively through fuel switching in response to price changes via the linkage with the MACRO model. In the industrial sector, the demand for steel and cement is modelled by linking it to industrial activity. In the transport sector, different fuel efficiencies, modal splits, transitions, and behavioural changes are provided endogenously in the demand projection by the scenario generator. Limitations in the supply chain due to infrastructure constraints and the rate of technology diffusion are reflected through constraints on the fuels.

Technological change, including costs and diffusion, can be provided exogenously, or determined endogenously. The cost of technological development is aligned with that of the SSP narratives. The diffusion of technology is modelled using dynamic constraints based on the lifetime, type, and activity level of the technology in various time intervals. Technology diffusion can be accelerated by incurring additional costs.

MACRO is a single-sector macroeconomy model that iteratively interacts with MESSAGE. It uses the energy supply costs determined in MESSAGE to compute the final energy demand by solving an optimisation problem i.e., maximising the intertemporal utility function of a representative producer-consumer in each region. In the absence of price changes, the main drivers of change in energy demand are GDP growth rates and the rate of energy intensity reduction.

Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) is a standalone emissions and air pollution model that determines pollution trajectories and parameters under various scenarios provided as exogenous inputs to the model. The projections of energy use, industrial production, agriculture, etc., determine the pollution trajectories which are then used as inputs in the MESSAGEix-GLOBIOM framework. In addition to GAINS, other emissions such as crop sector emissions, livestock emissions, and land-use change emissions are computed in the GLOBIOM module (Figure 5).

Figure 5: MESSAGEix-GLOBIOM



Source: Fricko et al. (2017).

GLOBIOM

GLOBIOM is a partial equilibrium model that focuses on land-use dynamics. It has been in development since the late 2000s by IIASA. The model represents the agriculture, forestry, and bioenergy sector, and covers grid-level details on biophysical constraints, as well as environmental and other AFOLU (Agriculture, Forestry, and Other Land Use) parameters. GLOBIOM has a bottom-up development structure, with a detailed geographic resolution of about 5 to 20 arcmin pixels (grid layout). The model is recursive dynamic and can iterate through to 2100.

GLOBIOM and G4M (forestry model) together simulate the dynamics of the AFOLU sector in the MESSAGEix-GLOBIOM framework. The main objective is to maximise consumer and producer surpluses by computing market equilibrium for agricultural and forest products through the allocation of land use among various activities, subject to constraints on resources, technology, and policies. Initially, the model was developed for the analyses of the impact of climate change on agriculture and forestry, and vice versa, and determining mitigation strategies. However, in recent times, GLOBIOM is also being used to evaluate agricultural and timber markets foresight, adaptation strategies, etc.

The link between MESSAGE and GLOBIOM is useful in analysing the impact of biofuel production on land use, GHG emissions, etc. Through its linkage to GLOBIOM, MESSAGE accounts for all GHG-emitting/reducing sectors, which include energy, industry, agriculture, and forestry. The CO_2 emissions or removals due to forest management are computed at a 0.5x0.5-degree geographic resolution.

The Model for the Assessment of GHG Induced Climate Change (MAGICC) is a carbon-cycle model that projects various climate change-related parameters, such as the composition of GHGs in the atmosphere, radiative forcing, air pollutants, and global average surface air temperature. It is a global model that allows analyses of various mitigation policies, including their cost estimation. Technology-specific air pollution parameters used in MESSAGE are derived from MAGICC. The MESSAGEix-GLOBIOM and IMAGE IAMs use MAGICC to evaluate the change in global mean temperature for determining the effect on the environment. The comprehensive modelling framework thus lends itself as a reliable tool for the assessment of various policy measures and actions for climate change mitigation, albeit with some limitations, such as extensive input data requirements across regions due to the complex integration of multiple models and high computational requirements to perform analyses.

8. EPS India

The Energy Policy Simulator (EPS)[12] is a system dynamics model originally developed by Energy Innovation LLC, which was adapted for India in collaboration with the World Resources Institute (WRI) India, resulting in the EPS India model. It is a free-to-use computer model developed in a proprietary program called Vensim, designed for creating and simulating system dynamics models. EPS India allows simulation of different energy and climate policy scenarios within the Indian national context, enabling policymakers and researchers to assess the cost-effectiveness and emissions reduction potential of policy choices.

EPS India accounting metrics include emissions from 12 different pollutants, changes in governmental cash flows, industry, and consumer choices, changes in the electricity generation fleet, and shifts in fuel usage, among others. The model is designed for national-scale estimations operations and generates outputs at annual intervals from 2019 to 2050. EPS India encompasses major sectors of the economy in its analysis, such as transportation, electricity supply, buildings, industry, and agriculture and land use. Additionally, the model incorporates components like hydrogen supply, waste management, and CCS as sources of emissions or sinks to assess a wide spectrum of energy and environmental policies.

[12] Website: https://india.energypolicy.solutions/

The theoretical foundation of EPS is based on systems dynamics which is a modelling approach focused on assessing the non-linear behaviour of complex systems. EPS India utilises a Business-As-Usual (BAU) scenario based on the IESS 2.0 model projections by the NITI Aayog (2015) and uses it as the base case. The BAU scenario/base case projection is adjusted based on the policy settings assumed by the user.

The system dynamics model driving EPS maintains variables or 'stocks' that vary with time steps according to 'flows' into and out of the variables. The state of the system in any given time step impacts the system's state in the subsequent time step. The stock variables are remembered for every year of the model run, while the flow variables are calculated afresh annually. Stocks track quantities that fluctuate with time and the disparities from the BAU input data, which tend to accumulate as the model runs. This interplay of stocks and flows captures the interactions and feedbacks between the variables over time. Leveraging this, the model evaluates the effects of user-selected policies across sectors, providing insights into key metrics such as cash flows and emissions relative to the BAU scenario.

EPS is conceptually divided into a visible structure, which consists of relationship equations for the variables, and a behind-the-scenes structure, which contains data arrays that serve as inputs for the equations. The model functions by operating through a sequence of sheets that serve as intermediaries in the calculation of the final results. It begins with the "Fuels" sheet, which governs fuels' properties and policies that influence fuel prices. This information is fed to the demand sectors, namely residential, industry, and transportation, which then compute their emissions from direct fuel consumption. These sectors also determine the yearly amount of electricity, heat, and/or hydrogen needed (supplied by the electricity, district heat, and hydrogen supply sectors, respectively). The model also integrates the land use and forestry (LULUCF) sector, which is responsible for incorporating emissions and CO_2 sequestration from activities such as afforestation, deforestation, and timber harvesting. The "Cross-Sector Totals" sheet then accumulates the pollution emissions data from all sectors, while the "Additional Outputs" sheet factors in health outcomes based on changes in pollutant emissions and health incident-per-ton multipliers.

