# Looking under the hood: A comparison of techno-economic assumptions across national and global integrated assessment models

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# Appendix A:
# Model description

### Table A-1: Summary of reviewed global and national IAMs

| IAMs | | Regional coverage | Time horizon | Time step | Developer |
|---|---|---|---|---|---|
| Global models | DNE21+ V.12A | Global 16 regions | 2050 | 5 years before 2030/ 10 years after 2030 | RITE, Japan |
| | GCAM4.2_ ADVANCE | Global 32 regions | 2100 | 5 years | JGCRI/PNNL, USA |
| | GEM-E3 | Global 38 regions | 2050 | 5 years | ICCS, Greece |
| | IMAGE 3.0 | Global 26 regions | 2100 | 1-5 years | PBL, Netherlands |
| | MESSAGEix-GLOBIOM_1.0 | Global 11 regions | 2100 | 10 years | IIASA, Austria |
| | POLES MILES | Global 24 regions | 2100 | 10 years | EC-JRC, University of Grenoble, Enerdata, France |
| | REMIND 1.6 | Global 11 regions | 2100 | 5 years before 2060/ 10 years after 2060 | PIK, Germany |
| | WITCH-GLOBIOM 4.4 | Global 13 regions | 2150 | 5 years | CMCC and FEEM, Italy |
| National models | BLUES | Brazil 6 regions | 2050 | 5 years | COPPE, Brazil |
| | IPAC-AIM/ technology_V1.0 | China 1 region | 2050 | 10 years | ERI, China |
| | PRIMES_2015 | EU 28 regions | 2050 | 5 years | ICCS, Greece |
| | AIM/E-India [IIMA] | India 1 region | 2050 | 5 years | IIMA, India |
| | India MARKAL | India 1 region | 2050 | 5 years | TERI, India |
| | AIM/Enduse[Japan] | Japan 10 regions | 2050 | 1 year | NIES, Japan |
| | DNE21+ V.MILES | Japan 1 region | 2050 | 5 years before 2030/ 10 years after 2030 | RITE, Japan |

**Table A-2: The Mechanism of technology lifetime modelled in the IAMs.**

| IAMs | | The way of lifetime modeled in the IAMs |
|---|---|---|
| Global models | DNE21+ V.12A | Fixed with explicit vintage of installed capacities; early shutdown allowed. |
| | GCAM4.2_ ADVANCE | The existing stock is assumed to retire according to non-linear smooth function over the lifetime; premature retirement possible. |
| | GEM-E3 | Fixed lifetime of installed capacities. |
| | IMAGE 3.0 | Technologies after retired using a vintage model after a prescribed technology lifetime (with a linear smoothing function applied). However, in the power sector technologies can also be retired prematurely, based on their economic competitiveness. |
| | MESSAGEix-GLOBIOM_1.0 | Fixed with explicit vintage of installed capacities; early shutdown and retirement allowed. |
| | POLES MILES | Fixed with explicit vintage of installed capacities. |
| | REMIND 1.6 | The model represents all technologies as capacity stocks with full vintage tracking; for each technology, the given lifetimes are used to calculate fractions of remaining capacity as a function of time after construction. This function is concave (not exponential) and reaches zero after a finite period of time. The integral over time equals the lifetime. Premature retirement of capacities is allowed. |
| | WITCH-GLOBIOM 4.4 | Given that the model uses a standard exponential depreciation rule. it calibrates the depreciation rate based on a finite lifetime of the power plant with a linear depreciation rate of 1% per year until the end of the lifetime and full depreciation thereafter; based on realistic plant specific life times, the exponential depreciation rate is computed equalizing the integral of both depreciation schedules, in order to obtain the equivalent potential output from the capacity. |
| National models | BLUES | Fixed, and historic capacity addition included to represent vintage of installed capacities. |
| | IPAC-AIM/technology_ V1.0 | The technology's lifetime is fixed for all more than 700 technologies. IPAC model is a least cost linear programing model, and lifetime of technologies is used in the model to calculate the replacement by cost of newly installed technologies, whether it is replaced when it reach lifetime, or replaced earlier. |
| | PRIMES_2015 | The model represents all electricity production technologies as capacity stocks with full accounting of vintages per power plant in each of the EU Member States; the representation of technology vintages of power plants is explicit in the model; based on cost-optimality, investments can be made for refurbishment of power plants or to extend the lifetimes of old plants, while premature replacement of power plants is also allowed. |
| | AIM/E-India [IIMA] | The lifetime for all technologies have been fixed with explicit vintage rates. |
| | India MARKAL | Fixed with explicit vintage of installed capacity. |

| | | |
|---|---|---|
| | AIM/Enduse [Japan] | Fixed, excluding some nuclear plants which are allowed to extend their lifetime to 60 years; after the lifetime, the capacity falls to zero. |
| | DNE21+ V.MILES | Fixed with explicit vintage of installed capacities; early shutdown allowed. |

**DNE21+ V.12A**

Dynamic New Earth 21 Plus (DNE21+) is an integrated assessment model. The model's assessment framework consists of 4 modules; (1) Key assessment model for energy-related $CO_2$, (2) assessment model for land use (land area for food production, energy crops, and afforestation) and LULUCF $CO_2$ emission, (3) Non-energy $CO_2$ emission scenario, which assumes specific non-energy $CO_2$ emissions separately from mitigation levels of energy-related $CO_2$, (4) assessment model for Non-$CO_2$ GHG, for mitigation of the five non-$CO_2$ greenhouse gases emissions of the Kyoto Protocol, based on the United States Environmental Protection Agency assessments.

