INTEGRATED ASSESSMENT MODELS (IAMs) APPLIED TO CLIMATE CHANGE AND ENERGY TRANSITION

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ABSTRACT:

The current climate change is due to the increased concentration of greenhouse gases (GHGs) in the atmosphere as a result of human activity. The large number of factors and variables that, directly or indirectly, affect GHG emissions, as well as the multiple and complex relationships between them, makes it more difficult to decide upon the best actions to take to curb or alleviate climate change and the analysis of the consequences that each decision brings with it. This has led to the development of complex simulation models called Integrated Assessment Models (IAMs) or Energy-Economy-Environment (E3) models, focused especially on climate change. The development and use of these models to guide policy decisions on climate change has grown in recent years, as highlighted in the reports of the Intergovernmental Panel on Climate Change (IPCC). This work is a panoramic review of the main existing IAMs and discusses their main features. The article focuses especially on analyzing the limitations of current IAMs, which should drive future developments towards these tools.

Keywords: integrated assessment models; climate change; system dynamics; energy

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1. - INTRODUCTION

Concern about climate change and its link to the necessary energy transition is increasingly present in our society, so scientists, policy makers and intergovernmental institutions are focusing their efforts on how to deal with these great challenges. To assist in decision-making to address these issues, scientists from a wide range of fields, from physics and chemistry to economics, engineering or sociology, collaborate to develop Integrated Assessment Models (IAMs).

An IAM is a numerical simulation tool designed to help understand the relationships between a large number of technological, economic, environmental and social variables that characterize the development of our society. Models built from historical data allow you to simulate future scenarios with different alternatives of action to guide decision-making. In recent years, these models have been applied, in particular, to the search for alternative solutions to climate change and the energy transition. To address these complex problems, an IAM requires knowledge to be integrated from a wide range of areas: climatology, economics, engineering, sociology or politics, seeking to represent the interactions between human beings and the environment.

IAMs began to develop in the 1970s with the pioneering World3, developed by a team led by Donella and Dennis Meadows and from which the report "The Limits of Growth" was obtained [1]. The goal of the World3 model was to understand better global behavior based on different subsystems, such as population, food production, pollution or consumption of non-renewable resources, in order to be able to propose policies to correct the unsustainable trends observed in the continuity scenarios. From then on, different IAMs appeared. At the end of the same decade, Willian Nordhaus developed a model showing atmospheric emissions and CO_2 concentrations [2], which would result in 1992 to the DICE (Dynamic Integrated Climate-Economy) model [3]. The DICE model already completely integrated economic and climate systems, and was rewarded in 2018 with the Nobel Prize in Economics.

Over the next few years, and as the power of computers increased, new IAMs such as IMAGE [4], GCAM [5], MESSAGE [6], MERGE [7], and WITCH [8] emerged. As new models were being developed, new features were also added. There are currently dozens of IAMs in the literature with very different approaches that assist in decision-making at all institutional levels.

However, although their approaches and evolution have been very different, most IAMs have similar structures. They are usually structured in different modules that correspond to the different dimensions represented in the model (economy, energy, climate, land use...). There are relationships and feedbacks between the different modules of the model that make the characteristics of one module influence the others. As can be seen in Figure 1 [9], different inputs affect these modules. These inputs usually correspond to different hypotheses and assumptions made, such as population or GDP. Policies are also inputs in the model. To the right of the figure are the outputs, which are the results obtained in the different modules of the model once the policies have been applied.