The direct cash flow changes from various sectors are calculated for nine entities (e.g., government, non-energy industries, labour, and consumers), while 36 International Standard Industrial Classification (ISIC) code categories are also used to track cash flows. These direct cash flow impacts are summed in the "Cross-Sector Totals" sheet. The indirect and induced economic impacts through changes in spending habits of households, government, and industries are assessed in the "Cost Outputs" sheet. The direct financial results are input to the EPS' input-output (I/O) model, which estimates the effects on GDP, jobs, and employee compensation. The indirect impacts have feedback loops from the I/O model to the demand sectors, thereby capturing the impact of these economic activities on energy use and emissions outputs. There are two modules that affect the supply and demand sectors. First, users can employ a set of R&D levers to define fuel economy enhancements and reductions in capital costs of technologies. Second, the model incorporates a CCS module to specify carbon sequestration capacity, which impacts emissions. The "Policy Control Center" allows users to manage policy levers. Additionally, an "Endogenous Learning" sheet governs emerging technologies, and the "Web Application Support Variables" sheet facilitates conversion of outputs to commonly used units for the EPS web application. Lastly, the "Debugging Assistance" sheet aids in verifying total calculations that should ideally sum to zero.

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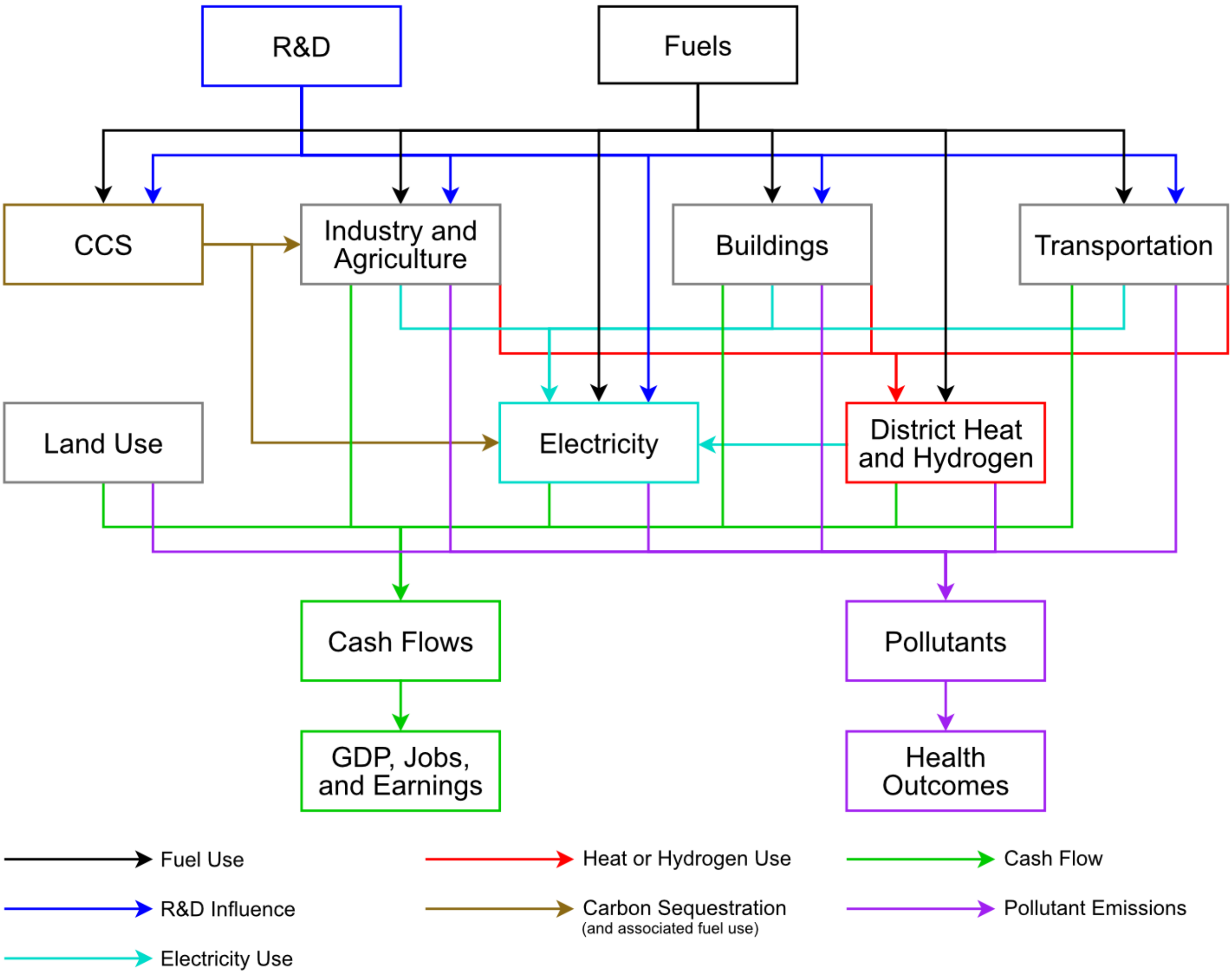
Figure 6: Major Components of the EPS Model (arrows denote the order of calculation)



Source: Energy Innovation LLC.

EPS also features Government Revenue Accounting levers, which let users modify how the government manages revenue. These levers can be executed for governments through mechanisms such as changing regular spending, modifying spending deficit, and changes in various taxes like household and payroll taxes.

Despite its comprehensiveness, the EPS makes several assumptions. An increase in the model's outputs uncertainty is observed with an increase in the number of policies and when there is a significant deviation of a policy scenario being assessed from the policy settings in the BAU scenario. Since uncertainty cannot be quantified, EPS offers a Monte Carlo analysis, enabling users to assess the sensitivity of results to changes in inputs and obtain probability distributions for specific outputs. EPS is not designed to find an 'optimal' set of policy actions to achieve a specific target; instead, it simulates the result and impact of combinations of policy actions. Further, EPS' pricing policies may sometimes get double counted as they interact with other policy levers. To assess the cumulative effects of pricing and non-pricing policies within a package, the model either defines the policy lever as additive to price-induced impacts or specifies it as a floor or ceiling, taking effect only after price-induced impacts. Another limitation is that EPS uses static IO tables from OECD (2018b); therefore, the changes in the structure of the economy or the impact of policies on supply chains are not captured.

India EPS makes additional assumptions regarding input data due to limitations in data availability. As stated above, the I/O model in India EPS derives data from IESS 2.0 and other public databases or publications, and in some cases, it imputes data from proxy sources/variables. Limited to the default 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, its reliance on system dynamics and assumptions may compound uncertainty in the output. On balance, the India EPS model is particularly useful for performing scenario analysis under different policy targets. It also incorporates emerging technologies such as hydrogen, making it versatile for energy policy assessment and design. Its web interface is especially conducive for users without modelling experience to generate custom policy scenarios and project their outcomes.

9. IESS 2047 v3

India Energy Security Scenarios (IESS) 2047 Version 3.0[13] is an Excel-based energy calculator developed in collaboration with IIT Bombay by NITI Aayog to model the energy supply and demand scenarios for India up to 2047. It originally derives from the 2050 Global Calculator developed by the UK Department of Energy and Climate Change. It incorporates recent technological advancements and national policy announcements impacting the energy sector, such as in renewable energy, green hydrogen, carbon capture and storage, grid-scale battery storage, nuclear energy, etc. The model offers various options for creating scenarios based on different assumptions of economic growth, shares of industry, services and agriculture, population growth, rate of urbanisation, final energy demand, energy efficiency, and adoption of different technologies. It enables users to assess the implications of the energy transition on emissions, investments, water resources, and land use.