The key assessment model for energy-related $CO_2$ consistently represents energy systems (e.g., energy flows, capacities of energy-related facilities, and performances and costs of various technologies) in which the worldwide costs are to be minimized, with the amounts of production activity (e.g., the production amounts of crude steel, and cement), the amounts of service activity (e.g., the traffic amount in the road transportation sector), and the final energy demands in other top-down sectors being met by the best combination of technologies. When any emission restriction (e.g., an upper limit of emissions, emission reduction targets, carbon taxes) is applied, the model specifies the energy systems whose costs are minimized and still meet all the assumed requirements.

The salient features of the model include (1) analysis of regional differences with fine regional segregation while maintaining common assumptions and interrelationships (The world is divided into 54 regions), (2) a detailed evaluation of global warming measures by modeling around 300 specific technologies that can be used to counter global warming, and (3) explicit considerations on facility transition for the specific technologies over the entire time period.

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[3] Hayashi, A., Akimoto, K., Sano, F., Tomoda, T., Evaluation of global energy crop production potential up to 2100 under socioeconomic development and climate change scenarios, Journal of Japan Institute of Energy, Vol. 94, No. 6, pp. 548-554, 2015.

**GCAM4.2_ADVANCE**

The Global Change Assessment Model (GCAM) is an open-source model primarily developed and maintained at the Pacific Northwest National Laboratory's Joint Global Change Research Institute. The full documentation of the model is available at the GCAM documentation page (http://jgcri.github.io/gcam-doc/).

GCAM is a dynamic-recursive model, combining representations of the global energy, economy, agriculture, water, and land-use systems(Edmonds et al., 2004; Edmonds and Reilly, 1985; Kim et al., 2006; Sands and Leimbach, 2003). Outcomes of GCAM are driven by assumptions about population growth, labor participation rates and labor productivity in thirty-two geo-political regions, along with representations of resources, technologies and policy. GCAM operates in 5-year time-steps from 2010 (calibration year) to 2100 by solving for the equilibrium prices and quantities of various energy, agricultural and greenhouse gas (GHG) markets in each time period and in each region. GCAM tracks emissions of twenty-four gases, including GHGs, short-lived species, and ozone precursors, endogenously based on the resulting energy, agriculture, and land use systems.

The energy system formulation in GCAM comprises of detailed representations of extractions of depletable primary resources such as coal, natural gas, oil and uranium along with renewable sources such as bioenergy, hydro, solar and wind. GCAM also includes representations of the processes that transform these resources to secondary energy carriers, which are ultimately consumed in the buildings (divided into the residential and commercial), transportation and industrial sectors. Secondary energy carriers include refined liquids, refined gas, coal, commercial bioenergy, hydrogen, and electricity. The electricity sector in GCAM includes representations of a range of technologies with cost assumptions based on Muratori et al. (2017).

[1] Edmonds, J., Clarke, J., Dooley, J., Kim, S., Smith, S., 2004. Stabilization of $CO_2$ in a B2 world: insights on the roles of carbon capture and disposal, hydrogen, andtransportation technologies. Energy Economics 26, 517-537.

[2] Edmonds, J., Reilly, J., 1985. Global energy: assessing the future. Oxford University Press, Oxford, U.K.

[3] Kim, S., Edmonds, J., Lurz, J., Smith, S., Wise, M., 2006. The ObjECTS framework for integrated assessment: hybrid modeling of transporation. . Energy Journal 27, 63-91.

[4] Muratori, M., Ledna, C., McJeon, H., Kyle, P., Patel, P., Kim, S.H., Wise, M., Kheshgi, H.S., Clarke, L.E., Edmonds, J., 2017. Cost of power or power of cost: A U.S. modeling perspective. Renewable and Sustainable Energy Reviews 77, 861-874.

[5] Sands, R., Leimbach, M., 2003. Modeling agriculture and land use in an integrated assessment framework Climatic Change 56, 185-210.

## GEM-E3

GEM-E3 is a global multi-region multi-sectoral CGE model that provides details on the macro-economy and its interactions with the environment and the energy system (Capros et al., 2013). The model includes a detailed representation of labour and capital markets. GEM-E3 covers the entire economy and can evaluate consistently the distributional effects of policies on GDP, investment, consumption, public finance, foreign trade and employment for various economic sectors across countries.

Countries and regions are linked in GEM-E3 through bilateral trade flows that are modelled endogenously. All major public finance aspects (taxes, subsidies, public expenditures, deficit financing), institutional regimes and market clearing mechanisms are represented in GEM-E3 (Fragkos et al, 2018). The model includes all major economic agents (firms, households, government and the external sector) the supply and demand behaviour of which is formulated separately. Production factors include labour, capital, energy and intermediate inputs. Total demand of agents consists of demand for domestic and imported goods that are imperfect substitutes (Armington assumption).

The model is calibrated on Social Accounting Matrices for every country and region included in the model, that are constructed based on EUROSTAT data for EU countries and the Global Trade Analysis Project (GTAP) for non-EU countries. The representation of consumption and investment behavior is based on consumption and investment matrices respectively; the former link consumption by purpose to demand for specific goods, while the latter link investment by origin to investment by destination.

