Integrated Assessment Models (IAM) How to integrate Economics, Energy and Climate?

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Integrated Assessment Models (IAM)
How to integrate Economics, Energy and Climate?

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From the pioneering work of Forrester (1965, 1969) and Meadows (1972) with the World 2 and World 3 models based on system dynamics methodology, to the models developed by IPCC experts (2001, 2015), modeling from a global environmental prospective (Matarasso, 2003) has become increasingly integrated. In the 1990's, some models were developed to combine different key elements of biophysical, social, and economic systems into one integrated system (Dowlatabadi, Morgan, 1993, 1995). What we call today Integrated Assessment Models (IAMs) became powerful tools for thinking, simulation and decision support.

Kelly and Kolstad (1999, p. 3) defined an integrated assessment model as "*any model which combines scientific and socio-economic aspects of climate change primarily for the purpose of assessing policy options for climate change control*". Integrated assessment induces an "*interdisciplinary and participatory process of combining, interpreting and communicating knowledge from various scientific disciplines to enable understanding of complex phenomena*" (Parker, 2002).

Weyant et al (1996) gave three purposes for integrated assessment: (1) Assess climate[1] change control policies, (2) Constructively force multiple dimensions of the climate change problem into the same framework, (3) Quantify the relative importance of climate change in the context of other environmental and non-environmental problems facing mankind. The final goal of integrated assessment is to build the best possible response[2], with present knowledge, to the questions asked by decision makers about environmental issues (Kieken, 2003). This goal is usually achieved by integrating work from various disciplines into an interactive process that includes researchers, managers, and stakeholders. The release and sharing of knowledge between communities is ensured by the implementation of three kinds of complementary

[1] If energy system and macroeconomic structure have been usually connected, the integration of climate in a global system is a recent practice. Climate has been invited to the debate following the various IPCC reports (1990, 2018) and the controversies related to global warming.

[2] Pearson and Fisher-Vanden (1997, p. 593) considered that IAMs brought four broad contributions: evaluating potential responses to climate change; structuring knowledge and characterizing uncertainty; contributing to broad comparative risk assessment; and contributing to scientific research.

tools[3]: (1) Integrated assessment computer models designed as methodological frameworks for interdisciplinary work which are the means to integrate knowledge from a variety of disciplines, (2) Qualitative scenarios to take into account what is not modellable, (3) Participatory methods involving stakeholders other than scientists and politicians, with the aim of improving the acceptability of decisions through a better understanding of the issues, legitimizing the decision-making process through the early involvement of stakeholders, and introducing non-expert knowledge of the issues).

IAMs are usually divided into two categories: policy optimization IAMs and policy evaluation IAMs. Policy optimization IAMs search for the optimal policy. They can be split into three principal types: (i) Cost/benefit models which try to balance the costs and the benefits of climate policies, (ii) Target based models which simulate the effect of an efficient level of carbon abatement in the world economy, (3) Uncertainty based models which deal with decision making under conditions of uncertainty (Manne, Richels, 1992; Nordhaus, 1994). Many policy optimization models start with a market economy in which the regulatory instrument is a tax and then convert the model to an equivalent problem which finds the optimal emissions. Such models maximize the weighted sum of utilities where the weights are adjusted until individual budgets balance (which is equivalent to a Pareto Optimum (second welfare theorem)), or start with optimal emissions and convert the results into a tax. So optimization models are standardized and provide a description of the world, given the assumptions of the equivalence theorems. Policy evaluation IAMs are well-known as simulation models. They include deterministic projection models in which each input and output takes a single value, and stochastic projection models in which at least some inputs and outputs take a range of values. Policy evaluation models take actions by agents and governments as given, provided by policy proposals, assumption, observation and expert opinion.

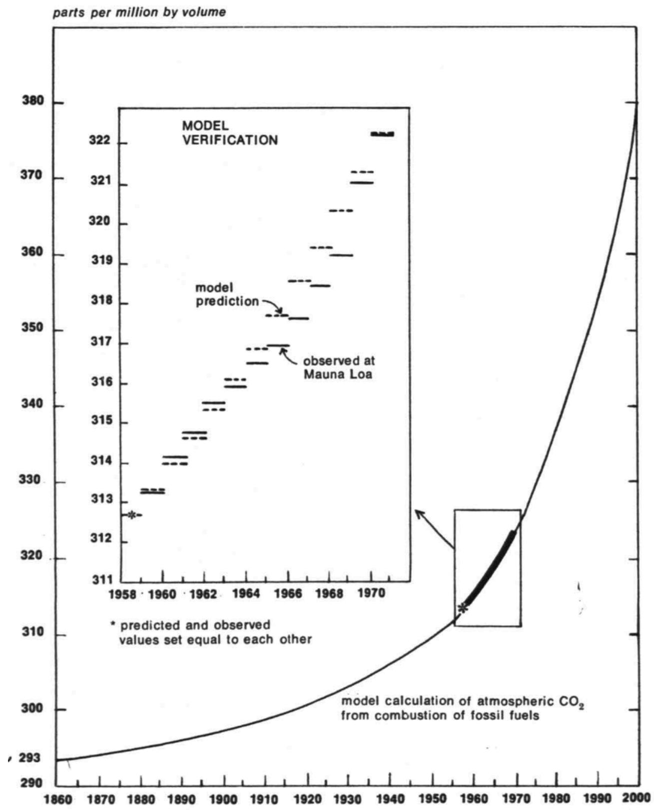
In this chapter, we propose to review 6 IAMs (World 3, DICE, IMAGE, MESSAGE, GEM-E3 and REMIND) to understand how these models are able to integrate Energy, Climate and Economics. We will resume their main results in a table to present goals, structure, policy evaluation, policy optimization, and dynamics associated with the models. We will identify the future challenges for research design and policy decisions.

[3] Rotmans and Dowlatabadi (1998) noted that current integrated assessment research used one or more of the following methods : (i) computer-aided IAMs to analyze the behavior of complex systems, (ii) simulating gaming in which complex systems are represented by simpler ones with relevant behavioral similarity; (iii) scenarios as tools to explore a variety of possible images of the future; (iv) qualitative integrated assessments based on a limited heterogeneous data set, without using any models.

1. World 3 - the first design of an IAM?

In the 1972 *Limits to Growth* report, the climate system is not part of the model. The pollution variable is captured by the concentration of carbon dioxide in the atmosphere. Meadows et al (1972, p. 71) introduced a positive loop: the more industrial production increases, the more fossil energy (coal, oil and natural gas) is used; this releases CO2 into the atmosphere and causes an increase in mortality.

Figure 1: Concentration of CO2 in the Atmosphere

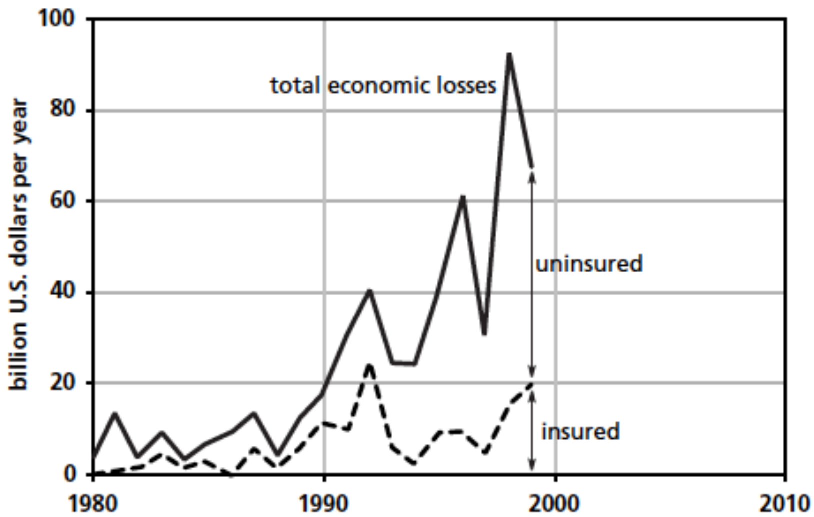


Source : Meadows et al. (1972, p. 72)

It would be necessary to wait for the publication of *Beyond The Limits* (1992) for climate to be explicitly integrated into system dynamics, but it was only mentioned in Chapter 3 (The Limits: Sources and Sinks) on pollution and waste. While global climate change is clearly presented as the new challenge for the coming years (scientific evidence of global warming is accumulating), its analysis continues to feed into the growth debates: "*Many scientists believe that the next global limit humanity will have to deal with is the one called the greenhouse effect, or the heat trap, or global climate change*" (1992, p. 92). Thus, global climate change cannot be detected in the short term, but over decades. To these long-term observations, three types of uncertainties must be added: 1. What would the global temperatures be without human intervention? A reduction in growth may not be sufficient to reduce CO2 concentrations if they increase naturally in the long term, 2. What are the consequences of global warming on precipitation, winds, ecosystems and human activities at particular locations on Earth? 3. How to understand all the loops associated with carbon and energy flows. The modelling of such a system is complex and control loops can be used to stabilize CO2 emissions (the oceans can absorb some of them).

The publication of *Limits to growth, the 30 years update* (2004), deserves attention, as the climate generates many loops in World 3. The report does not hesitate to target economists, the main climate skeptics and to highlight the consequences of climate change on economic activities, and therefore on economic growth: "*More scientists, and now many economists as well, believe the next global limit humanity will have to deal with the greenhouse effect, or global climate change... Even some economists - a group well known for its skepticism about environmentalist alarmism - are becoming convinced that something unusual and significant is going on in the atmosphere, and that it may have human causes*" (2004, p. 113-115).