The model is programmed to let the user choose between four different levels of effort for each sector, called levers. The levels are defined as follows:

- Level 1 - Pessimistic scenario, whereby minimal interventions are expected on either the supply or demand side.
- Level 2 - Business-as-Usual (BAU) scenario, where historical trends are projected to continue across various sectors, absent any substantial increase in effort.
- Level 3 - Optimistic scenario, which presupposes a substantial boost in aspirations and objectives to meet the NDCs.
- Level 4 - Heroic scenario, which postulates extremely ambitious alternatives that are technically achievable for mitigating climate change.

The following industrial sectors are modelled individually in the IESS: cement, iron and steel, aluminium, fertiliser, textile, pulp and paper, and chemicals (chlor-alkali). The rest of the industries were grouped as 'others.' Energy consumption for each industry is analysed by fuel type, including the future inclusion of green hydrogen in the energy mix. A higher level of ambition in this sector implies higher electrification,

[13] Website: https://iess2047.gov.in/

deployment of more energy-efficient technologies, waste heat recovery, better processes, and use of alternate feedstocks (such as green H_2).

Passenger transport demand is tied to economic growth, with passenger-kilometres linked to GDP. This assumes that as an economy develops, there is a growing demand for both inter-city and intra-city transport. IESS considers several powertrains (battery electric, H_2 fuel cell, CNG, and hybrid) across different vehicle categories. Mitigation efforts include switching to electric vehicles, modal shifts in transport (i.e., from private to public modes of transport, particularly railways), and moderated demand for transport because of better urban planning.

Energy performance index, quantifying energy use per unit area, is modelled for different projections of total commercial building floor space, depending on GDP growth rate. The output trajectories under different levers are produced based on the level of penetration of different building types, according to efficiency levels specified in the Energy Conservation Building Codes of the Bureau of Energy Efficiency. Residential housing stock is categorised into economic categories (EWS, LIG, MIG+) for urban and rural areas based on Monthly Per Capita Expenditure (MPCE) data. Average floor space area and electricity consumption per household data are used to calculate energy consumption per unit area.

Energy usage in agriculture is accounted for primarily by irrigation pumps and tractors (both diesel and electric). Energy demand from pumps is modelled based on parameters such as irrigated area, pump set power and efficiency, and annual energy consumption per pump set. The shift to solar pumps is reflected in higher effort scenarios. Energy consumption by tractors is based on fuel consumption per hour and the total number of operating hours per year. In optimistic/heroic scenarios, faster switching to electric tractors is projected.

On the supply side, demand for non-coking coal is assumed to decrease as power generation shifts to other sources, while that of coking coal to increase due to steel production. IESS models the adoption of energy efficiency technologies in coal power plants until 2047, enabling users to estimate coal requirements for desired power supply levels. Ambitious settings imply a higher share of ultra and advanced ultra-super critical plants, yielding higher efficiency of coal power production. The user can also set an equally ambitious lever for Carbon Capture and Storage (CCS), wherein some coal plants are assumed to have CO_2 capture facility. It also allows a similar lever for nuclear power, and higher settings estimate a significant share of nuclear power in India's electricity mix.

The model also includes hydroelectricity, and the capacity utilisation of both large and small hydro plants is assumed to remain at around the levels observed in the past. Higher level of interventions in this area would assume that existing capacity is modernised as more is built to exploit the potential.

In the optimistic scenario, India not only achieves its solar PV target for 2030 (280 GW) but also continues with a more ambitious target for the subsequent years for both utility-scale and rooftop installations. This is supported by conducive policies (such as feed-in tariffs and net metering) and a fall in PV panel costs. In the case of wind, policies make land acquisition easier, engineering and technical challenges with offshore projects are overcome, supporting infrastructure such as power evacuation lines are built at a faster rate, and the cost of taller wind turbines come down.

Besides the above sources of energy, biofuels are also considered in the model, and high effort scenarios assume that the 20% ethanol blending mandate is achieved by the stated target data and is increased further in the following years. In the case of bioenergy-based power generation, future capacity projections assume a higher rate of capacity installation and better conversion efficiency.

The user also gets to choose different levels of cross-border electricity trading. Favourable scenarios assume that the capacity of interconnections with neighbouring countries increases, allowing a higher share of hydropower imported from Nepal and a rise in electricity exchange for balancing needs. Additionally, improvement in transmission and distribution losses can also be set, with higher efforts corresponding to the losses coming down to 7% by 2047, from 20% at present, with the help of better technology such as HVDC transmission lines.

There are also several limitations of the IESS elicited by the developers, such as not considering land-use change emissions from solar PV installation, CCS for industries, growth in T&D infrastructure, or infrastructure for EV charging. In terms of cost calculations, infrastructure costs related to EV chargers, oil refineries, biofuels production, H_2 electrolysers, etc., are not considered in the model. These limitations imposed by technological assumptions can affect the reliability of model projections and policy recommendations and may require additional sensitivity analyses. In addition, while the Excel-based platform is very accessible and relatively easy to use by users without modelling experience, it restricts the computational capabilities of the model, necessitating researchers and policymakers to consider other ESM/IAMs for more complex analyses.

10. OSeMOSYS

OSeMOSYS or Open Source energy Modelling System[14] is a free and open-source optimisation-based energy systems modelling tool that was developed by M. Howells et al. in 2011. 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. With its relatively easier learning curve, OSeMOSYS enables studies on long-term energy planning and serves as a learning tool for early-career energy modelers and researchers.

OSeMOSYS 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. These abstract technologies are defined with properties such as type of fuels/energy used and produced, fixed and variable costs, activity (in terms of energy), and emissions, which feature in the optimisation model in both the objective function and constraints. An energy system is modelled using a reference diagram where the flow of energy (including its transformation and distribution) from the primary source to final consumption is represented as blocks in a flowchart.

Figure 7 shows an example of a reference diagram used to create an instance of an energy system called Utopia.