GEM-E3 is specifically designed to evaluate energy and environmental policies. The model can quantify the macro-economic impacts of various energy and climate policy instruments, including carbon taxes, pollution permits, energy efficiency standards and RES support policies. Emission reductions are driven by substitution between fuels (e.g. from coal to gas or biofuels) and between energy and non-energy inputs, the purchase of clean energy equipment and investment directed to energy efficiency. GEM-E3 has recently been expanded with bottom-up representation of power generation technologies, detailed modelling of transport modes and investment in energy efficiency and explicit representation of clean energy technology options including biofuels and electric cars (Karkatsoulis et al, 2016).

[1] Capros, P., Van Regemorter, D., Paroussos, L., Karkatsoulis, P., Fragkiadakis, C., Tsani, S., Charalampidis, I. &Revesz, T. (2013), GEM-E3 Model Documentation, JRC-IPTS Working Papers JRC83177, Institute for Prospective and Technological Studies, Joint Research Centre.

[2] Fragkos P., K. Fragkiadakis, L. Paroussos, R. Pierfederici, S. Vishwanathan, A. Köberle, G. Iyer, C. He, K. Oshiro (2018), Coupling national and global models to explore policy impacts of NDCs, Energy Policy, Volume 118, July 2018, Pages 462–473.

[3] Karkatsoulis P., P. Capros, P. Fragkos, L. Paroussos and S. Tsani,"First-mover advantages of the European Union's climate change mitigation strategy", International Journal of Energy Research, DOI: 10.1002/er.3487.

**Link to model documentation:**
GEM-E3 Model Manual, http://www.e3mlab.eu/e3mlab/GEM%20-%20E3%20Manual/GEM-E3_manual_2015.pdf

**IMAGE 3.0**

The IMAGE modelling framework explores the chain of global environmental change for both climate and land use (Van Vuuren et al., 2016). The IMAGE model is a simulation model, i.e. changes in model variables are calculated based on the previous time-step.

The global energy system model TIMER simulates long-term trends in energy supply, conversion and demand. The model describes the investments in and use of different types of energy carriers, influenced by technology development and resource depletion. TIMER includes technology development in the form of learning curves for most fuels and renewable energy options. Costs decrease endogenously as a function of the cumulative energy capacity. On the other hand, resource costs increase as they get depleted, based on cost supply curve information. The supply of energy is assumed to always meet the demand, and the decision to invest in additional capacity is based on the costs of energy produced per technology, with larger market shares assigned to lower cost options. Inputs to the model are macro-economic scenarios and assumptions on technology development, preference levels and restrictions to fuel trade.

The second part within IMAGE describes food demand and agriculture, using projections made by the computable-general-equilibrium MAGNET model. It describes changes in food production and trade for a broad set of crops and animal products. An important part of the earth system is the LPJmL model that is included in IMAGE. This model is used to determine productivity and at grid cell level for natural and cultivated ecosystems on the basis of plant and crop functional types. Based on the regional production levels and the output of LPJmL, a set of allocation rules in IMAGE determine actual land cover. Emissions from land-use changes, natural ecosystems and agricultural production systems, and the exchange of $CO_2$ between terrestrial ecosystems and the atmosphere are also simulated. Through the linkage to IMAGE, internally consistent projections of GDP and energy demand are calculated iteratively, taking price-induced changes of demand and GDP into account.

Climate policy is modelled through the implementation of a global carbon tax affecting in the energy sectors the fossil fuel costs. The carbon tax path required to remain within a specific temperature is based on marginal abatement cost curves (MACs) that reflect the additional costs of abating one extra tonne $CO_2$ equivalent emissions, derived from the modelled regional energy, agriculture and land use systems. Those sectors and those measures of which the cost to reduce pollution are low will be reflected in the low side of the MAC curve while the critical sectors will typically be represented on the higher side. In TIMER the increased fuel price will results in different effects: 1) shift toward more efficient technologies, 2) shift toward non fossil fueled technologies (both technology options have become relatively cheaper) and 3) reduction of demand as energy costs have become more expensive.

[1] VAN VUUREN, D. P., STEHFEST, E., GERNAAT, D. E., DOELMAN, J. C., VAN DEN BERG, M., HARMSEN, M., DE BOER, H. S., BOUWMAN, L. F., DAIOGLOU, V. & EDELENBOSCH, O. Y. 2016. Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Global Environmental Change*.

**MESSAGEix-GLOBIOM_1.0**

MESSAGEix-GLOBIOM 1.0 integrates the energy engineering model MESSAGE with the land-use model GLOBIOM via soft-linkage into a global integrated assessment modeling framework (Fricko et al., 2017; Krey et al., 2016). It utilizes the ix platform for integrated and cross-sectoral modeling (Huppmann et al., 2018).

MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) is a linear programming (LP) energy engineering model with global coverage (Riahi et al., 2012; Riahi, Grübler, & Nakicenovic, 2007). As a systems engineering optimization model, MESSAGE is primarily used for medium- to long-term energy system planning, energy policy analysis, and scenario development. The model provides a framework for representing an energy system with all its interdependencies from resource extraction, imports and exports, conversion, transport, and distribution, to the provision of energy end-use services such as light, space conditioning, industrial production processes, and transportation. MESSAGE-Access (Cameron et al., 2016) is a standalone residential cooking energy choice and demand model that can be applied jointly with MESSAGEix-GLOBIOM to estimate implications of energy and climate policies on access to clean cooking fuels. To assess economic implications and to capture economic feedbacks of climate and energy policies, MESSAGE is linked to the aggregated macro-economic model MACRO (Messner & Schrattenholzer, 2000).