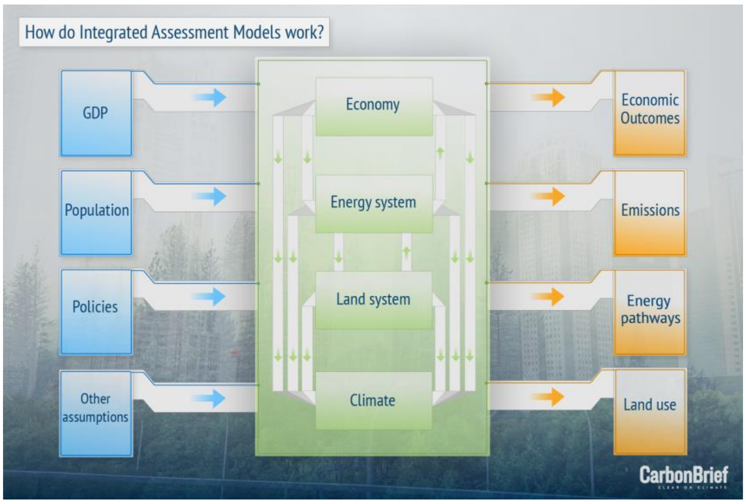

Figure 1: Basic structure of operation of IAMs. Source: CarbonBrief [11]

It is important to note, in relation to the outputs and results provided by IAMs, that the objective of such models is not to make an accurate forecast of the different variables in the future, but to provide viable representations of what may happen in the future based on a coherent set of assumptions and hypotheses.

In this regard, and as Joeri Rogelj, report coordinator for the International Panel on Climate Change (IPCC), reflects in Carbon Brief [9]: what IAMs do is try to answer different conditional questions ("What if questions"). Some of the typical questions that IAMs answers are: What if no action is taken to limit climate change? or What if the capacity of renewable energy is increased? In short, the objective of IAMs is to assist in decision-making by comparing different alternatives for solving energy, economic, social or environmental problems.

In order to answer these questions and evaluating variable behavior based on feedbacks, system dynamics is a methodology sometimes used in IAMs. System dynamics is used to analyze and model temporal behavior in complex environments due to its ability to explicitly and dynamically represent feedbacks, existing system delays, and non-linearities. This is because system dynamics models are not rigidly determined in their structure by mathematical limitations as optimization models are [10]. The World3 pioneer was developed using system dynamics and this methodology is still used today in such models as iSDG [11], En-ROADS [12], FeliX3 [13] or MEDEAS [14].

The information provided by an IAM presents a large number of uncertainties, both parametric and structural, which has generated criticism and controversy throughout history. The interpretation of the results of IAMs should be accompanied by uncertainty analysis tools that narrow the margins of such uncertainty in probabilistic terms.

Another basic requirement for interpreting the results of IAMs is the transparency and substantiation of the assumptions made. To this end, in recent decades, a series of international scenarios or narratives have been developed that attempt to unify hypotheses and allow viable descriptions of how the future could develop under different socioeconomic, technological and environmental conditions. Most models currently use the scenarios generated through the "Shared Socio-Economic Pathways" (SSPs) [15]. These narratives, based on demographic, economic, technological, and even lifestyle change assumptions, enable a better analysis of mitigation and adaptation policies.

However, uncertainty is not the only limitation that IAMs have. Some of the criticisms that IAMs receive are that there is a great lack of transparency in many of the models, the relationships and feedbacks between modules are often very limited or simplified, especially in the case of climate change [9,16], or the models tend to focus on the economic-technological part, largely forgetting the social part and human behavior [17,18]. Section 4 will discuss the limitations of IAMs.

Despite these limitations, the models have already proven useful in assessing the magnitude of the problem of climate change and the effectiveness of possible solutions [19]. A good proof of this is that they are the tools used by the main institutions to develop and evaluate their policies. For example, the IPCC uses multi-model studies, such as AMPERE [20] or EMF27 [21], and the European Commission uses the POLES model [22].

2. - CLASSIFICATION OF IAMs

The difficulty in representing the relationships between energy, the economy and the environment, together with uncertainty in the assumptions made in the models, leads to the existence of very different approaches in the development and structure of IAMs.