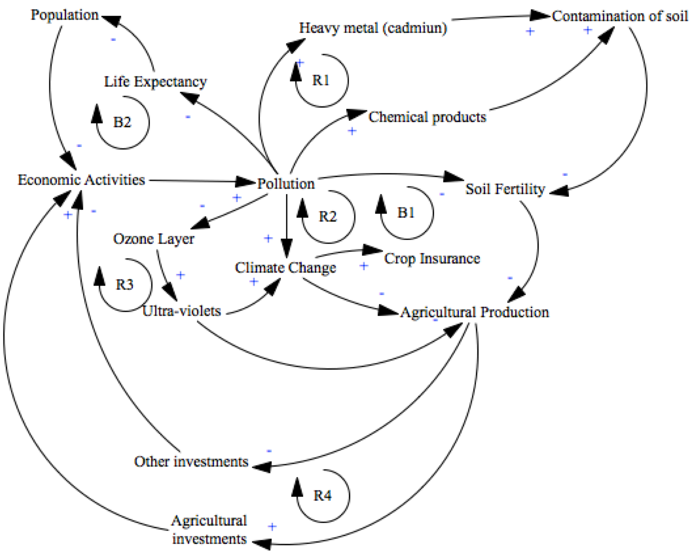
Figure 2: Worldwide Economic Losses from Weather Related Disasters



Source : Meadows et ali. (2004, p. 117)

Climate change is causing economic losses that call into question the viability of insurance systems (the 1990s and 2000s marked a break in the trend, with the share of damage not giving rise to big reimbursement increases). Scenario 2 (Global Pollution Crisis) introduces the damaging effects of pollution and climate change. The positive loop is as follows: an increase in pollution reduces land fertility, which in turn reduces agricultural production, investments move to agricultural sector to maintain food production and decrease in other sectors, pollution leads to lower life expectancy and increased mortality. This loop is reinforced by three effects: land contamination by heavy metals and chemicals, climate change that randomly and repeatedly alters agricultural production, and ultraviolet radiation related to ozone depletion.

Figure 3: Positive and negative loops in the scenario "more pollution"



This work has been widely criticized by economists, William Nordhaus (1972, 1973) was the main architect of this critique. In an article co-written with James Tobin entitled "Is Growth Obsolete? ", Nordhaus responded to the report: (« *We mention this point now because we shall return later to the ironical fact that the antigrowth men of the 1970s believe that it is they who represent the claims of a fragile future against a voracious present*", 1972, p. 4) by mobilizing theory around three questions: 1. The measurement of economic growth, 2. The link between growth and natural resources, 3. The link between population growth rates and economic well-being.

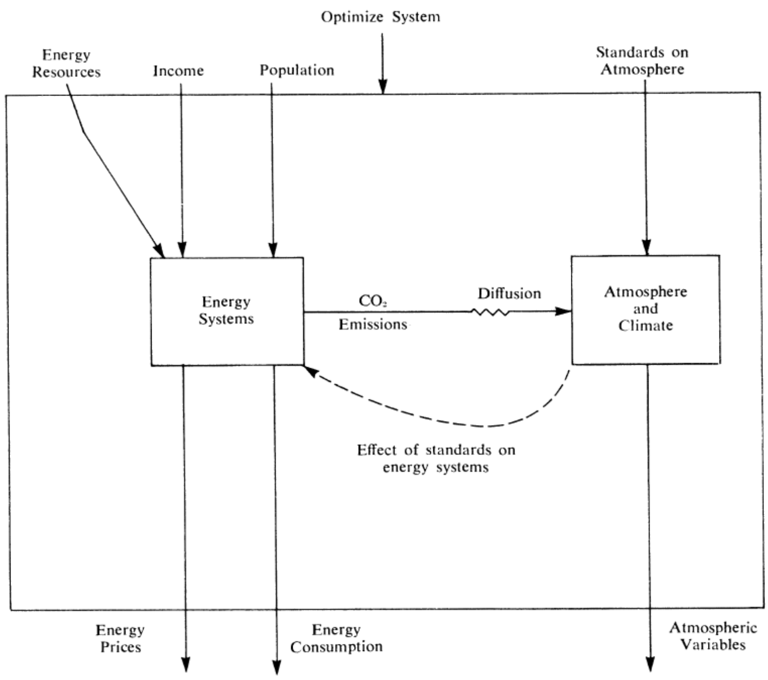
A year later, Nordhaus (1973) repeated his critique, targeting Forrester's *World Dynamics*. The title "World Dynamics Measurement without data" and the content of the article are unequivocal. « *What is the overall impression after a careful reading of World Dynamics? First, the dynamic theory put forward in the work represents no advance over earlier work… Second, the economic theory put forth in World Dynamics is a major retrogression from current research in economic growth theory… Third, Forrester has made no effort in World Dynamics to identify any relation between his model and the real world… Fourth, the methodology of modelling in World Dynamics differs significantly from other studies of economic systems…Fifth, the predictions of the world's future are highly sensitive to the specification of the model… Sixth, there is a lack of humility toward predicting the future*" (1973, p. 1183).

2. DICE - the Carbon Dioxide Problem

It is in this context that Nordhaus would undertake his research "Resources as a constraint to growth" (1974), into the management of energy resources, and then take into account the impact of CO2 concentration in the atmosphere. He concludes that assuming that "*10 percent of the atmospheric CO2 is absorbed annually (G. Skirrow), the concentration would be expected to rise from 340 ppm in 1970 to 487 ppm in 2030 - a 43* *percent increase*" (1974, p. 26). His paper is a first attempt at integrated climate modelling. It is rudimentary (only the CO2 variable is taken into account), but it does reflect the debates of the 1970s. Against the backdrop of the energy crisis, Nordhaus intended to develop a global energy model that could be coupled with a climate model. Nordhaus presented this theoretical framework in two articles, one presented to the Cowles Commission (Strategies for the Control of Carbon Dioxide, 1976), the other published in The American Economic Review (Economic Growth and Climate: The Carbon Dioxide Problem, 1977).

Figure 4 provides an overview of the model used by Nordhaus to study carbon dioxide emission control strategies.

Figure 4: Optimization model of energy and environmental system



Source: Nordhaus (1977, p. 343)

The "energy system" block is a system combining market mechanisms and economic policies. The key variables are energy, natural resources, income, and population. The interaction of supply and demand leads to a trajectory of optimization of prices and consumption over time. To take into account externalities, such as the carbon cycle, Nordhaus proposes to take into account CO2 emissions and distribution. This step leads to the imposition of standards on atmospheric concentrations (right side of the figure). By imposing such standards, it becomes possible to close the loop and force the energy system to act on the structure of supply and demand. Nordhaus is examining two strategies to keep atmospheric CO2 concentrations at a reasonable level. The first strategy is to reduce carbon dioxide emissions. This means replacing high CO2 fuels with low CO2 fuels. The second strategy is to offset the effects of carbon dioxide emissions or use new industrial processes (environmental technologies) to "suck" carbon dioxide from the atmosphere. In order to avoid "*the odor of science fiction*" (1977, p. 343), Nordhaus favors the first strategy by seeking to optimize the system based on standards.

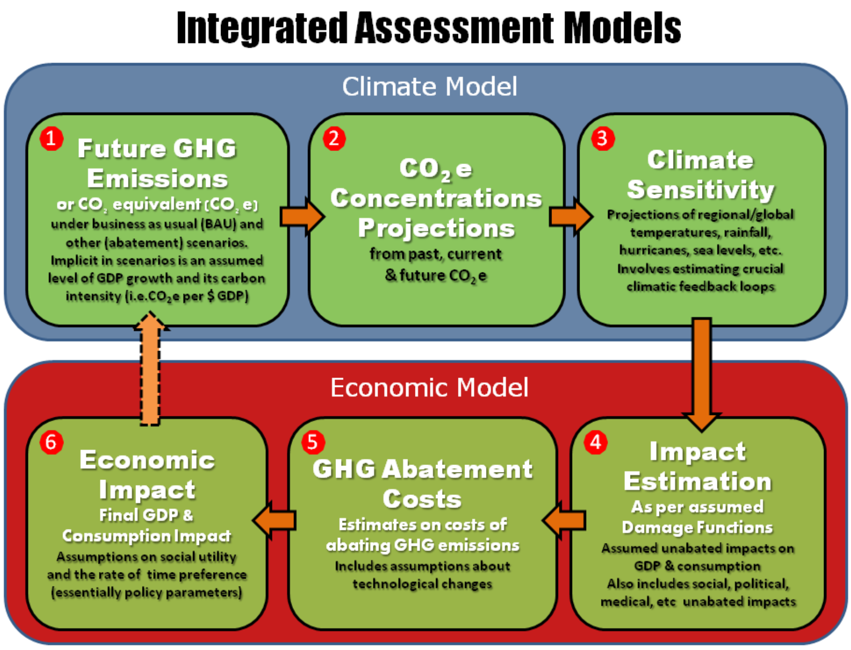
It was not until the 1990s that the DICE (Dynamic Integrated Model of Climate and the Economy) and RICE (Regional Integrated Model of Climate and the Economy) family of models was born (Nordhaus, 1992, 1994). The DICE model is a dynamic optimization model (Ramsey, 1920) which seeks to estimate the optimal GHG reduction trajectory. The optimal trajectory can be interpreted as the most effective way to slow climate change, taking into account inputs and technologies (Veille-Blanchard, 2007). It can also be interpreted as a competitive market balance in which externalities are adjusted using appropriate social prices for GHGs. In the DICE model, emissions include all GHGs, however, those associated with CO2 are preferred. GHG emissions, which accumulate in the atmosphere, can be controlled by increasing the prices of inputs (such as energy) or GHG-intensive products. Climate change is captured by the overall average global temperature, a variable used in most current climate models. The economic impacts of climate change are assumed to increase as the temperature increases.