Land-use dynamics are modelled with the GLOBIOM (GLobal BIOsphere Management) model, which is a partial-equilibrium model (Petr Havlík et al., 2011; P. Havlík et al., 2014). GLOBIOM represents the competition between different land-use based activities. It includes a detailed representation of the agricultural, forestry and bio-energy sector, which allows for the inclusion of detailed grid-cell information on biophysical constraints and technological costs, as well as a rich set of environmental parameters, incl. comprehensive AFOLU (agriculture, forestry and other land use) GHG emission accounts and irrigation water use. For spatially explicit projections of the change in afforestation, deforestation, forest management, and their related CO2 emissions, GLOBIOM is coupled with the G4M (Global FORest Model) model (Gusti, 2010; Kindermann, Obersteiner, Rametsteiner, & McCallum, 2006). As outputs, G4M provides estimates of forest area change, carbon uptake and release by forests, and supply of biomass for bioenergy and timber.

MESSAGEix-GLOBIOM covers all greenhouse gas (GHG)-emitting sectors, including energy, industrial processes as well as agriculture and forestry. The emissions of the full basket of greenhouse gases including CO2, CH4, N2O and F-gases (CF4, C2F6, HFC125, HFC134a, HFC143a, HFC227ea, HFC245ca and SF6) as well as other radiatively active substances, such as NOx, volatile organic compounds (VOCs), CO, SO2, and BC/OC is represented in the model. Air pollution implications of the energy system are accounted for in MESSAGEix-GLOBIOM by a linkage to the GAINS (Greenhouse gas and Air pollution INteractions and Synergies) model (Amann et al., 2011). MESSAGEix-GLOBIOM is used in conjunction with MAGICC (Model for Greenhouse gas Induced Climate Change) version 6.8 (Meinshausen, Raper, & Wigley, 2011) for calculating atmospheric concentrations, radiative forcing, and annual-mean global surface air temperature increase.

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Meinshausen, M., Raper, S. C. B., & Wigley, T. M. L. (2011). Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 - Part 1: Model description and calibration. Atmospheric Chemistry and Physics, 11(4), 1417-1456. doi:10.5194/acp-11-1417-2011

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**POLES MILES**

The **POLES** (Prospective Outlook on Long-term Energy Systems) model[1] is a global partial equilibrium simulation model of the energy sector with an annual step, covering 38 regions world-wide (G20, OECD, principal energy consumers) plus the EU. The model covers 15 fuel supply branches, 30 technologies in power production, 6 in transformation, 15 final demand sectors and corresponding greenhouse gas emissions. GDP and population are exogenous inputs of the model. The model can provide insights of the evolution of global and local technology developments. The model can assess the market uptake and development of various new and established energy technologies as a function of changing scenario conditions. The global coverage allows an adequate capture of the learning effects that usually occur in global markets [2]. The model represents the adjustments of energy supply and demand to prices, while accounting for delayed reaction. POLES can also assess the global primary energy markets and the related international and regional fuel prices under different scenario assumptions. To this end, it includes a detailed representation of the costs in primary energy supply (in particular oil, gas and coal supply), for both conventional and unconventional resources. Major countries for the oil, coal and gas markets are represented.

The model can therefore be used to analyse the impacts of energy and climate policies, through the comparison of scenarios concerning possible future developments of world energy consumption and corresponding GHG emissions under different assumed policy frameworks[3]. Policies that can be assessed include: energy efficiency, support to renewables, energy taxation/subsidy, technology push or prohibition, access to energy resources, etc.
Mitigation policies are implemented by introducing carbon prices up to the level where emission reduction targets are met: carbon prices affect the average energy prices, inducing energy efficiency responses on the demand side, and the relative prices of different fuels and technologies, leading to adjustments on both the demand side (e.g. fuel switch) and the supply side (e.g. investments in renewables). Non-CO2 emissions in energy and industry are endogenously modelled with potentials derived from literature (marginal abatement cost curves). Air pollutants are also covered (SO2, NOx, VOCs, CO, BC, OC, PM2.5, PM10, NH3) thanks to a linkage with the specialist GAINS model. Projections for agriculture, LULUCF emissions and food indicators are derived from the GLOBIOM model (dynamic look-up of emissions depending on climate policy and biomass-energy use), calibrated on historical emissions and food demand (from UNFCCC, FAO and EDGAR). A full documentation of POLES is available at http://ec.europa.eu/jrc/poles.

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[3] T. Vandyck, K. Keramidas, B. Saveyn, A. Kitous, and Z. Vrontisi, 'A global stocktake of the Paris pledges: Implications for energy systems and economy', Global Environmental Change, vol. 41, no. Supplement C, pp. 46–63, Nov. 2016.

**REMIND 1.6**

**REMIND** models the global energy-economy-climate system for 11 world regions and for the time horizon until 2100. For the present study, REMIND in its version 1.6 was used (Luderer et al. 2015). REMIND represents five individual countries (China, India, Japan, United States of America, and Russia) and six aggregated regions formed by the remaining countries (European Union, Latin America, sub-Saharan Africa without South Africa, Middle East / North Africa / Central Asia, other Asia, Rest of the World). For each region, intertemporal welfare is optimized based on a Ramsey-type macro-economic growth model with perfect foresight. The model explicitly represents trade in final goods, primary energy carriers, and in the case of climate policy, emission allowances and computes simultaneous and intertemporal market equilibria based on an iterative procedure. Macro-economic production factors are capital, labor, and final energy. REMIND uses economic output for investments in the macro-economic capital stock as well as consumption, trade, and energy system expenditures.

