Integrated Assessment Models: Classification and Synthesis

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1. Introduction

Integrated Assessment Models (IAMs) are complex computational frameworks used in the fields of environmental science, economics, and policy analysis to assess and evaluate the interrelationships between different factors and systems that influence critical issues, such as climate change, energy policy, and sustainability. These models use a multi-disciplinary approach to integrate data, knowledge, and methodologies, merging inter alia climate science, economics, energy systems, to provide a comprehensive and holistic understanding of how different policies and scenarios can impact the environment, society, and the economy in the medium and the long run. IAMs represent the coming together of three different worlds of scientific thinking in relation to energy and climate science: energy system and technological progress models, economic system models, and climate science models.

IAMs play a pivotal role in addressing complex and multifaceted societal challenges, particularly those related to environmental policy and the trajectory to net zero. Integrated assessment models (IAMs) aim to provide policy-relevant insights into global environmental change and sustainable development issues by providing a quantitative description of key processes in the human and earth systems and their interactions. They are utilized in all major publications and reports referring to climate change and climate projections and are gaining ground in the science-based information of policymakers across the globe (Schwanitz, 2013).

This chapter presents a thorough review and classification of selected IAMs for comparing and evaluation sustainable pathways. The main goal of this work is primarily to collate and characterize widely used and potent IAMS in terms of:

i. Coverage
ii. Potential
iii. Accessibility
iv. Inputs-Outputs
v. Synergies & Complementarities
Moreover, this work is conducted with the aim to assess the added value of each IAM individually as well as an integral part of model synergies for the design of sustainable pathways for the Global Climate Hub. Harnessing distinct IAMs is of material importance to the work of the Global Climate Hub and a particular area of focus for the Climate & Energy Systems Modelling Unit and the Land Use and Marine Use Modelling Unit. The objective is to assess the feasibility and performance of different socio-economic and environmental pathways using a science-driven and human-centric approach.

The issue of synergies is particularly challenging and needs to be carefully studied in order to undertake a holistic approach to decarbonization pathways and develop socio-economic narratives associated with the diverse model projections. There are three main types of synergies:

i. Cooperative: The output of one model is used as input in another model.
ii. Complementary: Two or more models need to work together in order to produce an output and you cannot use one without the other, or the output you receive is incomplete without the other.
iii. Independent: Two or more models can create their own distinct and complete output, but due to the coverage of each model (i.e., they both study land use issues), the results of each model can be joined together, to create a new output that conveys more information than either model did individually.

2. Methods

In order to evaluate the relevance, scope, and complementarities of IAMs, we start with a set of classifications. Models are categorized according to the following traits:

i. Field: Sectors of the Economy and Focal Points (Figure 1). Primary and secondary fields are assigned to cover the multidisciplinary nature of most of the models
ii. Suite: Programming and software requirements
iii. Economic Complexity: general equilibrium versus partial equilibrium models

Having said that, we cast our focus to the main outputs of each model, in order to identify the projections derived from each exercise. In addition, this allows us to identify
potential synergies between models through (i) model averaging techniques and (ii) integration whereby outputs from a certain model feed into another model as inputs.

**Figure 1. Classification of IAMs by primary field**

Source: Authors’ Elaborations
3. IAMs Review

Twenty-nine IAMs were evaluated (see Table 1) in this exercise, however, due to spatial constraints, one model of each of the primary fields will be presented here.

Table 1. List of assessed IAMs

<table>
<thead>
<tr>
<th>FABLE</th>
<th>PRIMES Model</th>
<th>PLEXOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>bayesMig</td>
<td>GAINS</td>
<td>C-ROADS</td>
</tr>
<tr>
<td>bayesPop</td>
<td>CAPRI</td>
<td>GACMO</td>
</tr>
<tr>
<td>climate4R</td>
<td>GLOBIOM</td>
<td>IBC</td>
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<tr>
<td>InVEST</td>
<td>G4M</td>
<td>EnerMED</td>
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<tr>
<td>KrigR</td>
<td>BALMOREL</td>
<td>WEAP</td>
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<tr>
<td>MaGE</td>
<td>LEAP</td>
<td>Prospects+</td>
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<tr>
<td>MIRAGE-e</td>
<td>SWITCH</td>
<td>SCREEN</td>
</tr>
<tr>
<td>ReMIND</td>
<td>GCAM</td>
<td>CLIMTRADE</td>
</tr>
<tr>
<td>WITCH Model</td>
<td>TIMES</td>
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3.1 Selected IAMs description
Agricultural primary field:

**G4M**

(Global Forest Model) is a climate model comparing the income derived from forests with the income that could be derived from an alternative use of the same land, for example, to grow grain for food or biofuel. G4M demonstrates whether it would be more profitable to grow agricultural crops or biofuels at the location, or whether forestry is the best option for the land. G4M is a versatile model that can be integrated with other models to gain greater clarification of land use potential.

As well as demonstrating the pros and cons of different land uses, it can compute optimal forest rotation times to optimize biomass stocking and harvesting rates and can also help to rationalize other important aspects of forest management. Its primary field is land use, while its categories are forestry, economics, population, migration, agricultural, food, water, ecosystems. Its schematic can be seen in Figure 2 that follows.

*Synergies: GLOBIOM*

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1. [https://previous.iiasa.ac.at/web/home/research/researchPrograms/EcosystemsServicesandManagement/G4M.en.html](https://previous.iiasa.ac.at/web/home/research/researchPrograms/EcosystemsServicesandManagement/G4M.en.html)
BayesPop is an open access R package for probabilistic population projections using outputs from bayesTFR and bayesLife as inputs. Raftery et al. (2012) describes the methodology. Azose (2016) and Ševčíková et al. (2014) give details that are more technical. Its categories are population, fertility, mortality and migration and its primary field includes economics.

**Input:** The input components needed to run the simulation include the initial male, female age-specific population counts; Estimates of historical male and female age-specific death rates; Estimates of historical age-specific fertility rates as percentages of TFR; Projection of future sex ratio at birth and others.

**Output:** The BayesPop model is a probabilistic projection model that provides, as output, a set of sex- and age-specific population trajectories (Figure 3), which can be used to construct posterior distributions of various population quantities of interest.

**Synergies:** (Cooperative) bayesTFR, bayesLife, MortCast

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2 [https://bayespop.csss.washington.edu/](https://bayespop.csss.washington.edu/)
Figure 3. Population trajectories for aggregated regions using BayesPop obtained via the country-based method³

Climate category: IBC

IBC⁴ (Integrated Benefits Calculator) is an add-on module included in LEAP energy model. It translates emissions scenarios from LEAP into estimates of air pollution-associated health issues (premature mortality), ecosystem impacts (crop yield loss), and climate impacts (global temperature change). IBC examines the numerous benefits in taking measures regarding the long- and short-lived climate pollutants (SLCPs) and the local air pollutants.

Inputs: utilizes parameterized results from the global atmospheric geochemistry model GEOS-Chem Adjoint, which are combined with emission estimates to calculate population-weighted concentrations of fine particulate matter (PM2.5) and ground-level ozone (O3).

Output: The above concentrations are then used with standard concentration-response functions to estimate premature mortality associated with PM2.5 and ozone exposure and crop yield losses associated with ozone exposure. The results can be viewed by a) geographic source (in-country, natural background, and rest of the world), b) the

⁴https://leap.sei.org/default.asp?action=IBC
contribution of emissions of different pollutants to the impact (e.g. the contribution of NOx, black carbon, organic carbon, etc.), c) age group (for premature mortality) or d) crop type (for crop losses, currently rice, wheat, maize, and soy). Health impact functions are based on the standard dose-response functions used in the Global Burden of Disease Study. The process from emissions to impacts investigated by LEAP and IBC is seen in Figure 4.

**Synergies:** LEAP, GEOS-Chem Adjoint

**Figure 4. The pathway from emissions to impacts in LEAP-IBC**

Source: SEI

**Economy category: ReMIND**

**ReMIND** (REgional Model of Investment and Development) is a numerical model that represents the future evolution of the world economies with a special focus on the development of the energy sector and the implications for global climate.