In the space of two decades, the DICE model has been a huge success, for which three reasons can be given. The first reason is the multiple revisions proposed by Nordhaus: an intermediate version (Nordhaus, 2008) and an updated version (Nordhaus 2017). The DICE model has been iterated many times, incorporating recent economic and scientific results and updated economic and environmental data. The second reason is based on a detailed description of the model (Nordhaus, Sztorc, 2013) with the availability of the DICE manual and the possibility of carrying out simulations. The third reason is the media coverage of DICE through the publications and work of the IPCC (since 1995) and many energy agencies (including the US agency).

To this, we add a fourth reason that affects the way Integrated Assessment Models (IAM) are approached today. This fourth reason is that the DICE model has initiated a way of thinking about integration, which can be summarized by the following process: integration of CO2 emissions, impacts on economic activities, economic policy measures. As a result, Climate, Energy, and Economics are now the main building blocks for integrated assignment models (Ha-Dong, Matarasso, 2006; Gladkykh, Spittler, Dierickx, 2017).

Integrated models are not limited to the DICE model, other models emerged in the 1990s - ICAM (Dowlatabadi, Morgan, 1993), IMAGE (Alcamo, 1994), MERGE (Manne et al, 1995), MiniCAM (Edmonds et al, 1996). Some like IMAGE (Integrated Model to Assess the Global Environmental) even follow in the footsteps of World 2 and World 3, adopting an architecture built around the main drivers (population, economy, politics, technology, lifestyle and resources) of the human and earth ecosystems. Thus, alongside small, simplified and discipline-based models (DICE and economics), there are global, complex and interdisciplinary models (World 3, IMAGE). These two main families of models have contributed to enriching the debate about the integrated approach to climate change, each with its strengths and weaknesses.

Figure 5: Coupling climate system and economic system



Source: deconstructingrisk.com

The 2000s were marked, not by rivalry between models (although it does exist), but by a reflection about the processes of integration (Matarasso, 2003) and evaluation (Schwanitz, 2013) of IAMs (Pearson and Fisher-Vanden, 1997). This is particularly visible through the many definitions which have been used. Integrated assessment can thus be defined as "*an interdisciplinary and participatory process aimed at combining, interpreting and communicating knowledge from various scientific disciplines to enable the understanding of complex phenomena*" (Parker, 2002). It aims to build the best possible response, in the current state of knowledge, to questions asked by decision-makers on environmental issues (Kieken, 2003). This objective is generally achieved by integrating the ongoing work of various disciplines into an interactive process that includes researchers, managers, and stakeholders. The circulation and sharing of knowledge between communities is ensured by the implementation of three families of complementary tools: (1) Computer models of integrated assessment designed as a methodological frameworks for interdisciplinary work and the means of integrating knowledge from various disciplines, (2) Essentially qualitative scenarios to take into account what is not modellable, (3) Participatory methods involving stakeholders other than scientific and political (the aim here is to improve the acceptability of decisions through a better understanding of the issues; to legitimize the decision-making process through the early involvement of the actors concerned; to introduce non-expert knowledge).

These interdisciplinary computerized models, designed to address issues of climate impact, climate adaptation and climate change, are still not robust. While each discipline provides some knowledge about the processes which determine the evolution of the Earth/Society system, their interaction poses a number of problems. For example, climatologists' General Circulation Models (GCMs) do not allow us to study in detail the strategies for reducing greenhouse gas emissions. It is therefore necessary to look at the energy system in order to identify energy production and transformation technologies. These technologies must, in turn, be included in a macroeconomic model, designed to understand the major monetary and financial balances that regulate the economy. To address these limitations, the modelers have developed a modular approach, based on the coupling of existing models, which are themselves based on a discipline. Integration is based on the following: (1) Climate models (more or less complex), (2) Energy system models, (3) Macroeconomic models of global activity, (4) Carbon cycle models (often related to land use). These couplings generate a multitude of challenges (depending on whether the modules are solved simultaneously or successively or according to the finesse of the different representations of the modules), which demand the creation of a real network of modelers, users, and decision-makers at the IAM level. This is the price to pay for the necessary changes in our behavior with regard to climate change.

3. MESSAGE - Shared Socioeconomic Pathways

The IIASA IAM framework is a combination of five different models – The energy model MESSAGE, the land use model GLOBIOM, the air pollution and GHG model GAINS, the aggregate macro-economic model MACRO, and the climate model MAGICC. These five models provide inputs, drivers and dynamics to describe alternatives futures for societal development. Scenarios of global development focus on the uncertainty of the future conditions of society, describing future societies that can be combined with climate change projections and climate policy assumptions to produce integrated scenarios to explore climate mitigation, climate adaptation and residual climate impacts in a consistent framework. Society’s development scenarios consist of qualitative and quantitative components (Raskin et al, 2005). Quantitative components introduce assumptions for variables such as population, economic growth (GDP), technological progress, food, etc which are quantified and used as inputs to model energy use, land use, GHG emissions (Rothmans et al, 2007). Qualitative storylines describe the evolution of society such as quality of institutions, environmental awareness, and political stability to “*provide a certain logic to the multiple assumptions and to help to define possible developments for those areas where formal modeling is not meaningfully possible due to ignorance and complexity*” (Van Vuuren et al, 2012, p. 888). If the process to develop a new set of integrated scenarios describing climate, society and environmental change, is still happening, a few researchers (Krieger et al, 2012, O’Neill et al, 2014, Kriegler et al, 2014, Riahi et al, 2017; O’Neill et al, 2017; Van Vuuren et al, 2017, Bauer et al, 2017) have introduced alternative pathways of future development of society called *shared socioeconomic pathways* (SSPs)[4]. A conceptual framework has been produced for the development of SSPs (O'Neill et al, 2014, 2015) and for the combination of Integrated Assessment Model (IAM) scenarios based on SSPs with future climate change outcomes and climate policy assumptions, to produce integrated scenarios and support other kinds of integrated climate change analysis. SSPs describe plausible alternative changes in aspects of society such as demographic, economic, technological, social, governance' and environmental factors.

Figure 6: Five shared Socioeconomics Pathways

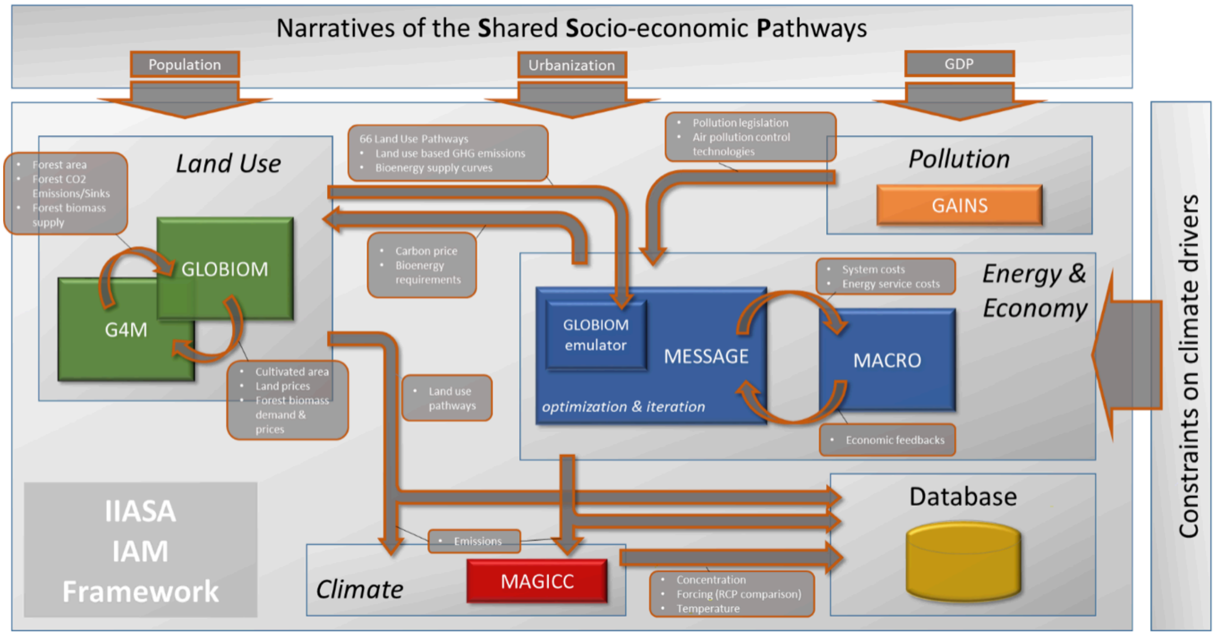
Source: O'Neill et al (2014, p. 391; 2015, p. 2)

Five shared socioeconomic pathways have been proposed to represent different combinations of challenges to climate change mitigation and to climate adaptation (O'Neill et al, 2014, 2015): SSP1 (Sustainability: taking the green road), SSP2 (Middle of road), SSP3 (High challenge: Regional Rivalry, a rocky road), SSP4 (Adaptation challenges Dominate: Inequality, a road divided), SSP5 (Mitigation challenges dominate: fossil fueled development, taking the highway).

From these five SSPs, three following narratives have been introduced into the IIASA – IAM framework: SSP1 (sustainability), SSP2 (middle of the road) and SSP3 (regional rivalry, a rocky road).

[4] *"We define SSPs as reference pathways describing plausible alternative trends in the evolution of society and ecosystems over a century timescale, in the absence of climate change or climate policies* » (O'Neill, 2014, p. 387 – 388).