By coupling a macroeconomic equilibrium model with a technology-detailed energy model, REMIND combines the major strengths of bottom-up and top-down models. The macro-economic core and the energy system module are hard-linked via the final energy demand and costs incurred by the energy system. A production function with constant elasticity of substitution (nested CES production function) determines the final energy demand. For the baseline scenario, final energy demands pathways are calibrated to regressions of historic demand patterns. More than 50 technologies are available for the conversion of primary energy into secondary energy carriers as well as for the distribution of secondary energy carriers into final energy. Explicit representation of end-use technologies is restricted to the light-duty vehicle sector, where three representative technologies are represented (internal combustion engine vehicle, battery electric vehicles (BEVs) and fuel-cell vehicles (FCVs)). Endogeneous technology cost degression based on learning curves with floor costs is represented for five technologies: wind, solar photovoltaics, concentrated solar power and the two alternative vehicle technologies (BEVs and FCVs)(Pietzcker et al. 2014a, b).

The cost assumptions and consulted sources are documented in tables 5 and 6 of Luderer et al. (2015). In the case of rapid upscaling of a particular technology, an investment cost mark-up is applied, which scales with the square of the change in new installations from one time step to the next one. By this method, the scale-up of alternative technologies in scenarios with REMIND broadly follows historically observed diffusion patterns (Wilson et al. 2013). The challenge of integrating high shares of variable renewables into the power system are represented via additional demands for back-up storage, transmission as well as curtailment depending on the shares of wind and solar (Pietzcker et al. 2017).

REMIND uses reduced-form emulators derived from the detailed land-use and agricultural model MAgPIE (Lotze-Campen et al. 2008; Popp et al. 2014) to represent land-use and agricultural emissions as well as bioenergy supply and other land-based mitigation options. Beyond $CO_2$, REMIND also represents emissions and mitigation options of major non-$CO_2$ greenhouse gases (EPA 2013; Strefler et al. 2014).

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## WITCH-GLOBIOM 4.4

WITCH (World Induced Technical Change Hybrid) is an integrated assessment model designed to assess climate change mitigation and adaptation policies (Emmerling et al., 2016; Bosetti et al., 2007). It is developed and maintained at the Fondazione Eni Enrico Mattei and the Centro Euro-Mediterraneo sui Cambiamenti Climatici. WITCH is of a global dynamic model that integrates into a unified framework the most important drivers of climate change. An inter-temporal optimal growth model captures the long-term economic growth dynamics. A compact representation of the energy sector is fully integrated (hard linked) with the rest of the economy so that energy investments and resources are chosen optimally, together with the other macroeconomic variables. Land use mitigation options are available through a linkage with a land use and forestry model (Havlik, 2014). WITCH represents the world in a set of fourteen representative native regions; for each, it generates the optimal mitigation strategy for the long-term (from 2005 to 2100) as a response to external constraints on emissions. A modelling mechanism aggregates the national policies on emission reduction or the energy mix into the WITCH regions. Finally, a distinguishing feature of WITCH is the endogenous representation of R&D diffusion and innovation processes that allows a description of how R&D investments in energy efficiency and carbon-free technologies integrate the mitigation options currently available.

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**BLUES**

The Brazilian Land Use and Energy System model (Köberle, 2018; Rochedo et al., 2018) is a perfect foresight, partial equilibrium model for Brazil built on IIASA's MESSAGE model builder platform. The mode divides Brazil into five distinct geographic sub-regions plus a sixth national region that connects to the rest of the world. The model minimizes costs over the entire time horizon (2010 to 2050) and over the entire energy system, including electricity generation, industry, transport, the buildings sectors, agriculture and land use. It includes $CO_2$, $CH_4$ and $N_2O$ emissions. The model divides the year into 12 representative days (one for each month) divided into 24 representative hours, while each subregion also has its own electricity load curve as well as hydro, wind and solar potential curves at the same resolution.