The goal of ReMIND is to find the optimal mix of investments in the economy and energy sectors of each model region given a set of population, technology, policy, and climate constraints. It also accounts for regional trade characteristics on goods, energy fuels, and emissions allowances. All greenhouse gas emissions due to human activities are represented in the model. It is an open access, R-package, general equilibrium model.

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5 [https://ehp.niehs.nih.gov/doi/10.1289/ehp.1307049](https://ehp.niehs.nih.gov/doi/10.1289/ehp.1307049)
It covers twelve world regions, differentiates various energy carriers and technologies, and represents the dynamics of economic growth and international trade. ReMIND uses economic output for investments in the macro-economic capital stock as well as for consumption, trade, and energy system expenditures. It falls into the economic, energy and climate categories, while its fields of functioning also include population and migration. The structure of ReMIND is depicted in Figure 5.

Synergies: Part of the Potsdam Institute for Climate Impact Research (PIK), specifically MAgPIE and MAGICC.

Figure 5. ReMIND structure

Source: Baumstark & al. (2021)

Energy category: PRIMES

**PRIMES** (Figure 6) is an EU energy system model, which simulates energy consumption and the energy supply system. It is a partial equilibrium modelling system simulating an energy market equilibrium in the European Union and each of its Member States. This includes consistent EU carbon price trajectories. The full PRIMES suite comprises models involving transportation, biomass supply, industry, electricity and heat supply.

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7 https://e3modelling.com/modelling-tools/primes/
and several others. However, despite the diversity of these fields the focus of all of them is on energy supply and consumption.

The distinctive feature of PRIMES is the combination of behavioural modelling (using microeconomic foundations) with engineering aspects, covering all energy sectors and markets. The model provides a detailed representation of policy impact assessment instruments related to energy markets and climate, including market drivers, standards, and targets by sector or overall. It handles multiple policy objectives, such as GHG emissions reductions, energy efficiency, and renewable energy targets and provides pan-European simulation of internal markets for electricity and gas.

PRIMES inputs include GDP and economic growth per sector, for many sectors; world prices of fossil fuels; taxes and subsidies; interest rates and risk premia; environmental policies and constraints and several others. The outputs include detailed energy balances, in EUROSTAT format; detailed demand projections by sector including end-use services, equipment and energy savings; detailed balance for electricity and steam/heat, including generation by power plants, storage and system operation; production of fuels (conventional and new, including biomass feedstock); emissions of atmospheric pollutants; Policy Assessment Indicators and quite a few others. The outputs depend on the model used and the inputs that provided.

*Synergies/ linked models: GEM-E3 and IIASA’s GAINS*
4. Synergies

4.1 The Stockholm Environment Institute (SEI) models’ synergies

LEAP and IBC developed by SEI\(^9\) maintain a cooperative synergy, where the outputs from LEAP model are used as input for IBC model. The calculations of IBC are based on emissions inventories and projections developed in LEAP for a specific country. Users are required to specify extensive emissions inventories and forward-looking scenarios for all major long-lived and short-lived climate pollutants (SLCPs), and local air pollutants such as CO2, CH4, black carbon, organic carbon, PM2.5, non-methane volatile organic compounds (NMVOCs), NOx, SO2 and NH3. A comprehensive set of default emission factors for these pollutants has been evolved by SEI that can be added to existing data sets, which is applicable, for instance,

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8 https://e3modelling.com/modelling-tools/primes/

9 https://www.sei.org/
in the case of a country that has already developed a LEAP data set for its analysis of its Nationally Determined Contributions (NDCs). A template LEAP structure for performing these types of analysis, named "Asiana" data set, and focused on sectors that are important in terms of generating emissions of important SLCPs, has been also developed by SEI. Furthermore, users can merge their existing data sets with parts of the standard template structure, to create a data set that meets the needs of the subject country.