Figure 7: Narratives of the Shared Socio-economic Pathways in IAM



Source: http://data.ene.iiasa.ac.at/message-globiom/overview/index.html

MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) represents the core of the IIASA (International Institute of Applied Systems Analysis) IAM framework. It was developed in the 1980s. While it is possible to use the model on a global scale it has also been applied to various national energy systems. The model is a technology-rich bottom-up energy system model, which is very detailed on the supply side but not on the demand side. It is used for modelling the supply side and its general environmental impacts, planning medium- to long-term energy systems, and analyzing climate change policies on a national level or for global regions. This is possible because the model has been developed further and many hybrid versions exist. Some important aspects of energy system modelling have been integrated into MESSAGE (i.e. Stochastic MESSAGE, Myopic MESSAGE, MESSAGE-Access), while other relevant models are linked to it to some extent (i.e. from soft to hard link). The various hybrids of MESSAGE make it possible to apply MESSAGE for a broad range of future scenario and policy analysis. The following hybrids exist:

(i) MESSAGE-MACRO: MACRO is a general equilibrium model (it was derived from GLOBAL 2100 and MERGE models) which maximizes the over time utility function of a single representative producer/consumer in each world region and evaluates energy demand. The main variables of the model are capital stock, available labor, and energy inputs, which together determine the total output of an economy according to a CES (Constant Elasticity of Substitution) production function. MACRO's production function includes seven energy service demands which are provided by MESSAGE (residential/commercial thermal, residential/commercial specific, industrial thermal, industrial specific, industrial feed stock, transportation, non-commercial biomass). The primary drivers of future energy demand in MESSAGE are forecasts of total population size and GDP at purchasing power parity exchange rates, denoted as GDP (PPP).

(ii) MESSAGE-MAGICC: MAGICC (Model for the Assessment of Greenhouse gas Induced Climate Change) covers several aspects related to climate change processes. These CLDs do not offer an exhaustive representation of GE3M dynamics. More precisely, MAGICC is a reduced-complexity coupled global climate and carbon cycle model which calculates projections for atmospheric concentrations of GHGs and other atmospheric climate drivers, like air pollutants, together with consistent forecasts of radiative forcing, global annual mean surface air temperature, and ocean heat uptake. Through the link to MESSAGE it is possible to investigate the impact of different energy pathways on the economic and energy system.

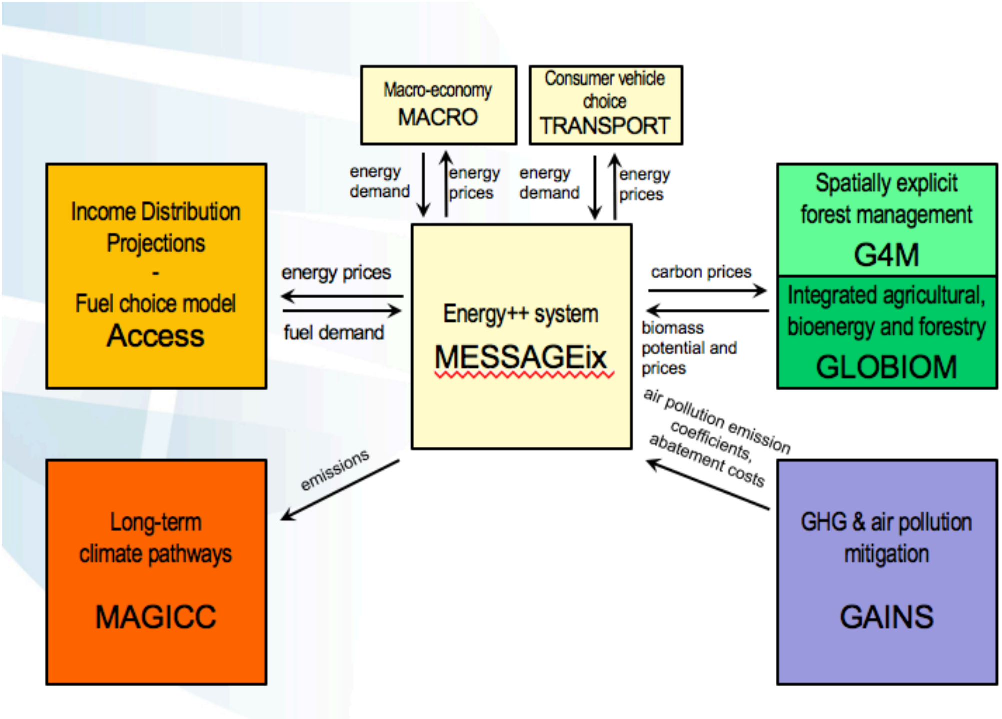
(iii) Linkages to models such as the agricultural model GLOBIOM (Global BIOsphere Management) and the air pollution one GAINS (Greenhouse gas – Air pollution Interactions and Synergies) permit the assessment of other possible effects of energy system developments in other relevant fields. GLOBIOM is a partial equilibrium model which shows the competition between different land use based activities including the agriculture, forestry, and bioenergy sectors. Production adjusts to meet demand for 30 economic regions. GAINS[5] was launched in 2006 as an extension of the RAINS model, which is used to assess cost-effective response strategies for combating air pollution (fine particles and ground level ozone). GAINS gives the historic emissions of 10 air pollutants and 6 GHGs for each country based on data from international energy and industrial statistics. The model may be used in two ways: (i) scenario analysis mode - it follows emission pathways from source to impact; (ii) optimization mode - it identifies where emissions can be reduced most cost effectively.

Today, GAINS tools offer three ways to explain policy interventions which have multiple benefits: (1) Cost simulation, (2) Cost-effectiveness analysis to identify lowest-cost packages of measures, (3) Cost-benefit assessments that maximize net benefits of policy interventions.

Despite MESSAGE being originally developed as a bottom-up, technology-rich, supply-side focused model it is used for a wide range of integrated assessments. These assessments are possible because of the continuous development of the model as well as its linkages to other models, covering important aspects related to sustainable (energy) system development.

[5] GAINS is used for policy analyses under the Convention on Long-range Transboundary Air Pollution (CLRTAP) e.g. for the revision of the Gothenburg Protocol, and by the European Commission for the EU Thematic Strategy on Air Pollution and the air policy review.

Figure 8: IIASA Integrated Assessment Framework



Source: Giddens (2018)

4. GEM-E3 - a General Equilibrium Model

GEM-3E (General equilibrium Model for Energy Economy Environment), partly funded by the European Commission (DG Research, 5th Framework programme) and by national authorities, is the result of a collaborative effort by a consortium involving National Technical University of Athens (NTUA – E3M lab), Katholieke Universsiteit of Leuven (KUL), University of Manheim, the Centre for European Economic Research (ZEW), and the Ecole Centrale de Paris (ERASME).

The model is used "*to examine the potential for the EU to gain a first mover advantage if adopts earlier than others ambitious GHG emissions reduction policies*" (Paroussos, 2018, p. 2). GEM-E3 provides details on the macro-economy and its interaction with the environment and the energy system. The model is able to fix the optimum balance of energy demand and supply, atmospheric emissions, and pollution abatement, simultaneously with the optimizing behaviour of agents and the fulfillment of the overall equilibrium conditions.

The model calculates the equilibrium prices of goods, services, labor, and capital which simultaneously clear all markets under the Walras Law (Capros, Van Regemorter, Paroussos, Karkatsoulis, 2015). The model follows a computable general equilibrium approach[6].

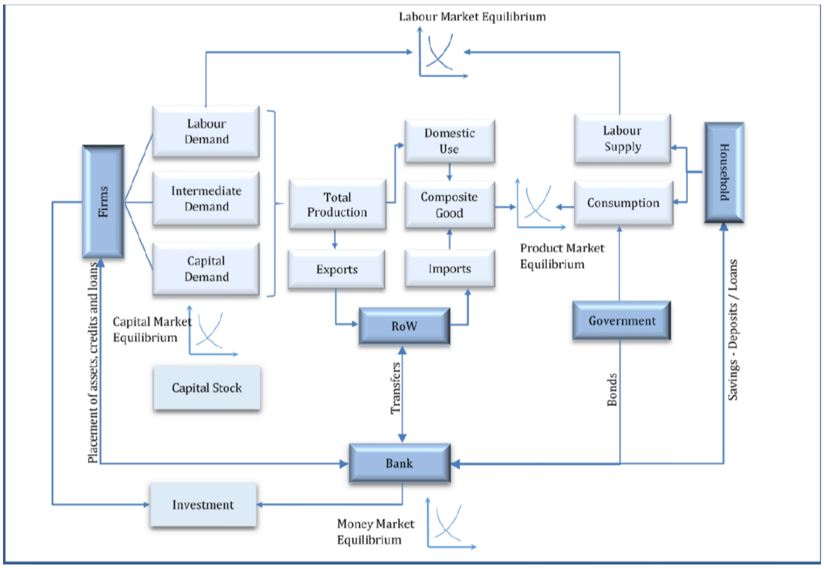
[6] The distinguishing features of general equilibrium modelling derive from the Arrow-Debreu economic equilibrium theorem and the constructive proof of existence of the equilibrium based on the Brower-Kakutani theorem. The Arrow-Debreu theorem considers the economy as a set of agents, divided into

The main features of the model are as follows (Paroussos, 2018):

- it is a global and multi-regional model, treating separately each EU-15 member state and linking them through endogenous trade of goods and services.

- it includes multiple industrial sectors and economic agents, which permits the consistent evaluation of the distributional effects of policies. An economic circuit describes the relations between agents (firms, households, banks, etc) and the main drivers (capital, investment, exportations, importations, consumption, etc).