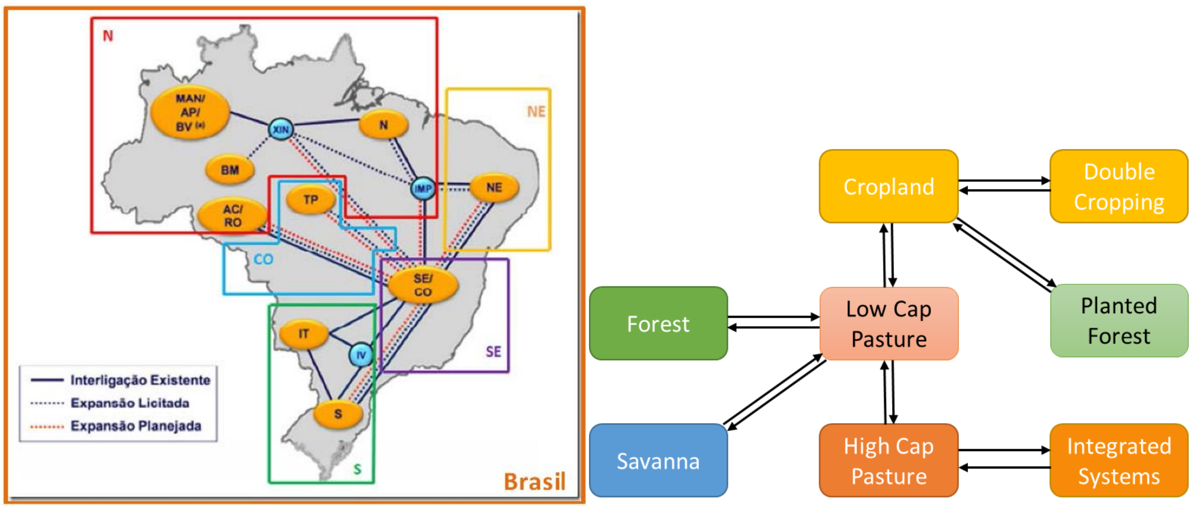



*Figure 1 - BLUES geographic representation (left) and allowed land use transitions (right).*

Final use in BLUES is defined in terms of energy services provided by end use processes such as cars, airplanes, light bulbs or stoves for example, each with several options of varying costs and efficiencies. These end-use processes (technologies) take as input energy carriers at the final energy level such as gasoline, diesel, kerosene (jetfuel), electricity, natural gas, LPG, firewood, charcoal. Represented sectors include industry, transportation, power generation, energy supply, buildings, agriculture and land use. Industry is divided in to eleven detailed subsectors (cement, ceramics, chemicals, mining, iron & steel, metallurgy, alloys, pulp & paper, textiles, food & beverages, and "other" for the remaining industries). Transport includes passenger and freight, public and private, with detailed technological options including cars, motorcycles of various types (including electric options for both), trucks, airplanes and ships, which meet exogenous demand expressed in passenger-kilometers or ton-kilometers. The buildings sector includes residential, commercial and public sectors, which have demands for lighting, air conditioning, refrigeration, cooking, water heating and appliances. Land use includes forests, savannas, low- and high-capacity pastures, integrated livestock-cropland-forestry systems, cropland, double cropping, planted forests and protected areas. The agricultural sectors use Cropland (single- and double-cropped) to produce the major agricultural products in Brazil following the United Nations Food and Agriculture Organization (FAO) definitions for each category: wheat, fruits, soybeans, maize, cereal, vegetables, roots, rice, pulses, oilseed, nuts, sugarcane, coffee, fiber, and grassy biomass.

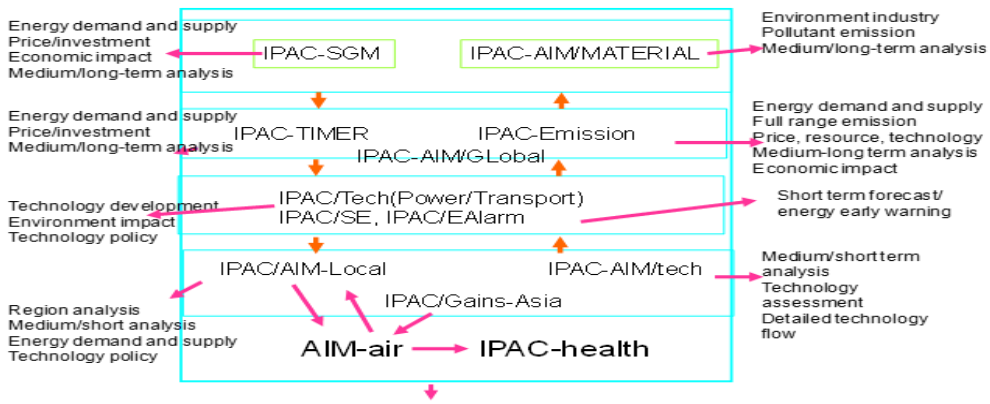
Biofuels production is modelled in considerable detail. Ethanol can be made from sugarcane or lignocellulosic material. The sugarcane chain is disaggregated to include steps in the process involving the generation of steam, electricity, solid biomass in addition to ethanol. There are four possible configurations of combined heat and power (CHP) that burn bagasse to power the processes that produce ethanol and bioelectricity, some of the latter can be exported to the grid. Biodiesel cane be made from vegetable oils, animal fat or lignocellulosic material through various processes including fatty-acid transesterification, Fischer-Tropsch, and gasification. All the processes have carbon capture and storage options available.

Carbon capture and storage is also available in fossil power generation and in some industrial proesses, as well as in the extraction of crude oil from the offshore Pre-Salt fields which have a mandate to not vent any greenhouse gases during production. The construction of pipelines for $CO_2$ (carboducts) is modelled separately and using different cost and efficiency parameters than the construction of conventional oil and gas pipelines.

For more information see Köberle (2018), the supplementary online materials of Rochedo et al (2018), or the ADVANCE wiki site http://themasites.pbl.nl/models/advance/index.php/Model_Documentation_-_BLUES.