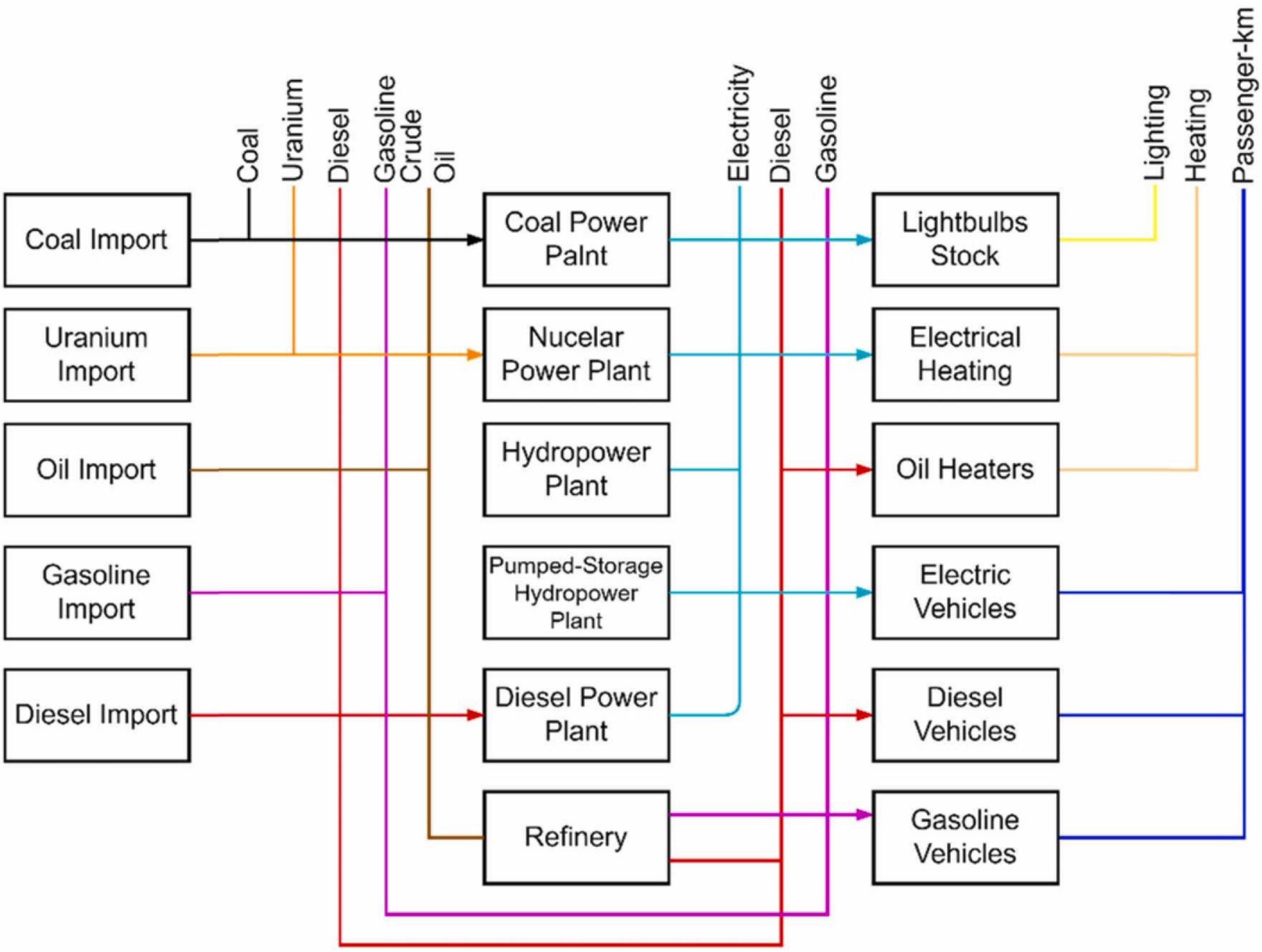
The model functions as a linear program. It is structured in various blocks of functionality such as the objective, costs, capacity adequacy, energy balance, storage, constraints, and emissions. These blocks of functionality can be extended as new features into the model's framework. In addition, the model has customisable spatial and temporal granularity that provides flexibility to have a resolution ranging from hours to years, spread across various geographic regions.

By supplying various parameters as exogenous inputs, several policy options can be explored through the variables and constraints. The linear programming solver optimises the defined objective and determines variables in its solution, such as installed capacity of different technologies, energy dispatched from generators across different time periods, emissions, and costs incurred. Therefore, it is possible with OSeMOSYS to determine factors like investment costs in energy supply to meet the expected demand, the least-cost composition of the energy mix subject to emissions constraints, and annual emissions from the power sector.

OSeMOSYS has been developed in popular programming languages such as GNU MathProg, GAMS, and Python, thereby enabling a widespread adoption by the modelling community. It is published as an open-source software license.

[14] Website: http://www.osemosys.org/

Figure 7: The Reference Energy System (RES) of the Utopia case study



Source: Ramos et al., 2022.

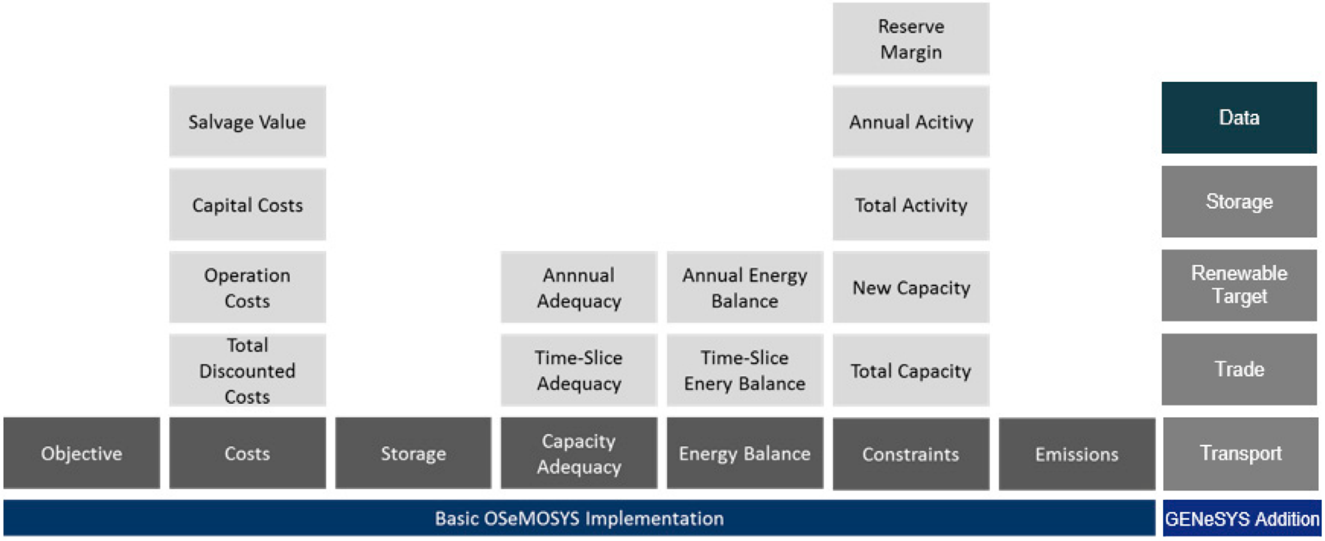
In addition to the core features, additional features have been developed for OSeMOSYS to enable easier pre- and post-processing and adoption. GUI tools such as Model Management Infrastructure (MoManI) (a browser-based UI) and clicSAND for OSeMOSYS have been developed to make the tool user-friendly for non-programmers. A Python-based package called otoole helps users validate the input data and convert it into data formats necessary for the OSeMOSYS GNU MathProg version and provides a module to post-process the results with data visualisation features.