IBC makes a complex and highly computing-intensive modelling methodology accessible to planners in the developing world. It parameterizes the calculations of GEOS-Chem Adjoint that takes a few days to perform per country, and hereinafter, the calculations in LEAP are run in a few seconds. LEAP is furthermore used for all data management and results visualization, making it readily usable by developing country planners. Up to 2018, LEAP-IBC worked for a selected set of national-scale applications, designed to operate for 71 countries for PM2.5, and 20 countries for Ozone-related impacts. An expansion of coverage to 150 countries in 2018 was planned. Moreover, an IBC tool with city scale application, providing greater information on the impacts of indoor air pollution, including gender-based disaggregation of impacts has been also scheduled.

4.2 Compass Toolbox from New Climate Institute

New Climate Institute\textsuperscript{10} has developed the “COMPASS” toolbox within the framework of the Climate action Outcomes and Mitigation Policy Assessment. The toolbox involves New Climate Institute produced climate scenario modelling tools, for understanding and assessing the impacts of climate action and policies for climate change mitigation. The models are excel based analytical tools to expedite the comparison of different scenarios, policies, and outcomes and to investigate potential opportunities and obstacles in raising climate ambition. All these tools can be utilized independently, or with soft links to other COMPASS tools and/or third-party models.

The following IAMs are harnessed under a cooperative synergy scheme model:

i. PROSPECTS+ and CAAT (Climate Action Aggregation Tool) for tracking and projecting GHG emission scenarios at sectoral and economy-wide levels.

\textsuperscript{10} \url{https://newclimate.org}
ii. SCAN (SDG Climate Action Nexus tool), EIM-ES (Economic Impact Model for Electricity Supply), AIRPOLIM-ES (Air Pollution Impact Model for Electricity Supply), TRACE (Transport sector climate action co-benefit evaluation tool), SCREEN (Sustainable development and climate action green recovery screening tool) and CLIMTRADE (Economic impacts of climate regulation in trade tool) for understanding the impacts of climate action on sustainable development objectives.

iii. EV policy impact assessment tool and RE policy impact assessment tool, both supporting policy impact projections drawing on technology S-curve modelling logic.

5. Model Integration for Sustainable Pathways

5.1 Global Climate Hub’s Modelling Suite

This section discusses the potential for system integration under the auspices of the GCH and highlights the areas of Hub’s future work in promoting net zero pathways. Model-based scenario quantification will support impact assessments and analysis of policy options towards decarbonization, using the classification and evaluation of IAMs described in Section 2.

Model-based scenario quantification is a technique used to evaluate and measure the potential outcomes of different scenarios using mathematical or computational models. It is commonly employed in various fields, including economics, finance, environmental science, and engineering. The primary goal is to assess the impact of various inputs or assumptions on the model's outcomes under different scenarios. Scenarios represent different possible future states, conditions, or events. These scenarios could be based on different assumptions, policies, external factors, or interventions. For example, in economics, scenarios might include different economic growth rates, inflation levels, or economic policy changes. In environmental science, scenarios could involve varying levels of greenhouse gas emissions or climate change impacts.

The GCH’s Modelling suite aims both to identify the interlinkages between the different models (Economics, Energy/ Transportation, Land Use/ Forest/ Agriculture and Non
GHG emissions Air Pollution), as well as to improve the predictive accuracy by applying achieving a soft integration and model averaging techniques, which involves combining the predictions or outputs of multiple models in a way that allows for a gradual or weighted influence of each model’s input.

5.2 Model inter-linkages

Harnessing the inter-linkages and complementarities of different models is the key for generating and evaluating diverse sustainable pathways which entail environmental, energy and socio-economic outcomes. Figure 7 presents a working scheme using the interlinkages between a series of models presented throughout the current report. The models are linked in formally defined ways to ensure consistency in the building of scenarios.

**Figure 7: Model inter-linkages**

The models included in Figure 7 are indicative and intent to cover all GHG emissions and removals. It covers emissions from energy and processes (BALMOREL), CH4, N2O, fluorinated greenhouse gases (GAINS), CO2 emissions from LULUCF (FABLE), air
pollution SO2, NOx, PM2.5-PM10, ground level ozone, VOC, NH3 (GAINS). Considering emission reduction and removals, the models cover the structural changes and technologies in the energy system and industrial processes (PRIMES), technological non-CO2 emission reduction measures (GAINS), as well as changes in land use (GLOBIOM-FABLE).