Figure 9: Economic circuit of GEM-3E



Source: Paroussos (2018, p. 7)

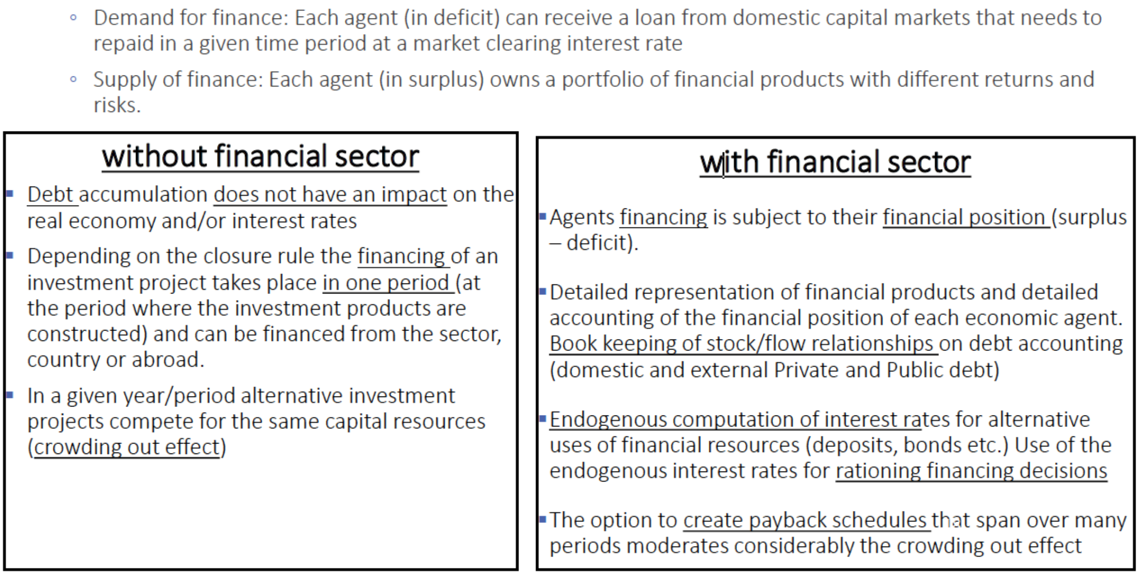
- it covers the major aspects of public finance including all substantial taxes, social policy subsidies, public expenditures, and deficit financing, as well as policy instruments (for environment and energy system). A financial/monetary sub-model is connected to the macroeconomic structure, following the IS/LM methodology.

- it is a dynamic, recursive over time, model, which involves the dynamics of capital accumulation and technology progress (measured by R&D expenditure by private and public sectors), stock and flow relationships, historically-based forecasts and spill-over effects.

- it proposes an explicit description of a detailed financial sector for each country that includes agent specific debt profiles and market clearing interest rates.

suppliers and demanders, interacting in several markets for an equal number of commodities. Each agent is a price-taker, in the sense that the market interactions, and not the agent, are setting the prices. Each agent individually defines his supply or demand behavior by optimizing his own utility, profit, or cost objectives. The theorem states that, under general conditions, there exists a set of prices that bring supply and demand quantities into equilibrium and fully (and individually) satisfy all agents. The Brower-Kakutani existence theorem is constructive in the sense of implementing a sort of trial and error process around a fixed point where the equilibrium vector of prices stands. Models that follow such a process are called computable general equilibrium models.

Figure 10: Computer General Equilibrium with financial sector



Source: Paroussos (2018, p. 18)

- it includes also a detailed representation of the power generation system (10 power generation technologies) and discrete representation of the sectors manufacturing clean energy technologies (wind, PV, electric cars, biofuels, etc).

Figure 11 : GEM-E3 model dimensions

Countries/regions	Each of the 28 EU MS, plus 18 other countries/global regions (All G-20 countries individually represented)
Sectors	51 production sectors including detailed representation of transport, power generation and clean energy technologies
Energy users	47 firms by country and households
Fuels	Biomass, Ethanol, Bio-diesel, Coal, Crude Oil, Oil, Gas
Emissions	All GHGs, both energy and process related
Energy technologies	Coal fired, Oil fired, Gas fired, Nuclear, Biomass, Hydro-electric, Wind, PV, CCS Coal, CCS Gas
Economic agents	Households, Firms, Government, Banks, Foreign Sector
Periodicity and time horizon	Annual to 2020, five-year time step to 2070, more suited for medium and long-term analysis
Policy applications	Capable of analyzing a wide range of policy measures (like ETS allowances, carbon taxes, investments in alternative power generation technologies and energy efficiency)
External sensitivities	Global energy prices, policy measures in non-EU countries, different uptake of low-carbon technologies
Model results/impact assessment	GDP, jobs, energy prices, consumer prices, sectoral production, budget deficit, competitiveness, balance of payments, energy use, GHG emissions, welfare

Source: Parroussos (2018, p. 4)

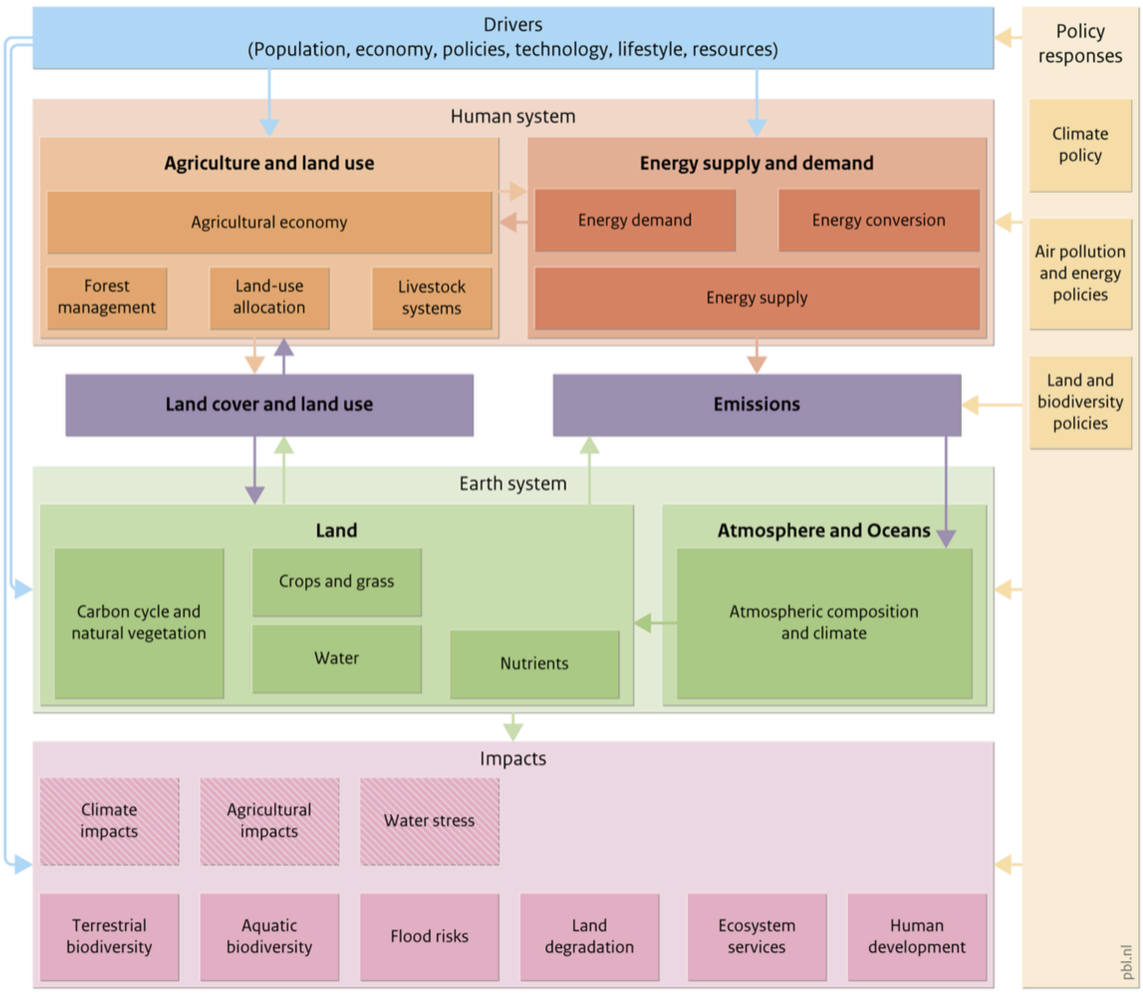
- it includes projections of the Input/Output Table (IOT) for country national accounts, employment, capital, monetary and financial flows, etc based on Eurostat data.

In general terms, the GEM-E3 model covers the general subject of sustainable economic growth and supports the study of related policy issues. Even if the model is based on economic theory (general equilibrium, price adjustment, carbon tax, emissions permits), it aims to analyze the global climate change issues for Europe, and provides an analysis of distributional effects (distribution among European countries and distribution among social and economic groups within each country).

5. IMAGE - a detailed biophysical system

IMAGE (Integrated Model to Access the Global Environment) is an ecological/environmental based model that simulates the environmental consequences of human activities. The first version of IMAGE was developed in the 1980s. Its main goal is exploring interactions between human and Earth systems to better understand how to approach multiple sustainability issues (i.e. climate change, biodiversity loss, human well-being). The objective of the IMAGE model is to explore the long-term dynamics and impacts of the global changes which result from interacting socio-economic and environmental factors (Stehfest et al, 2014). The latest improvements to IMAGE 3.0. focus on human development and explore the dynamics and trade-offs between different model sectors to reach sustainability goals.