Though OSeMOSYS is developed as an energy system model, it can be linked to modelling tools for other sectors such as macroeconomy, climate, and land use by establishing a feedback loop to and from other sectors. It can also be linked to other tools that can help generate input data for the model or perform further detailed analyses from the outputs generated by the tool. For example, OSeMOSYS Global, which is an open data global electricity system model generator based on OSeMOSYS, is soft-linked with PLEXOS-World, an electricity modelling tool, to understand the operational feasibility of the results generated in OSeMOSYS Global. A stochastic load profile generator is linked to OSeMOSYS to study the variation in optimal capacities and costs with respect to the variation in load (Riva et al., 2019).

Due to OSeMOSYS' highly modular nature, new modelling tools have been developed by extending the features of the base framework. For example, GENeSYS-MOD introduces additional modules or blocks of functionality such as transport sector, trade, losses, and capacities for fuels between regions, as well as modified storages and renewable energy target equations.

OSeMOSYS has been widely used by researchers around the world to design region-specific models and conduct energy planning studies (Barnes et al.

Figure 8: Structure of GENeSYS-MOD (an extension of OSeMOSYS)



Source: Löffler et al., 2014.

2022). The open-source South American Model Base (SAMBA) has been developed to study the long-term power system integration of the South American grid. In this model base, the 13 countries of South America are modelled individually and linked with each other via trade links, to project their energy mix under various scenarios. Similarly, The Electricity Model Base for Africa (TEMBA) is the first electricity model representing each African country's electricity supply and transmission links between them. This work was used in the World Energy Outlook 2014 (IEA 2014). Aboumahboub et al. (2020) have simulated the decarbonisation of the Australian energy system, where they model the country's electricity, transport, and industrial sectors in OSeMOSYS and investigate the impacts of different CO_2 emissions limits on the energy system transformation. Many other similar studies have been performed on countries such as Indonesia, Bolivia, Kenya, Morocco, Brazil, etc. It must also be noted that the trade-off between its simplicity and accuracy has been minimal. In a comparative study conducted by Welsch et al. (2014), an extended version of OSeMOSYS (with increased operational details such as operating reserve requirements and minimum stable generation) performed about 95% similar to TIMES-PLEXOS, which has 700 times higher time resolution.

With its easy-to-learn modelling structure and the availability of different types of versions (GUI, non-GUI, Python, GAMS, etc.), OSeMOSYS has become useful for quickly designing and evaluating energy systems of varied scales and features to help evaluate policy choices for a region. In addition, the open-source development and engaging research forums have made OSeMOSYS a go-to framework among other energy system modelling tools.

While the open-source licence and the simple representation of real-world energy systems make OSeMOSYS an accessible and easy-to-use energy system model, the difficulty of performing detailed sectoral analysis is a limitation. The need for additional tools for data processing and analysis, and external modules (through soft-linkages) for sectoral analysis can be a challenge for new users and might necessitate the use of integrated models for more comprehensive analyses.

11. Rumi/PIER

Rumi is an open-source, demand-oriented energy systems modelling platform for evaluating long-term energy scenarios and policies. It is developed by the 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. Perspectives on Indian Energy based on Rumi (PIER) 1.0 is an India-specific model developed by Prayas for studying the Indian energy sector using Rumi.

Rumi allows users to define any energy system of their choice in terms of spatial granularity, types of energy carriers, consumer types, etc. Programmed in Python, it uses the Pyomo package to solve linear programming problems with solvers like CBC, CPLEX, or Gurobi. The energy system described in the model is an abstract system of technologies that store or transform energy from one form to another. Supply parameters are customisable based on exogenous inputs relating to technologies and energy/fuels provided by the user. As the geographic resolution is user-defined, Rumi can be used to design global models with multiple regions or national models with sub-national regions. PIER 1.0 is a national model on India, with 25 sub-national regions (24 states plus northeast India excl. Assam), modelled for the period from FY21 till FY31, with a time step of 1 year (further divided into five seasons and six 4-hour slices of a typical day in each season). In the newer version (v1.5), the time horizon is increased to FY41, with the initial year being FY24, and the time granularity has been increased to 24 slices (i.e., hourly).

Figure 9 shows the two modules—energy demand and energy supply—of Rumi. The energy demand module is categorised into various sectors: residential, industry, transport, agriculture, and others. Each demand sector can be specified in four different ways:

1). *Bottom-up: Demand is computed using technical specifications of the energy service, technology used to deliver the service, efficiencies, consumer types, etc. The disaggregated energy demand of various types and attributes is aggregated according to the requirement*

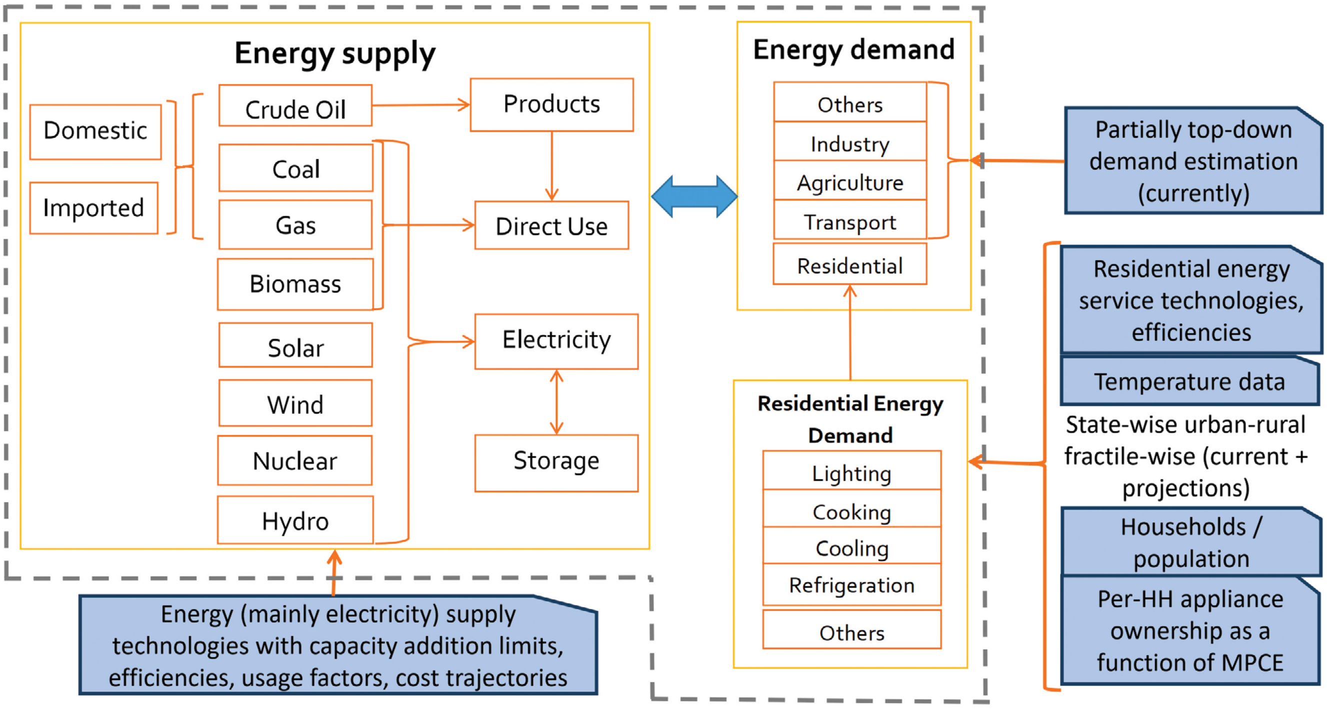
2). *Exogenously: Demand of a particular sector can be specified as a direct input to the model*