One of the most widespread classifications in the literature is what Weyant does in his contribution to the state of IAMs [19]. It defines the **profit-cost models** as those simple models that provide a very aggregate representation of climate change mitigation costs. They generally use simplified equations and have been used to calculate the optimal trajectory of global greenhouse gas (GHG) emissions, and the corresponding prices to be charged for these emissions. These models do not show the detailed relationships between energy, the economy and the environment. Examples of these models are DICE [3], FUND [23], and PAGE [24]. On the other hand, Weyant defines **detailed process models** as those complex models that seek to provide more detailed projections of the effects of climate change using economic issues and projections of physical effects, such as the reduction of energy resources, lands flooded by rising sea levels, etc. This vision of IAMs as more complex models is the one that best fits a multidisciplinary view of the relationships between human behavior and its effects on the environment. Examples of these models are GCAM [5], IMAGE [4], and MESSAGE [6].

Other widespread classifications of models in the literature are the proposals in the revision of IAMs of Capellán-Pérez [25]. In his study he classified the main existing models according to the following criteria: the method of implementing policies, the level of complexity of systems, the level of integration between subsystems (feedbacks), the treatment of uncertainty, the economic balance and the treatment of energy in the economy [25]. It is important to note that each of these modeling criteria has its own strengths and weaknesses, making it difficult to conceive an integrated model capable of providing the best solutions to all issues.

The classifications of the IAMs shown so far are quite "theoretical", but when studying the models and analyzing the results obtained in them, as is done in IPCC multi-studies, it is necessary to classify them according to other more "technical" aspects. In these studies, models are classified according to:

- The **type of license**: Models can be for public use (Open Access) or have some type of ownership license.
- The **programming language**: Models use different languages, such as Python, GAMS, Vensim, or Visual Basic, in their development.
- The **flexibility of the model**: This shows the extent to which predefined conditions can be changed in the model, for example: reallocating capital across sectors, how easily the economy can replace energy technologies, or whether there are limitations on fossil fuels and renewable resources.
- The **forecasting method**: In perfect forecasting models, all future decisions are accounted for with current decisions. In contrast, recursive-dynamic (myopic) models make decisions at any given time based only on information from that time period.
- The **level of geographic aggregation**: Models can be developed for one or more regions or be global models.
- The **temporal dimension**: Models differ in their base year, their time step and their time horizon.

Finally, models are also differentiated in the inputs that drive the model (drivers), the way they represent the different sectors and systems, and by the type of policies applied. Each model, being developed with a different approach and with very different objectives, elaborates some parts of the system in more detail than others. In order to compare the different models in all these issues, the consortium of IAM developers (IAMC) has created a wiki where the main features of many models are explained (https://www.iamcdocumentation.eu/index.php/IAMC_wiki).

3. - DESCRIPTION OF IAMs

MODELS MOST USED IN INTERNATIONAL PROJECTS

Among the models most commonly used in periodic reports published by the IPCC [26] are these six models:

- The Asia-Pacific Integrated Model (**AIM**): A set of models developed since 1990 with the collaboration of several institutes in Asian countries. The main model is AIM-CGE, which is a computable general equilibrium model [27].
- The Global Change Assessment Model (**GCAM**): The model was developed in 1985 [5] by the Pacific Northwest National Laboratory (PNNL) in the United States and is now an open model. It is available free of charge and documented online [28]. It is managed by The Joint Global Change Research Institute (JGCRI).
- The Integrated Model to Assess the Global Environment (**IMAGE**): Developed in its first version in 1990 [4], it has been developed up to IMAGE 3.0 [29] under the authority of the Netherlands Environmental Assessment Agency (PBL).
- The Model for Energy Supply Strategy Alternatives and their General Environmental Impact (**MESSAGE**): This is a model of the energy system developed by the International Institute for Applied Systems Analysis (IIASA) [6]. MESSAGE is used in combination with other models, such as MAGICC (climate), MACRO (economy) or GLOBIUM (land use). It is an open access model with online documentation [30].
- The Regional Model of Investments and Development (**REMIND**): Developed by the "Potsdam Institute for Climate Research (PIK)" in Germany, it is an open access model with online documentation of its latest versions [31].
- The World Induced Technical Change Hybrid (**WITCH**) model: The model was developed in 2006 by different Italian organizations [8]. It is currently maintained and developed at the RFF-CMCC European Institute on Economics and the Environment (EIEE) in Italy. It is used in combination with other models, such as MAGICC (climate) and GLOBIUM (land use). It has an online policy simulator [32].