Figure 12: IMAGE model schematic framework



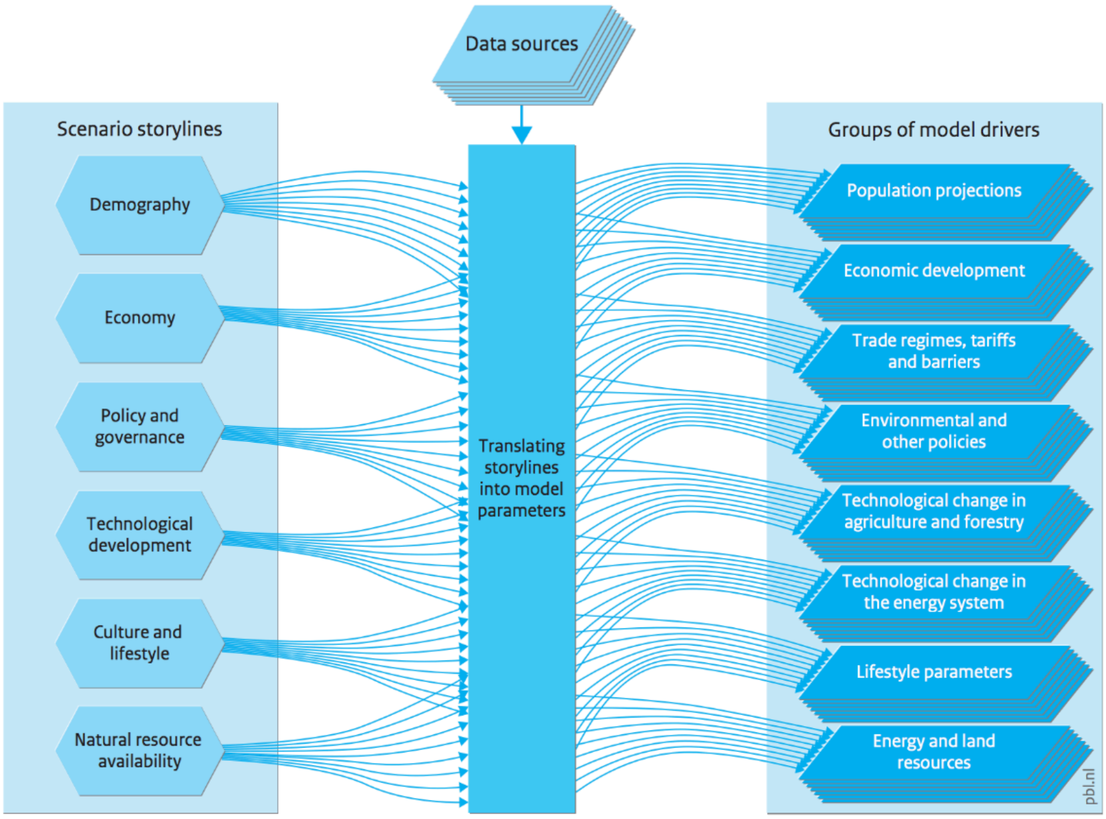
Source: Stehfest et al., (2014)

IMAGE is a simulation model, which implies the exploration of simulations of alternative scenarios for human and natural system developments over the long term and communicating them in a participatory setting.

Within the family of the IAMs, IMAGE developers classify the model within the IAM typology as a *Process-oriented energy/land IAM framework*. The models of this type are of an intermediate complexity for the human and the earth systems (van Vuuren et al, 2015).

IMAGE is a global/multi-regional model. It presents 26 world regions for the socio-economic system. Structurally, the model and the its documentation are designed in line with the *DPSIR* framework (Drivers Pressures State Impact Response). There are several models integrated into the IMAGE framework: GISMO (Global Integrated Sustainability Model) – sustainable development model, GLOBIO – biodiversity model, PIK-LPJmL – land use model, TIMER (the IMAGE Regional Energy Model) – energy model, MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) – climate model.

Figure 13: IMAGE model scenario storylines



Source: Stehfest et al. (2014)

Originally designed to assess the global effect of greenhouse gas emissions, IMAGE now covers a broad range of environmental issues beyond climate change (e.g. land-use change, biodiversity loss, modified nutrient cycles, and water scarcity). Human societies harnessing natural resources to support their development are seen as the systems that put pressure on the earth system and create environmental problems. The authors of the model formulate the uniqueness of the model in the following way: "*The unique aspect of IMAGE is that is contains a consistent description of the physical aspects of environmental change, both in the human economy (also in relation to monetary trends) and the earth system. This makes the framework well suited to analyse the impact of individual measures and combined strategies in terms of synergies and trade-offs*" (van Vuuren et al., 2015).

The plans for the further development of the IMAGE model aim to make it a useful tool for exploring complex sustainability issues and trade-offs between the human and the natural systems in the context of the SDGs agenda. The IMAGE scenario section, which is aimed at exploring potential long-term pathways for human and natural system development, contains several main storylines and drivers. There are six main scenario storylines which are translated into the model's parameters. The alternative simulation results based on these scenarios are explored.

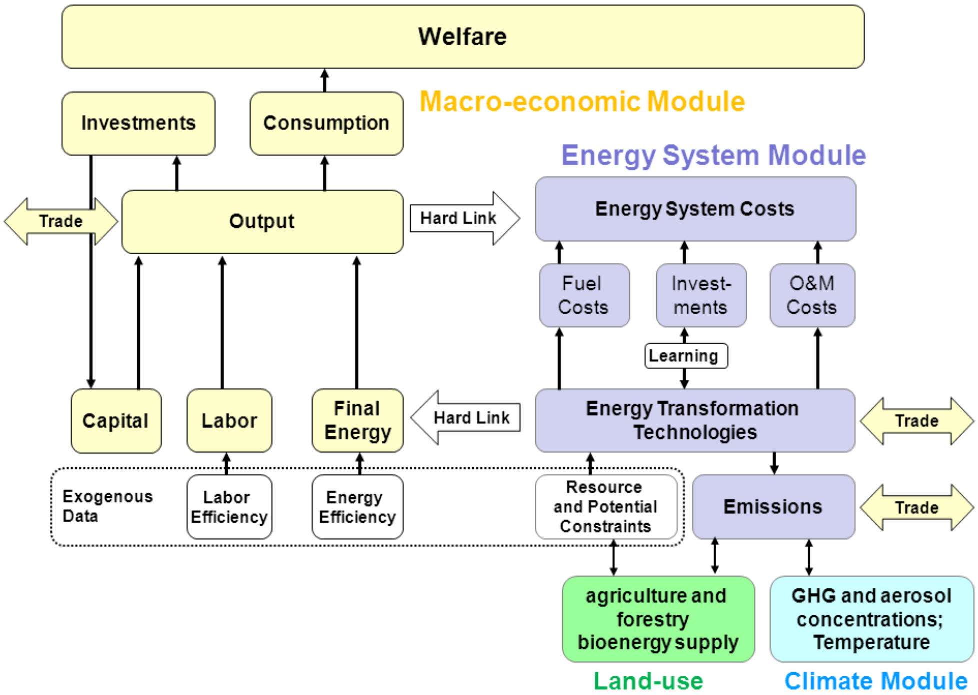
IMAGE is aimed at providing an Integrated Environmental Assessment and at being used for policy analysis. The main clients of IMAGE include the Dutch Government, the European Commission, international organizations, such as IPCC, UNEP and OECD, and the research community. In the future, efforts will be made to "*expand this client base to sector and business associations*" (van Vuuren et al., 2015).

6. REMIND-R - an Economic Growth Model

REMIND-R is a multi-regional hybrid model which incorporates an economic growth model, a detailed energy system model, and a simple climate model (Leimbach and al, 2010). The existence of interdependency between energy systems and macroeconomic systems over time is the core of REMIND-R (Bauer and al, 2009). Firstly, energy is a production factor in the macroeconomic growth model (MGM), and energy production requires financial means that are accounted for in the budget equation of the macroeconomic model. Secondly, the decision to couple the two systems is based on a "hard link"[7] approach which "*integrates the technico-economic contraints of the energy system model (ESM) into the macroeconomic growth model (MGM) as an additional set of functions and constraints and solves one very complex non-linear programming (NKP) program*" (Bauer and al, 2009, p. 97).

[7] A "soft link" approach separates the two models and integrates a reduced form model the ESM into the MGM resulting in a less complex model.

Figure 14: Structure of REMIND-R



Source: PIK (2017)

- ***The macro-economic system*** is a Ramsey-type optimal growth model in which global welfare over time is optimized subject to equilibrium constraints. It takes into account 11 world regions. Each region is modeled as a representative household with a utility function that depends upon per capita consumption.

$$U_r = \sum_t e^{-\rho t} L_{rt} \log\left(\frac{C_{rt}}{L_{rt}}\right).$$

with Population (L), consumption (C) and pure rate of time preference (ρ) of 3%. The objective of the REMIND-R model is to maximize a global welfare function that is a weighted sum of the regional utility functions:

$$W = \sum_r n_r U_r .$$

Economic output (gross domestic product, GDP) of each region is determined by a Constant Elasticity of Substitution (CES) function of the production factors, labor, capital, and end use of energy. In each region, GDP is used for consumption (C), investments into the capital stock (I), exports (X), and energy system expenditure (which consists of fuel cost (GF), investment costs (GI), and operation and maintenance cost (Go). Imports of the composite goods (M) increase GDP:

$$Y(t) - X_G(t) + M_G(t) \geq C(t) + I(t) + G_F(t) + G_I(t) + G_O(t)$$

REMIND-R follows the classical results from HOS (Heckscher-Ohlin-Samuelson) theorem and Ricardo's theory of comparative advantages. Trade between regions is induced by differences in factor endowments and technology.