3). *GDP-elasticity based: Demand can be projected based on the elasticity of the demand to GDP.*

4). *Residual specification: Demand is calculated as a residual share of the demand for some other services.*

In the PIER 1.0 study, the residential energy demand sector is modelled in detail using bottom-up methodology through parameters such as consumer types based on income levels, urban-rural divide, and end-use demand specifications like service technology penetration and energy efficiency. Five types of energy services are modelled in the residential sector: lighting, cooking, space cooling, refrigeration, and others. Other sectors like transport, industry, agriculture, and others are modelled using GDP-elasticity based specification. With these inputs, Rumi aggregates various demands of the energy carriers with respect to geographical specification

Figure 9: Rumi Architecture



Source: Prayas Energy Group.

and temporal granularity. Public data published by the Government of India have been used as inputs to determine the demand.

Energy supply is modelled using four types of inputs: energy carriers, energy conversion technologies, energy storage technologies, and energy transfers. Prices of various energy carriers are determined based on various assumptions, often through publicly available data such as the World Bank Commodities Price Index, Ministry of Petroleum reports, etc. Energy conversion technologies like generation plants and petroleum refineries are modelled with parameters such as pre-existing capacity, must-add capacity, maximum capacity addition, fixed costs, efficiency, maximum capacity utilisation factor, and ramp rates. Similarly, energy storage technologies and energy transfers are modelled with their associated parameters, based on data from public reports and equations in PIER 1.0.

Using the input data, the model finds an optimal solution for the linear programming problem by minimising the objective function (i.e., cost), subject to various constraints on technologies, fuels, emissions, and other parameters.

While Rumi is adept at addressing certain policy questions in the energy sector, its current version has some limitations. For instance, it lacks a feedback loop between the demand and supply modules and between the energy sector and the macroeconomy, which requires exogenous inputs. This limitation, for example, prohibits the assessment of the impact of energy taxes on demand. The model does not permit the import of derived energy into a region, and the energy conversion module currently represents only single-input and single-output technologies. Furthermore, Rumi has a predetermined temporal granularity, which can be modified by the user but may not be suitable for long-term projections and analysis.

Similarly, in PIER 1.0/.5, only residential demand is modelled bottom-up in detail (i.e., at appliance level), whereas the other sectors are modelled either as GDP-elasticity demand or the demand is provided exogenously by the user. On the supply side, carriers such as biofuels, hydrogen-derivatives, and offshore wind are not represented. PIER 2.0, which is currently under development, is expected to address some of the limitations acknowledged in the earlier versions.

12. TIMES

TIMES, short for The Integrated MARKAL-EFOM1 System,[15] is an advanced energy systems model designed to analyse energy dynamics on local, national, multi-regional, or global scales across different timeframes. Originating from the MARket Allocation (MARKAL) model introduced in 1980 by the International Energy Agency (IEA), TIMES has undergone significant evolution and enhancements over the years. In 2000, the first TIMES model was introduced, combining existing MARKAL capabilities with the ability to handle unequal time periods, a data-driven model structure, and vintaged processes, resulting in an advanced integrated energy system optimisation platform.

TIMES, like MARKAL, has explicit technology definitions and employs dynamic partial equilibrium modelling framework. Both models aim to minimise total discounted energy system cost by maximising the total surplus of both consumers and suppliers through linear programming. However, TIMES allows users to incorporate variable-length time periods and data decoupling, making it more flexible than MARKAL. This enables defining input data independent of the time period used for modelling, while separately specifying time-dependent data with respect to a year. TIMES also supports various time slices, from seasonal to hourly, which any commodity or process can specify. The model has a common set of fundamental features for each process that are controlled exclusively through data specification. Additionally, TIMES enables endogenization of common GHG (CO_2, CH_4, and N_2O) concentrations and computes global temperature variations and radiative forcing arising from emissions.

TIMES operates based on inputs provided by users, including end-use energy service demands, current energy-related equipment inventory, characteristics of potential future technology, and primary supply and capacity details of current and future energy sources. With the input data, the model optimises energy services globally at the lowest cost by concurrently determining equipment investments, operational activities, primary energy supply, and energy

[15] Website: https://iea-etsap.org/index.php/etsap-tools/model-generators/times

trade for each geographic region. TIMES, thus, is a representation of a vertically integrated model of the entire energy system. But it remains adaptable for examining either the entire energy sector or individual sectors like electricity or district heating. The model follows an equilibrium-based approach, ensuring that quantities and prices of commodities align to meet consumer demand, thus maximising the total economic surplus.

The TIMES model is structured around various key components that blend features pertaining to the economy, energy landscape, time, and input data to explore possible energy futures. The energy economy consists of producers and consumers of various commodities like energy carriers, emissions, energy services, etc. While competitive commodity markets are assumed, user-defined explicit constraints (e.g., emissions limits) and price distortions (through taxes, subsidies) can be introduced. TIMES has perfect foresight and operates dynamically as investment decisions for all periods are computed based on full knowledge of future events. The time horizon in the model is flexible, and the user can configure the number of time periods and intervals. In the standard TIMES model, the years within each period are typically assumed to be identical. The first period has fixed quantities of interest derived from historical values provided by the user. The decoupling of data specification and the model horizon is a critical feature that reduces the need for extensive database revisions or updates. Second, process and demand data are specified for applicable calendar years such that the model automatically handles interpolation and extrapolation of data for the time periods of a particular model instance.