SYSTEM DYNAMICS MODELS

There are several IAMs that use the system dynamics methodology to develop the model. Some of these are:

- **World3:** a pioneer of integrated assessment models, it was developed in the 1970s by a team led by Donella and Dennis Meadows and Jorgen Randers, from which the report "The Limits of Growth" was obtained [1]. Model equations are available in different system dynamics software.
- **EN-ROADS:** model developed using Vensim software by Climate Interactive, Ventana Systems, and MIT Sloan in 2019. It has a policy simulator and online documentation [12].
- Functional Enviro-economic Linkages Integrated neXus (**FeliX3**): model developed in 2013 using Vensim software by IIASA. It is an open access model with accessible documentation [13].
- The Integrated Sustainable Development Goals (**iSDG**) model: This was built by the Millennium Institute from the Threshold21 (T21) model. The iSDG model allows you to understand policies designed to achieve SDG and test their likely impacts before adopting them. It has a demo version and online documentation [11].
- **MEDEAS**: These models were developed in 2017 by the research Group of Energy, Economy and Systems Dynamics (GEEDS) of the University of Valladolid within the European MEDEAS project. They are open access models with accessible documentation. [14,33]

The tables 1, 2 and 3 show the objectives and main characteristics of these eleven models. A more detailed description of the models can be found in the IAMC wiki and in the documentation for each model.

Name	Reference	Objectives
AIM-CGE	(Fujimori et al., 2017) [27]	Analyze long-term climate change mitigation, using macroeconomic, energy, land use and carbon emissions variables.
GCAM	(Calvin et al., 2020) [28]	The model is used for a wide range of different objectives, from exploring the dynamics between humans and the environment to evaluating strategies to deal with long-term environmental issues. The model represents the relationships between five systems: energy, water, agriculture and land use, economy and climate.
IMAGE	(Stehfest et al., 2014) [29]	• Analyze long-term interactions between human development and the environment to better understand current environmental change processes. • Identify strategies to respond to environmental change based on the evaluation of mitigation and adaptation policies. • Indicate the main relationships and their associated levels of uncertainty in the processes of environmental change.
MESSAGE	(Krey et al., 2016) [30]	• Provide a flexible framework for the comprehensive assessment of major energy challenges and the development of energy scenarios. • Identify the socio-economic and technological strategies needed to respond to the energy challenges.
REMIND	(Aboumahboub et al., 2020) [31]	Analyze technological options and policy proposals for climate change mitigation. The model presents a very broad range of detail on interregional trade in goods and energy, including GHG emission allowances. REMIND imposes welfare maximization in climate policies.
WITCH	(WITCH, 2020) [32]	Analyze climate change mitigation and adaptation policies. Assess the impacts of climate policies on global and regional economic systems and provide information on the optimal responses of these economies to climate change.

Table 1: References and objectives of the most commonly used IAMs in international projects.

Name	Reference	Objectives
World3	(Meadows et al., 1972) [1]	Improve the understanding of global economic behavior based on different subsystems such as population, food production, industrial production, pollution or consumption of non-renewable resources, in order to propose policies to address unsustainable trends.
EN-ROADS	(Siegel et al., 2020) [12]	Understand how the climate goals can be achieved through changes in energy, land use, agriculture and other policies. The model is designed to provide a tool for climate solutions for policy makers.
FeliX3	(Rydzak et al., 2013) [13]	Analyze the impacts of new policies and technologies in the context of the critical and complex interconnections among social, economic, and environmental subsystems, including: population, GDP, land use, energy, the carbon cycle, and climate
iSDG	(Millennium Institute, 2017) [11]	Help policy makers and other stakeholders make sense of the complex web of interconnections between the SDGs. iSDG focuses on the dynamic interactions within the SDG system to reveal the best paths and progression towards achieving the SDGs.
MEDEAS	(Capellán-Pérez et al., 2017) [33]	Help in decision-making to achieve the transition to a sustainable energy system by focusing on biophysical, economic, social and technological constraints.