Finally, the integrated modelling suite includes impacts on energy, transport, industry, agriculture, forestry, land use, atmospheric dispersion, health, ecosystems (acidification, eutrophication), ecosystem services, macro-economy with multiple sectors, employment, and social welfare.

5.3 Modelling Averaging Techniques

The task of the optimal combination of different models for predicting the future evolution of quantities of interest is of particular importance in economics and in many other fields. This interdisciplinary modelling approach is met in the literature with various terms like model averaging (Hansen, 2007; 2012; Moral-Benito, 2015), model fusion (Hassan, 2007) or model aggregation (Papayiannis, 2018a; 2018b). This task refers to the situation when a set of different models which provide projections for the same quantity of interest (e.g., evolution of GDP, labor, inflation, etc.) are available and the decision maker needs to optimally combine these different sources of information to derive the most accurate aggregated projection. The great advantage of this approach is that it allows the aggregation of different models (allowing for them to be built under conflicting assumptions) since this approach is assumption-free. It can be implemented either at a static or at a dynamic setting allowing for a proper update and re-tuning of the aggregate model (Bayesian-type approaches, see e.g., (Fragoso et al., 2018; Raftery, 1997; Wasserman, 2000 and references therein). A sketch of how this aggregation scheme works is illustrated in Figure 8.
A crucial step for the accurate tuning of the aggregate model, i.e. the one which output will be used as the optimal projection, is the availability of both historical data for the quantity of interest (actual values) and both projections of all the models in the set. Both outputs are compared and combined during the training stage of the aggregate model (which is usually repeated at certain time instants) to determine the optimal model by assessing the accuracy of each one of the models that contribute to the aggregate one, and accordingly increase or reduce its model’s impact. The averaging scheme that is used depends on the field of application, the data availability, and the data nature. For simple point estimates a linear aggregation scheme may suffice but when complex data forms occur (e.g. measure-valued data, matrix-valued data, functional data, probabilistic projections, etc.), more sophisticated modelling approaches are considered and implemented. In the simplest case of a linear aggregate model, a set of weight is determined based on the empirical evidence compared to each model’s performance under several appropriate criteria. Moreover, the model averaging approach can be also used to aggregate models which provide projections for various quantities of interest (it is not necessary all the models to provide projections for the same quantities) by partially averaging the components of interest but considering in the assessment stage the total
performance of each model. This is quite the case when one wishes to combine general equilibrium models since could be quite different in nature and subject to much different assumptions. In this manner, it is possible for the resulting aggregate model to play the role of a data-driven integrated model able to provide more accurate projections for all projected quantities by the models in the set, respecting each model’s philosophy.

6. Conclusion

The examination of potent IAMs (Integrated Assessment Models) for sustainable pathways underscores the critical importance of robust decision-making tools in navigating the complexities of sustainability challenges. These models offer valuable insights into the interplay between economic growth, environmental conservation, and social equity, providing stakeholders with a framework to evaluate policy interventions and their long-term implications. However, while IAMs serve as powerful instruments for scenario analysis and policy formulation, their effectiveness hinges upon accurate representation of diverse systems and uncertainties, necessitating ongoing refinement and collaboration across interdisciplinary domains.

IAMs should be considered as complementary and not competing. Exhibiting a vast range of sectoral expertise, different IAMs can be utilized for different predictions, yielding precise results. The possibility of adaptation to local or sectoral level (downscaling) of an Integrated Assessment Model would further assist the predictions regarding a specific country or area.

Integrated Assessment Models (IAMs) offer great possibilities for scientific predictions. IAMs offer a holistic systems approach incorporating economy, energy, climate, and biodiversity sectors. However, the complementarity and synergies between the IAMs should be further investigated. Finally, IAMs can facilitate the evaluation of Sustainable Pathways within the framework of the Global Climate Hub. The UN SDSN Global Climate Hub promotes research harnessing knowledge, talent, and tools from a wide range of scientific fields to deliver socio-economic pathways which have human development in the epicenter. A key pillar of the work in the GCH includes using advanced modelling
techniques to estimate the projection of key economic, environmental, and social outcomes for the medium- and long-term horizon.

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