All technologies are represented in the model as capacity stocks. The possibility to invest in different capital stocks provides high flexibility of technological evolution.

With its macro-economic formulation, REMIND-R is similar to the MERGE (Manne and al, 1995) and RICE (Nordhaus, Yang, 1996) models. The only difference is the high technological resolution of the energy system, and the trade relations between regions over time.

- ***The energy system model*** *(ESM)* has a detailed description of energy carriers and conversion technologies. Luderer et al (2011, p. 8) insist on the fact that ESM is embedded into the macro-economic growth model: "*the energy system can be regarded as an economic sector with a heterogeneous capital stock that demands primary energy carriers and supplies secondary energy carriers. The structure of the capital stock determines the energy related demand-supply structure. The macro-economy demands final energy as an input factor for the production of economic output. In return, the energy sector requires financial resources from the capital market that are allocated among a portfolio of alternative energy conversion technologies*".

The primary carriers include both exhaustible resources (coal, gas, oil, uranium) which are characterized by extraction costs that increase over time as cheaply accessible deposits become exhausted and renewable resources (hydro, wind, solar, geothermal and biomass) whose potential are classified into different grades, each grade is characterized by a specific capacity factor. The secondary energy carriers include electricity, heat, hydrogen, other liquids, solid fuels, gases, transport fuel petrol, and transport fuel diesel. The energy system highlights the conversion of primary energy into secondary energy carriers via specific energy conversion technology.

The distribution of energy carriers to end-use sectors forms the interface between the macro-economic model and the energy system model. REMIND-R makes a difference between the stationary end-use sector (industry and residential buildings) and end-use in the transport sector.

- ***The climate model*** is represented as a set of equations that restrict welfare optimization. The climate system takes account of the impact of greenhouse gas emissions and sulphate aerosols on the level of global mean temperature (Leimbach, 2010). The REMIND-R model has two modes for climate policy analysis: 1. A *business as usual* scenario in which the global welfare function is optimized without constraints, this is a situation where the occurrence of climate change would have no effect on the economy and the decisions of households. 2. A *climate policy* scenario, in which an additional climate policy constraint is imposed on the welfare optimization (the constraint is the limit on temperature). REMIND-R is also able to analyze the impact of carbon tax as a penalty on emissions.

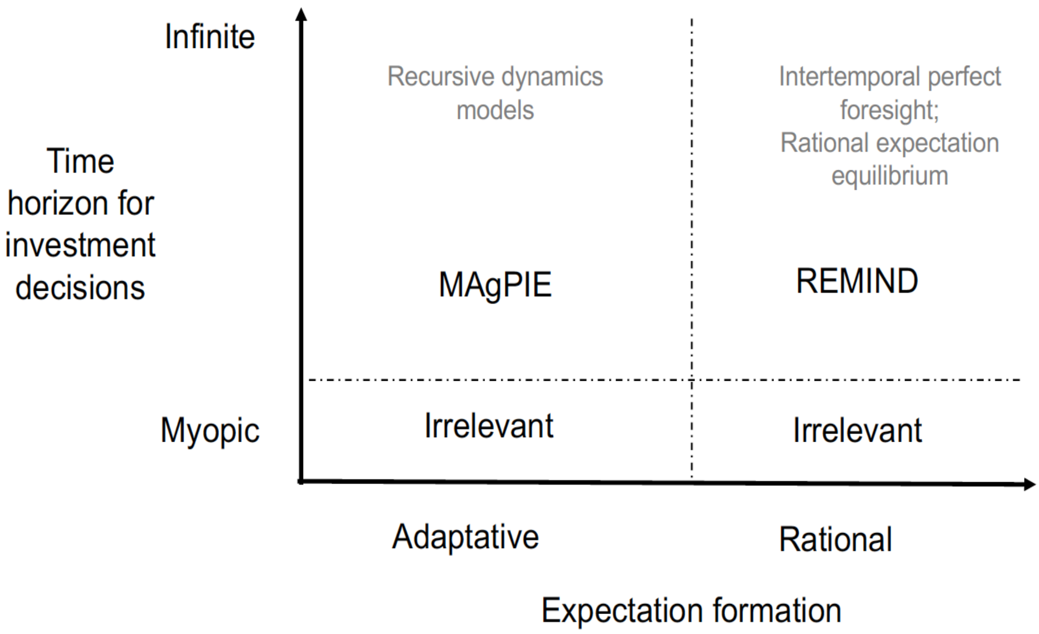
Table 1: Main characteristics of REMIND-R

key distinguishing feature	**REMIND - R**
Macro-economic core and solution concept	Intertemporal optimization: Ramsey-type growth model, Negishi approach for regional aggregation
Expectations/Foresight	Default: perfect foresight.
Substitution possibilities within the macro- economy /	Nested CES function for production of generic final good from basic factors capital, labor, and different end-use
Link between energy system and macro- economy	Economic activity determines demand; energy system costs (investments, fuel costs, operation and maintenance) are included in macro-economic budget constraint. Hard link, i.e. energy system and macro-economy are optimized jointly
Production function in the energy system / substitution possibilities	Linear substitution between competing technologies for secondary energy production. Supply curves for exhaustibles (cumulative extraction cost curves) as well as renewables (grades with different capacity factors)
Land use	MAC curves for deforestation
International macro- economic linkages / Trade	Single market for all commodities (fossil fuels, final good, permits)
Implementation of climate policy targets	Pareto-optimal achievement of concentration, forcing or temperature climate policy targets under full when-flexibility. Allocation rules for distribution of emission permits among regions.
Technological Change / Learning	Learning by doing (LbD) for wind and solar. A global learning curve is assumed. LbD spillovers are internalized. Labor productivity and energy efficiency improvements are prescribed exogenously
Representation of end-use sectors	Three energy end-use sectors: Electricity production, stationary non- electric, transport
Cooperation vs. non-cooperation	Pareto: full cooperation
Discounting	Constant rate of pure time preference (3%)
Investment dynamics	Capital motion equations, vintages for energy supply technologies, adjustment costs for acceleration of capacity

Source: Luderer (2011, p. 3)

Recently, REMIND-R has been improved by work on the scenarios, expectations, and narratives. Problems applying optimization methods have been solved by using the partial equilibrium model (MAgPIE). The formation of expectations plays a key role: adaptative expectations (investors assume current princes to remain constant) vs rational expectations (investors know the models' outcome and form consistent expectations).

Figure 15: the role of expectations in REMIND-MAgPIE model



Source: Bauer (2018)

The applications of REMIND-R are interesting: 1. Analysis of decarbonization pathways in an integrated framework (interrelation of climate policy, trade, renewable resources, and mitigating climate policy), 2. Regional distribution of mitigation costs (cost distribution may be broken down into differences in domestic abatement costs, effects related to shifts in trade volumes, prices of fossil energy carriers, and financial transfers in the context of the global carbon market), 3. Exploration of very low stabilization targets (including technologies and cost reduction), 4. Analysis of best vs second-best mitigation strategies (large number of mitigation options).

7. Concluding remarks and challenges

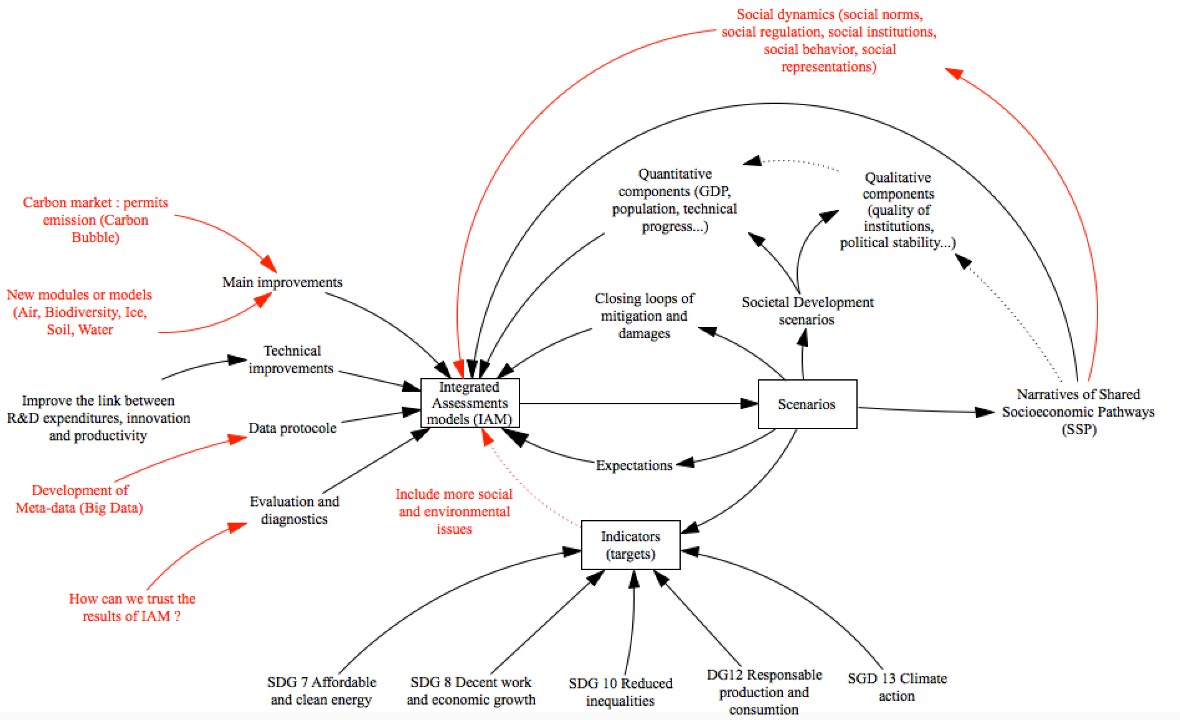
Over the past 20 years, IAMs have succeeded in bringing together a range of international institutions (IIASA, PIK, PLB, CIRED) around the issue of economics, energy, and climate change integration. These models are distinguished both by their structural forms (key variables, scale, representations, etc) and the level of complexity of the systems studied (economic system, energy system, climate system). While the nexus economy/energy/climate constitutes the main framework of the IAMs, it does not exhaust the subject nor the future developments of IAMs. The modular structure of IAMs makes it possible to integrate other nexuses (population/agriculture/food) or (biodiversity/water/air) which are equally important for the future of our societies. Table 2 presents many components (goals, macroeconomic structure, scale, type of models) of the different IAMs discussed.