Table 2: References and objectives of IAMs modeled in system dynamics.

Name	Model accessibility (2020)	Modeling language	Forecasting method	Geographical scope	Temporal scope
AIM-CGE	Proprietary	-	Myopic	Multiregional	2005-2100
GCAM	Open access	C++/R	Myopic	Multiregional	2015-2100
IMAGE	Proprietary	-	Myopic	Multiregional	1970-2100
MESSAGE	Open access	Python/R	Perfect foresight	Multiregional	2030-2110
REMIND	Open access	GAMS	Perfect foresight	Multiregional	2005-2100
WITCH	Proprietary	GAMS	Perfect foresight	Multiregional	2005-2150
World3	Open access	Vensim/ Modelica…	Myopic	Global	1900-2100
EN-ROADS	Proprietary	Vensim	Myopic	Global	1990-2100
FeliX3	Open access	Vensim	Myopic	Global	1900-2150
iSDG	Proprietary	Vensim	Myopic	Regional	2018-2050
MEDEAS	Open access	Vensim/ Python	Myopic	Global/ Regional	1995-2100

Table 3: Main features of the most commonly used IAMs in international projects and IAMs modeled in system dynamics.

4. - LIMITATIONS OF IAMs

The development of IAMs requires knowledge of a wide variety of disciplines and of the relationships between variables of a very different nature and characteristics. In the early decades of the IAMs' existence, it was doubted that they were useful tools for studying, for example, the effects of climate change or the evolution of energy resources, with the World3 model even being heavily criticized [34]. However, more than 30 years later, it has been observed that the historical data are largely in line with those obtained in the World3 base scenario [35]. In recent years, despite continuing to receive criticism [36], IAMs have been widely accepted and are seen as one of the best tools for analyzing the effects of climate change [19].

It is important to note that, in the field of IAMs, existing criticisms and limitations are constructively understood and help to improve the model development. As introduced in the first section of this article, the limitations of IAMs are still significant and of very different types. They can be gathered into four large groups:

First, there is a distinct **lack of transparency in many of the models;** some of these models could be considered "black boxes" with non-existent or difficult-to-understand documentation. In this sense, many models are developed with a private license, which makes it very difficult to review their internal equations. The lack of transparency in how models are developed and functioning makes them very difficult for policymakers, who are not used to getting involved in modeling. This, coupled with the lack of communication with developers, makes IAMs seem distant and complicated for policymakers.

In long-term projections, such as those provided by IAMs, uncertainties are large and cannot be ignored. Many of the models do not show what uncertainty their results have, which implies a drop in their credibility. One way to contribute to improving transparency is to carry out sensitivity analyses on the obtained results, although it is generally not a widely used technique in IAMs [37].

Second, although IAMs are composed of different modules, they are usually characterized by a fairly sequential structure and **the existing feedbacks between the different modules that structure the model are scarce**. Particularly relevant is the case with the feedback from the effects of climate change. Models that do consider this feedback often do so through damage functions. However, as Diaz and Moore show, damage functions have many limitations [16]. An example of this is that they consider temperature increases of up to 4 or 5ºC at the end of the century, with a negligible representation of impacts on the economy. In this sense, realizing the effects of climate change on the regions and sectors that suffer the most from their impacts is a formidable challenge for IAMs [19]. The feedback from land-use modules with energy modules to explore climate mitigation scenarios under diverse political and technological conditions is also very limited.