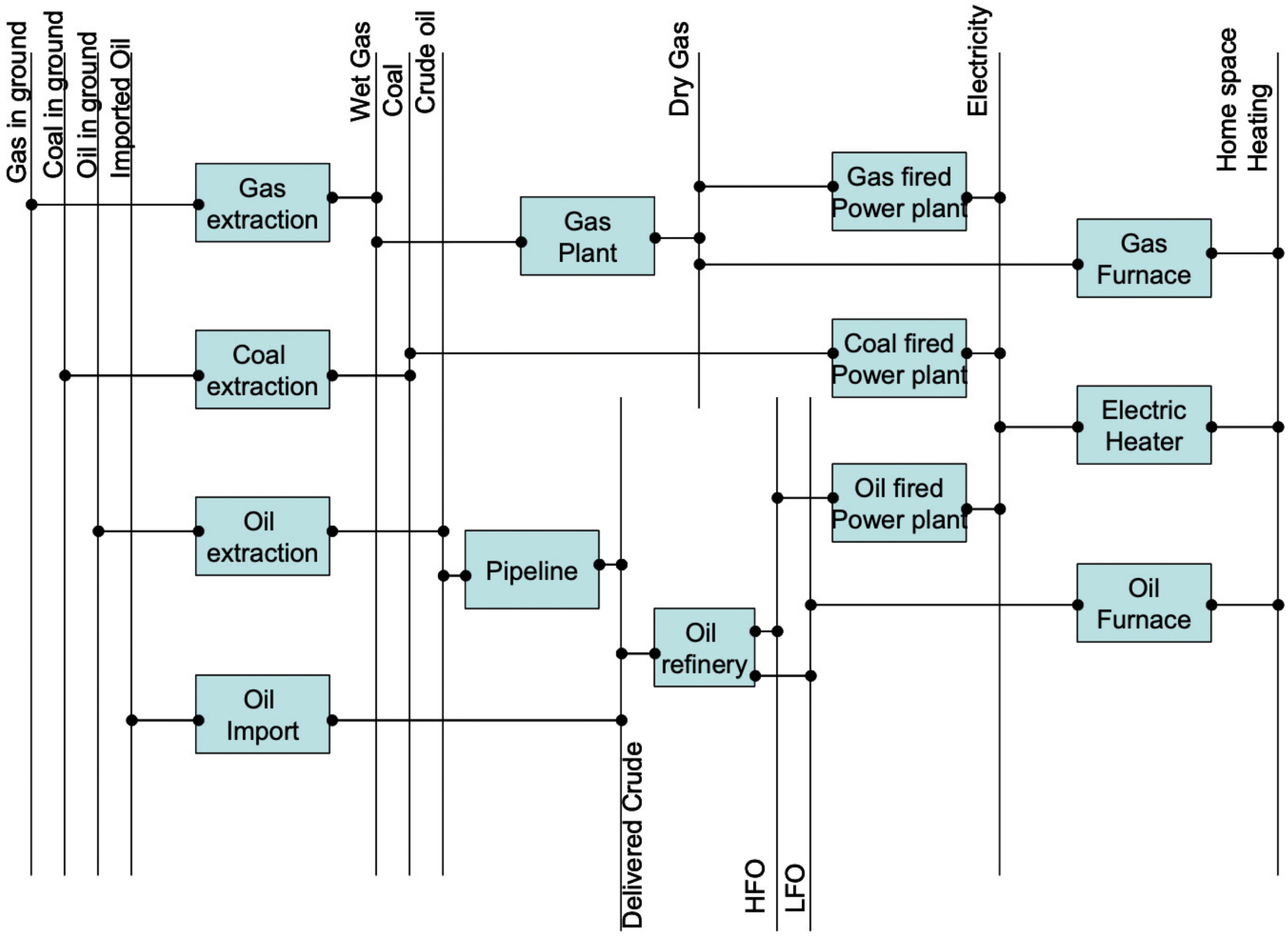
Within the TIMES model, a Reference Energy System (RES) serves as a network diagram that showcases the relationships among the entities of energy economy, viz., technologies/ processes, commodities, and commodity flows. A commodity is either consumed or produced by processes (or technologies), and these links are defined through commodity flows. The commodities are classified into major groups, including energy carriers, materials, energy services, emissions, and monetary flows. The processes are divided into different classes viz., general, storage, and inter-regional trading/exchange processes, thereby providing a comprehensive view of the energy system. The TIMES model is data-driven as it generates an 'instance' of a model by combining the foundational TIMES equations with the user-supplied input data.

The Climate Module within TIMES offers a robust framework for estimating critical climate parameters. The module first computes global emissions of key greenhouse gases (CO_2, N_2O, and CH_4) and subsequently assesses their impact on temperature by calculating the change in radiative forcing due to change in GHG concentrations in the atmosphere, in comparison to pre-industrial times. Additional forcing from other exogenously user-defined causes is also incorporated. Additionally, the module calculates temperature changes in two reservoirs, i.e., surface, and deep ocean, compared to pre-industrial times. These calculations are based on the three-reservoir CO_2 cycle model of Nordhaus and Boyer (1999), to provide a broad modelling of climate dynamics.

The TIMES model is written in GAMS. The modelling environment for TIMES is encapsulated within the VEDA 2.0 user interface and has several integral elements. The Model Generator is the foundational component that contains TIMES source code responsible for processing datasets and constructing a matrix defining the energy system model's equilibrium conditions. The core of the model consists of data files outlining an energy system encompassing technologies, commodities, resources, and energy service demands. A Model Management'shell' acts as a user interface for overseeing all aspects of model utilisation, like data management or reviewing the results. Finally, the Solver component solves the mathematical programming problem generated by the Model Generator for each instance of TIMES.

Figure 10: Partial View of an RES

(Please note: Links are oriented left to right)



Source: IEA Technology Collaboration Programme.

TIMES is targeted towards exploring possible energy futures or scenarios, which are a set of assumptions about the possible future pathways of an energy system's drivers. The model tests the coherence of the assumptions and the projected trajectories of the test scenarios to resolve the system under study. A scenario in TIMES is considered complete if it has the following inputs: demand curves of energy services, supply curves of primary resources, descriptions of technologies, and a policy setting. By incorporating these scenario components and their associated drivers, the TIMES model can simulate impacts of policies such as carbon pricing, technology subsidies, etc. Limitations of the model include the need for detailed input data, which may not be available for all regions, and proprietary software (GAMS), which may limit the use of the model.

Concluding remarks

Modelling tools have been an integral part of climate science research since their introduction in the early 1970s. Many tools have been developed since then for use by the scientific community as part of evidence-based policy research. Diemer et al. (2019) provides an overview of the evolution of IAMs since the 1970s. In addition to the increasing need for objective analysis of climate policy scenarios, various other factors, such as an active community[16] and institutional support, have contributed to the increasing relevance of modelling tools in climate research (Van Beek et al. 2020).

Researchers have attempted inter-model comparisons and their role in influencing policy. For example, Fragkos et al. (2021) and Schaeffer et al. (2020) have

[16] Integrated Assessment Modelling Consortium (IAMC). https://www.iamconsortium.org/

conducted comparative analyses between several models using harmonised scenario assumptions. Similarly, Wilson et al. (2021) developed a systematic multi-method evaluation to compare different IAMs on parameters such as adequacy, interpretability, credibility, and relevance. While these models are widely considered to play a central role in climate policy, there have been concerns about the transparency of the assumptions, methods, and data used in these models. Skea et al. (2021) attempt to document these issues and suggest measures to overcome them. Some studies have also tried to overcome the limitations of IAMs and energy system models by using a hybrid, multi-model approach. Gong et al. (2023), for instance, combined the REMIND IAM with a detailed power sector model, DIETER, for an enhanced analysis of the role of renewables in decarbonising the German power sector.

Several studies have also aimed to review existing modelling tools. Nikas et al. (2019) provide a comprehensive overview and classification of more than 60 climate-economy models into optimal growth, general equilibrium, partial equilibrium, energy system, macro-econometric, and others. They discuss the classification principles of these models, differentiate the model categories, and provide an overview of the key characteristics of the various models. Van Ouwerkerk et al. (2022) conducted a comparative analysis of five open-source power system models by modelling different scenarios for the German power system. Prina et al. (2020) classified 13 bottom-up energy system models based on the resolution of four different features: time, space, techno-economic detail, and in-sector coupling. Chang et al. (2021) classified existing review studies into seven categories based on the focus of the studies and try to address their limitations. They reviewed 54 energy system models by surveying modellers and users, focusing on various aspects of modelling such as technical descriptions, policy relevance, user accessibility, model linkages, etc. In their study, they acknowledge that "it is impossible to build a tool that can do it all" and that the focus of development should be on integrating modelling tools and improving transparency, communication between modellers and the modelling community, and accessibility by providing 'out of the box' usability of the tools.