**IPAC-AIM/technology_V1.0**

Since 1992, the Integrated Policy Assessment Model for China (IPAC) model group of Energy Research Institute began to build models. After more than twenty years of research and development, the current IPAC has become a comprehensive policy evaluation model, with a variety of model approaches (http://www.ipac-model.org). The currently used models and methods are somewhat reflected in the IPAC group, such as computable general equilibrium model, the dynamic economic model, the partial equilibrium model, the minimum cost optimization model based on linear programming techniques described in detail and industry simulation models. Figure below presents the framework of IPAC model. Taking into account the Energy Research Institute as a research institution in the National Development and Reform Commission, IPAC model has been widely applied to policy evaluation of energy and climate change in China. The research outputs of IPAC have been used in relevant planning research of 10-12th "Five-year Plan" in China, and meanwhile they have supported energy planning and polices in some provinces and municipalities. This research will provide quantitative analysis depended on the long-time model data and scenario research provided by IPAC model and issues some major future technologies, especially in low-carbon technology investment demands (Jiang et al. 1998; Jiang 2014).




IPAC-AIM/technology model is a major component of the IPAC model, whose aim is to simulate energy consumption process by giving a detailed description of energy services and technologies to provide these services with different level of energy efficiency, cost, emission factors. IPAC-AIM/technology model is the minimum cost optimization model based on linear programming. By doing this, it is easier for policy makers to understand the results of modeling simulation with telling the selection of technologies by various policies.

In the IPAC-AIM/technology model, technical parameters include the amount of service output, energy useby typies, other non-energy inputs, technology fixed investment, and technical pollutant emissions factors. Technical fixed investment is given by year, including both the technical learning curve and the description of future technology cost. The model covers more than 700 technologies in 55 sectors, of which more than 150 kinds of important technologies in low-carbon and energy-saving fields are selected as the focus of this analysis. In calculation of primary energy, 100% efficiency for renewable including hydro, wind, solar, 33% efficiency for nuclear and biomass were used here.

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**PRIMES_2015**

The PRIMES energy model simulates the European energy system and markets on a country-by-country basis for the entire energy system (E3MLab, 2015). The model provides projections of detailed energy demand and supply balances, CO2 emissions, investment in energy system, energy technology penetration, energy prices and costs. PRIMES simulates a multi-market equilibrium solution for energy supply and demand and for ETS by explicitly calculating prices which balance demand and supply. The simulation of demand and supply behaviour of each agent is based on modelling founded on micro-economics and includes technical (engineering-oriented) constraints. The PRIMES model has served to quantify energy outlook scenarios for DG ENER (Capros et al, 2016) and to provide model-based analysis for EU energy and climate policies (Capros et al, 2018), including Low Carbon Roadmap, Energy Roadmap to 2050 and the recent Winter Package for 2030 (E3Mlab & IIASA, 2016).

The distinctive feature of PRIMES is the combination of behavioural modelling following a micro-economic foundation with engineering and system aspects, covering all energy sectors and markets at a high level of detail. PRIMES focuses on prices as a means of balancing demand and supply simultaneously in several markets for energy products and emissions. The model determines market equilibrium volumes by finding the prices of each energy form such that the quantity producers find best to supply matches the quantity consumers wish to use. Investment is endogenous in PRIMES and in all sectors, including for purchasing of equipment and vehicles in demand sectors and for building energy producing plants in supply sectors. The model handles dynamics under different anticipation assumptions and projects over a long-term horizon keeping track of technology vintages in all sectors. Technology learning and economies of scale are fully included and are generally endogenous depending on market development. PRIMES model design is suitable for medium- and long-term energy system projections and system restructuring up to 2050, in both demand and supply sides. The model can support impact assessment of specific energy and environment policies and measures, applied at Member State or EU level, including price signals, such as taxation, subsidies, Emission Trading Schemes (ETS), technology promoting policies, RES supporting policies, efficiency promoting policies, environmental policies and technology standards. PRIMES is sufficiently detailed to represent concrete policy measures in various sectors, including market design options for the EU internal electricity and gas markets (Fragkos et al, 2017).

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**Link to model documentation**

PRIMES Manual,
http://www.e3mlab.eu/e3mlab/PRIMES%20Manual/PRIMES_ENERGY_SYSTEM_MODEL.pdf

## AIM/E-India [IIMA]

The AIM/E-India model is a bottom-up optimization model built on a disaggregated, sectoral representation of the economy, it provides a detailed characterization of technologies and fuel based on their availability, efficiency levels and costs. The model is driven by exogenous sectoral service demands and assumes that the agents of change are myopic in nature. Hence, it is assumed that the agents see and examine only the alleged dangers of rising CO2 levels in the atmosphere while ignoring the potential harmful effects of managing for CO2. The model accounts for final energy consumption and CO2 emissions in end-use sectors based on actual energy use and the way energy services are satisfied by energy device. It calculates the future demand for energy services in different sectors and determines the optimal set of technologies that can be used to satisfy the service demand through total cost optimization. Based on the energy consumed by the selected set of technologies, the model estimates the future energy consumption of various devices, as well as of the system as a whole. The model uses annual discount rate which is determined exogenously so as to fit the rate of payback period exogenously (Shukla, et al., 2004; Kainuma, et al., 2003). Unlike other bottom-up techno-economic models, the cost of device/technology/system is annualized (Shukla, 2013), therefore it can also capture the technology transitions that has been observed due to the rapid policy changes in the past decade.

The model has been set up for India for five major sectors and their respective services, technologies, reference years and discount rates. These sectors are power, industry, buildings, transportation and agriculture. Exogenous service demands trigger decisions regarding technology selection based on information on costs, which in turn define the energy mix and CO2 emissions resulting from information on the emission characteristics of fuels, materials and technologies. The methodology for demand projection used by Kapshe, et al. (2003) has been adapted in this study along with a few revisions. The maximum shares for the base year are taken from various government and research publications. Multiple services in each sector have been examined to provide a better understanding of the sector. For example, fifteen industries have been selected to represent the industry sector, while passenger and freight characterize travel demand in the transport sector. Each service is further disaggregated based on the mode of transport used, such as road, rail, air and water. The technologies considered in the model range from those currently available to those that are still in the research and development stage. The new technologies and their years of introduction are based on various Indian and international reports and expert opinions (Vishwanathan et al. 2017).