Although the shortage of feedback on the environmental part is the most relevant, there is also a lack of interconnectivity between the other modules. A large percentage of IAMs lack, for example, relationships that allow the economic impact of energy policies to be analyzed, the effect of mineral resource scarcity on the economy, or the consequences of changes in society's behavior. Especially striking is the case that population and GDPpc are exogenous in most models.

Third, **IAMs often focus on the economic-technological part**, forgetting in many cases human behavior and largely the social part [17]. For IAMs, capturing human behavior is arguably the most difficult of their goals, and models representing consumer preferences are very scarce [18]. Most of the decisions made in the models are from an economic point of view, even though this is not the only point of view that society uses to make its decisions. Generally, the welfare implications associated with these decisions have not been thoroughly evaluated in the literature.

Equity considerations have rarely been addressed directly in IAMs [19]. This is hardly understandable, because issues of fairness and justice often dominate the political debate about what to do with climate change. Many models often consider an average consumer, which is far from the impact of policies both nationally and internationally. Ethical issues do not usually get into IAMs either. Moreover, intertemporal equity is extremely important for policy implementation, as decision-makers in the present do so on behalf of those who are not yet alive, and need to make collective ethical decisions about what kind of future we will have [19].

We must also be aware, and it is one of the main limitations of IAMs, that both modelers and policymakers base their assumptions on the past, and are logically unable to predict exceptional situations such as war or COVID-19.

Finally, most **models follow a very similar line of thought**, consider similar hypotheses, the same technologies and achieve very similar results. Plurality in hypotheses and scenarios is very sparse, leading to proposals which are not generally very innovative. One of the most common hypotheses in the literature is that the economy follows the model of a perfect market through optimization methods and the perfect substitution of factors, as well as widespread use of prices as indicators of scarcity [38]. Another of the most repeated issues in IAMs is the use of negative emissions policies. Many models consider such options as bioenergy carbon capture and storage (BECCS) to reduce total emissions. However, these options do not currently apply, and uncertainty about their use is very high, as neither economic nor energy viability has been proven [39]. The abundance of fossil fuels is a default assumption in most IAMs. However, this assumption is questioned by studies in the literature showing that fossil fuel extraction could face significant constraints in the coming decades [40]. In general, there are always the same assumptions, so it is necessary to expand the range of options to explore, especially those outside the "mainstream".

By applying similar models and scenarios, a large part of the models achieve fairly similar results in terms of emission reduction, GDP or energy resource developments. Alternative models and scenarios developed outside major research groups have a more difficult scientific and social impact.

All of these limitations, as mentioned above, stimulate the continuous development of existing models. IAMs aim to keep pace with the development of sector-specific models. The limitations also stimulate the development of new IAMs that aim to fill the gaps that remain in the literature.

5. - CONCLUSIONS

The large number of variables linked to human activity that contribute to climate change, as well as the complexity of the relationships between these variables, have led to the increasing development and use of integrated assessment models (IAMs), which facilitate an understanding of the problem and decision-making. This work has described the fundamental aspects of these models. Knowing the characteristics of each IAM is essential to properly interpret its results. Both parametric and structural uncertainties in IAMs have historically led to doubts and criticisms about the usefulness of IAMs. Uncertainty analysis tools allow for an adequate probabilistic interpretation of model results, which should be used as qualitative guidance in decision-making and not as predictors of the future. Although there is a large number of IAMs, the plurality of approaches, hypotheses and scenarios among the best known and used is relatively sparse. Some of the limitations and flaws present in many of the IAMs have been revealed in this work. The most significant and frequent limitations that have been identified in IAMs are four: lack of transparency, scarcity of feedback between variables, homogeneity in the formulation of theoretical hypotheses and an imbalance between the high level of detail of economic and technological aspects compared to social aspects related to human behavior. Therefore, although IAMs are currently a useful tool in political decision-making to address climate change, they still have significant potential for improvement and updating, in order to address unforeseen scenarios, such as COVID-19, or regional disaggregation that allows for local analysis in detail.

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