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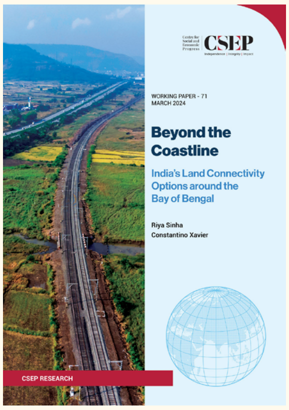
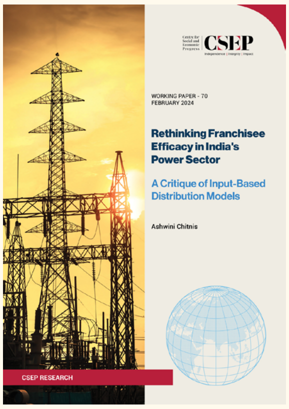
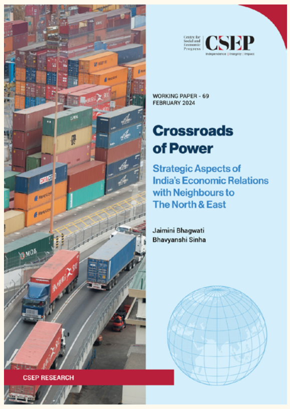
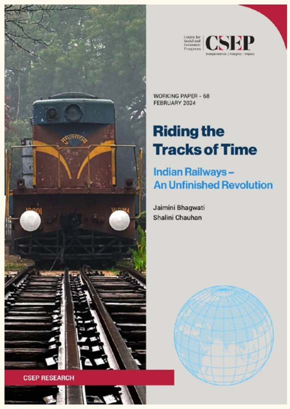
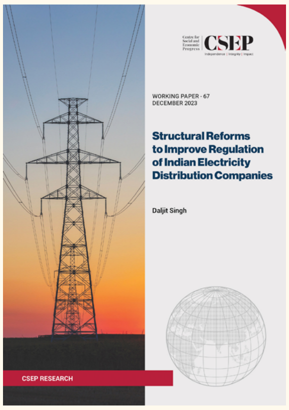
Other publications

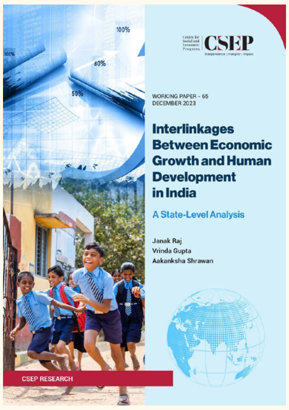


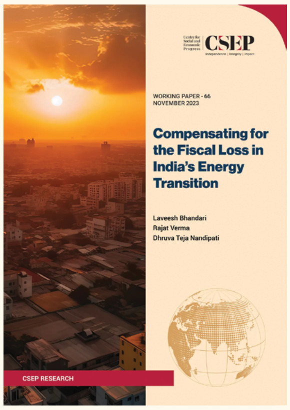


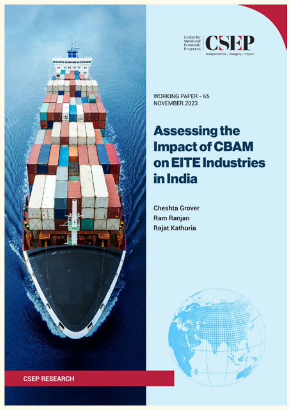


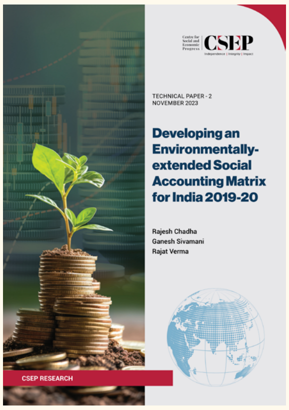


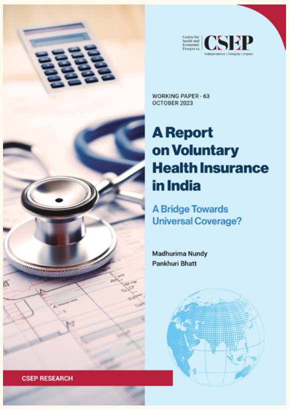


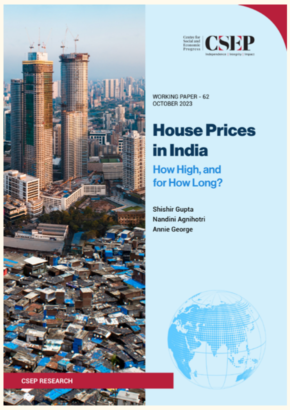


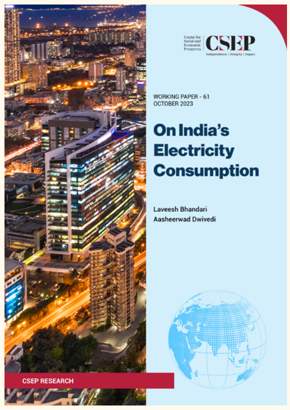


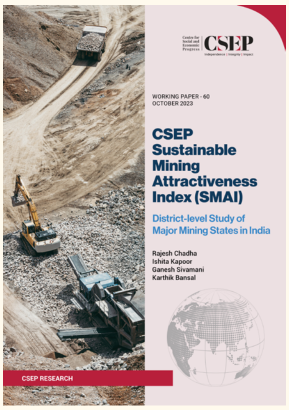


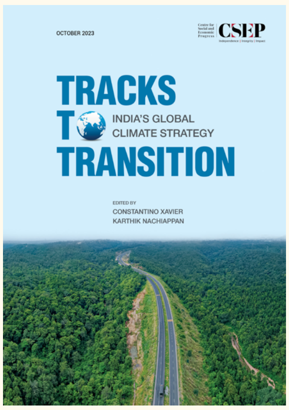


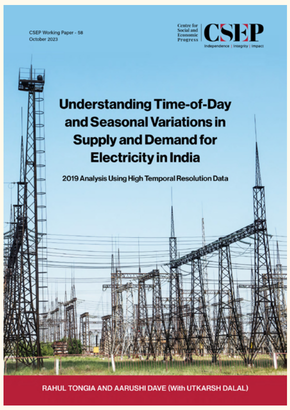


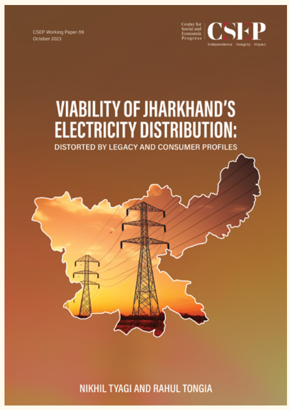












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