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**India MARKAL**

TERI's India MARKAL model has been developed over the past two decades and used for several studies undertaken in the past by TERI. These include Air Pollutant Emissions Scenario for India (Sharma & Kumar, 2016), Energy Security Outlook (TERI, 2015), pathways to deep decarbonisation (Sachs, et al., 2014) and The Energy Report- India 100% Renewable Energy by 2030 (TERI, 2013). The outputs from the model have also been used for the development of India's INDC document.

MARKAL (MARket ALlocation) is a bottom up dynamic linear programming model and depicts both the energy supply and demand sides of the energy system. The MARKAL family of models is unique, with applications in a wide variety of settings and global technical support from the international research community. MARKAL interconnects the conversion and consumption of energy carriers. This user-defined network includes all energy carriers involved in primary supplies, conversion and processing (e.g., power plants, refineries, etc.), and end-use demand for energy services that may be disaggregated by sector and by specific functions within a sector. The optimization routine used in the model's solution selects from each of the sources, energy carriers, and transformation technologies to produce the least-cost solution, subject to a variety of constraints. The user defines technology costs, technical characteristics (e.g., conversion efficiencies), and energy service demands.

The model database is set up over a 50 year period extending from 2001-2051 at five-yearly intervals originally intended to coincide with the Government of India's Five-Year plans. In the model, the Indian energy sector is disaggregated into five major energy consuming sectors, namely, agriculture, commercial, industry, residential and transport sectors. Each of these sectors is further disaggregated to reflect the sectoral end-use demands. The model is driven by the demands on the end-use side which are exogenously determined by excel-based econometric models.

On the supply side, the model considers the various energy resources that are available both domestically and from abroad for meeting various end-use demands. These include both the conventional energy sources (coal, oil, natural gas, and nuclear) as well as the renewable energy sources (hydro, wind, solar, biomass etc.). The availability of each of these fuels is represented by constraints on the supply side.

The relative energy prices of various forms and source of fuels play an integral role in capturing inter-fuel and inter-factor substitution within the model. Furthermore, various conversion and process technologies characterized by their respective investment costs, operating and maintenance costs, technical efficiency, life etc. that meet the sectoral end-use demands are also incorporated in the model.

India specific technology costs (capital costs and O&M costs) for various technologies included in the database have been obtained from various sources. Wherever India specific costs are not available, international figures are used. Cost reduction in future in the emerging technologies has also been assumed based on an understanding of the particular technology development.

The database in its current form incorporates 47 end-uses spanning nearly 350 technologies. The current database differs from the previous databases in terms of driver of the model like GDP and constituent parameters designed specifically to meet the requirements of CD-LINKS scenarios.

[1] Sachs, J., Guerin, E., Mas, C., Schmidt-Traub, G., Tubiana, L., Waisman, H., et al. (2014). pathways to deep decarbonization-2014 report. SDSN & IDDRI.

[2] Sharma, S., & Kumar, A. (Eds.). (2016). Air pollutant emissions scenario for India. New Delhi: TERI.

[3] TERI. (2013). The Energy Report- India 100% Renewable Energy by 2050. New Delhi: WWF-India.

[4] TERI. (2015). Energy Security Outlook: Defining a secure and sustainable energy future for India. New Delhi: TERI.

**AIM/ENDUSE [Japan]**

AIM/Enduse [Japan] [1]-[3] is a partial equilibrium, dynamic recursive national energy system model for Japan developed by the National Institute for Environmental Studies (NIES). It is characterized by the detailed descriptions of energy technologies in the end-use sectors (industry, buildings, and transportation) as well as the energy supply sectors in Japan. This model is characterized by detailed representation of technologies including several low-carbon options both in the energy end-use sectors and energy supply sectors. In this model, technology selection is implemented based on linear programing minimizing total energy system costs given exogenous parameters such as energy service demands, energy prices, technological parameters, and carbon prices or emissions constraints. This model covers not only energy sectors but also non-energy sectors such as industrial processes and waste management, but AFOLU sector is not taken into account. It also covers other Kyoto gases (CH4, N2O and F-gases) as well as CO2 emissions. Non-CO2 greenhouse gases emissions are converted into CO2-equivalents using GWP100 factors taken from the IPCC AR4, and can also be constrained by CO2-equivalent emission prices in this model. In this study, we used a multi-region version of AIM/Enduse [Japan] where the sub-regions are broadly consistent with the areas of 10 public power supply firms in Japan, so as to consider characteristics of energy supply and demand across the various-regions, such as differences in energy demand and potential of renewable energies among regions. The electricity dispatch module, that is hard-linked with the energy end-use and other energy supply sectors module, explicitly represents the load curve in each region, and capacity of electricity interconnection between sub-regions. Assumptions on technological parameters in power sector, such as conversion efficiency, capital and O&M costs, lifetime, and capacity factor are consistent with the report published by the Power Generation Cost Verification Working Group under the Subcommittee on Long-term Energy Supply-demand Outlook that was held in 2015[4].

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