Table 2: components of the IAMs

IAM	DICE	MESSAGE	IMAGE	GEM-3E	REMIND
Macroeconomic core of the model	Dynamic Optimization Model (Ramsey, 1920)	None but soft-linked to general equilibrium model MACRO	The economy is represented separately by different model components. The model is not suitable to assess detailed economic impacts, such as sector level impacts	Dynamic Optimization Model	Dynamic Optimization Model (Ramsey, 1920) Perfect foresight
Goal	Estimate the optimal GHG reduction trajectory	Medium- to long-term energy system planning and analysis of climate change policies	Exploring the long-term dynamics and impacts of global changes that result from interacting socio-economic and environmental factors	*Examine the potential for the EU to gain a first mover advantage if it adopts earlier than others ambitious GHG emissions reduction policies*	Analysis of decarbonization pathways in an integrated framework + regional distribution of mitigation costs
Scale	DICE – RICE Multiregional model	National & Multiregional models (11 regions)	Global (multi-regional)	Multiregional model (38 regions and 31 sectors)	Multiregional hybrid model (11 world regions)
Type of model	Optimization policy	Optimization policy	Simulation policy	Optimization Policy	Optimization Policy
Representation		Domestic resource utilization, energy imports and exports, trade-related monetary flows, investment requirements, types of technologies, pollutant emissions, inter-fuel substitution process	Say how and whether the transition is modelled	Economic circuit, energy technologies and GHG emissions	Trade in final goods, primary energy carriers, emissions allowance
Key variables	Energy, natural resources, income and population	Resource extraction, technology installation, technology activity	Exogenous scenario drivers (demography, policy and governance, technological development, culture and lifestyle, natural resource availability)	GDP, jobs, energy prices, consumer prices, sectoral production, budget deficit	Production, capital, labor and energy
Economic System	Competitive Market Balance Intertemporal optimization of price and consumption	Supply cost minimization		Economic circuit (national account + IOT) Public sector, transport and international trade, financial sector	Economic system is hard linked to the energy system (economic activity results in demand for final energy)
Energy System	System combining market mechanisms and economic policies	Detailed description of energy supply side and technologies	TIMER energy model focusing on long-term trends in energy supply and demand	Energy efficiency and Energy technologies (coal fired… CCS (SCC?) gas)	Energy system consider exhaustible primary energy resource and renewable energy potentials
Climate System	Climate change is captured by global average temperature	Only GHG emissions but linked to climate model MAGICC	Climate model MAGICC. Emissions beyond GHG are present	Climate by GHG emissions (energy and process related)	Carbon Cycle and temperature model
Technology		Technological learning endogenous	Endogenously modelled technological learning. Exogenous technological progress effects.	Modelling technical progress (R&D decision)	Technological change is exogenously driven

Today, the challenges of IAMs seem connected to the new aims of research design. The IAM framework links models, scenarios and indicators, especially Sustainable Development Goals. We can present the debate by the following diagram.

Figure 16: Model – Scenarios and Indicators issues for IAM



IAMs have to be improved, four possible key additions to IAMs may play roles: *main improvement* (carbon market introduces financial markets in the macroeconomic structure, the equilibrium between saving and investment is not realistic), *technical improvement* (knowledge of technology diffusion, learning curve, evaluation of transport costs, and cross elasticities), *data protocol* (development of spatial data exchange, big data, time series data), and *evaluation and diagnostic* of IAM.

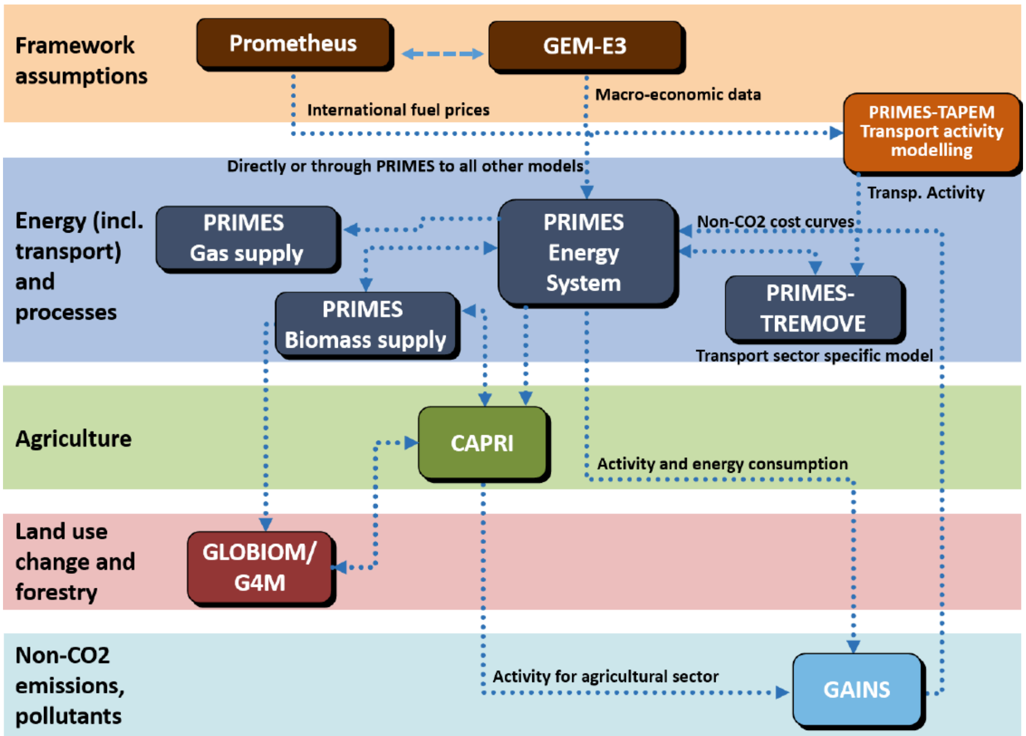
Indicators, like targets, can help to introduce more social and environmental issues - Stakeholders would fix the targets they want to reach; national policies could explain the gap between expectations and results.

Scenarios can be deduced from the structure of IAM - different scenarios give signals about trajectories and pathways. Scenarios depend on basic assumptions (implemented in the model) but are not able to anticipate the future.

Future uncertainty may be captured by different narratives - these narratives transform qualitative data into quantitative scenarios and engage modelers to propose shared socioeconomic pathways (SSP). Social dynamics (social standards, social institutions, social regulation, social behavior, social representations) may be useful to connect to the narrative of shared socioeconomic pathways and to modify behaviors (reducing energy consumption, water consumption, waste, etc).

In 2007, the Integrated Assessment Model Consortium (IAMC) was created in response to a call from the Intergovernmental Panel on Climate Change (IPCC) for a research organization to lead the integrated assessment modelling community in the development of new scenarios that could be employed by climate modelers in the development of prospective computerized model research for both the near term and long term. In the report EU reference scenario 2016 (Energy, transport and GHG emissions: trends for 2050), the European Commission used a series of interlinked models which combine technical and economic methodologies. The models were used to produce detailed projections per sector and per country. Most of them followed an approach which is based on micro-economics - they provided answers for a price-driven market equilibrium and combined engineering with economic representations for all sectors.

Figure 17: Reference Scenario for EU, trends to 2050



The PRIMES modelling suite is the core element for transport, energy, and CO2 emissions projections. The GAINS model is used for non-CO2 emissions projections. The GLOBIOMG4M models are used for LULUCF emission and removal projections. The GE3M macroeconomic model is used for value added (GDP) projections by branch of activity. The PROMOTHEUS global energy model is deployed for forecasts of world energy prices and the CAPRI model for agriculture activity forecasts.

These models were used to provide the fossil fuel price trajectories used for the EU modelling (Prometheus), to prepare consistent sectorial value added and trade projections which match given GDP and population projections by country (GEM-3E), to provide the transport activity projections (PRIMES – TAPEM), to provide the energy system projection for demand and supply side sectors included full energy balance, investment costs, prices and related CO2 emissions per country (PRIMES energy system model), to provide detailed forecasts for changes in the entire transport sector in terms of transport activity by mode and transport means (PRIMES – TREMOVE), to provide the supply and transformation projections of biomass / waste resources (PRIMES – biomass supply), to provide forecasts for gas imports by country of origin (PRIMES - gas supply), to provide an agricultural forecast (especially for livestock and fertilizers use (CAPRI)), to provide non-CO2 GHG and air pollutant emissions (GAINS), and to include the changes in land use and related CO2 emissions (GLOBIOM/G4M). If these models provide background information for international climate policy negotiations, they have started more debate about the evaluation of IAMs or trust in their results, especially when they are used to explain open and complex systems.

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