Integrated assessment climate policy models have proven useful, with caveats

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The headlines are bleak: Regions of our planet becoming uninhabitably hot (1), crippling droughts, wildfires, and floods, collapsing ecosystems. Extreme climate change, models suggest, is likely if nations continue to increase emissions at close to their current rate, with global average temperature rises of at least 1.1 to 3.1 °C by 2100.

Such warming is probably enough to trigger planetary tipping points, says Gavin Schmidt, director of the NASA Goddard Institute for Space Studies in New York, NY. "We may hit a threshold even with [low emissions]," Schmidt says. "We are at the top of the [ski] mountain and there's only black runs. And we've got to hope the one that we choose is not the one with the double-black diamond moguls that only a true expert can maneuver."

These projections stem in part from something called integrated assessment models (IAMs). The "process-based" versions of these models are mathematical representations of the world, with modules representing the climate, biosphere, energy, and economy. They're a popular and extremely important tool, but one that isn't always well understood. Better explicating their strengths and shortcomings will help refine projections and improve transparency in the years ahead.

The conundrum posed by climate change is that policymakers need to act immediately to avoid warming decades hence. IAMs help them to envisage the desired future and the impacts of climate policies. For example, researchers might specify an emissions target and then use an IAM to work out what policies and technologies might be the most cost-effective way to

Integrated assessment models have long made dire predictions about climate change and its myriad impacts. Some researchers would like to see more transparency in how these models are devised. Image credit: (*Clockwise from Top Left*) Shutterstock/ccpixx photography, Zenobillis, Witsawat.S, and Christian Roberts-Olsen.

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hit that target. These models aren't crystal balls used for predictions; rather, they are a way to inform the policy discourse. And they've been valuable, says Brian O'Neill, director of the Joint Global Change Research Institute at the Pacific Northwest National Laboratory in Richland, WA. When nations signed the Paris Agreement in 2015, one of the unknown challenges was what would it take to limit warming to well below 2 °C by 2100—a ramping up of renewables? Nuclear energy? Carbon capture and sequestration? IAMs helped stakeholders think through these challenges.

But some researchers note important drawbacks of IAMs that should be taken into account. The models can be opaque (2) and complex. "Creating a whole-world simulation means IAMs do often end up becoming a black box," says Justin Ritchie, an adjunct professor at the University of British Columbia's Institute for Resources, Environment, and Sustainability in Vancouver, Canada, "and therefore many researchers end up taking their outputs at face value."

IAM modelers say their efforts are constantly evolving and improving. Detlef van Vuuren, an IAM researcher at the PBL Netherlands Environmental Assessment Agency in The Hague, The Netherlands, says it is time to include recent changes such as the Paris Agreement and massive renewable energy deployment. "I think we will have to update our scenarios from time to time because of new insights," says van Vuuren. "There comes a time that we probably have to reassess whether [our projections] are still relevant."

Model History

In 1975, economist William Nordhaus at Yale University in New Haven, CT, created one of the first mathematical models that linked society's energy use to carbon dioxide concentrations in the atmosphere. Nordhaus and his contemporaries wanted to weigh the benefits of economic growth against the costs of environmental degradation. Their models, called "benefit–cost" IAMs, were highly stylized and used to estimate the impact of carbon taxes. Soon after, researchers at Stanford University in Palo Alto, CA, developed a second, more complex, class of IAMs called "process-based" models. These initially represented only the energy system but have since grown in complexity to include land-use, economic, and climate systems.

Carbon dioxide concentrations are, of course, a vital input for models designed to simulate climate change. In the 1980s, researchers made relatively crude assumptions about how these concentrations would rise every year. To better align economic projections and expected concentrations, the climate community requested that researchers provide more reasonable scenarios of future emissions, based on assumptions about demographics, the energy system, the economy, and other inputs.

For the IPCC's climate reports, starting in 1989, researchers met to imagine what the world might be like at the end of the century. These gatherings included researchers working on integrated assessment models, as well as climate, impact assessment, and vulnerability. "You bring together people [who] think differently and have different ideas," says Schmidt.

Before the IPCC's Fifth Assessment Report, released in 2014, researchers examined an ensemble of published process-based IAM results and selected four trajectories of future emissions representative of the ensemble. These are known as representative concentration pathways (RCPs).

In the first pathway, called RCP2.6, emissions fall rapidly after 2020. A wide range of climate models, which simulate the Earth's atmosphere, cryosphere, land, and ocean systems in great detail, found that in this case the planet would warm by 0.3 to 1.7 °C in the 21st century. The other pathways are less optimistic, with emissions only falling later in the century, or not at all. In RCP4.5, projected warming is 1.1 to 2.6 °C. In RCP6.0, it is 2.4 to 3.1 °C; and in RCP8.5, 2.6 to 4.8 °C. In 2015, most of the world's nations agreed to limit temperature rise in 2100 to well below 2 °C.

The researchers could not have predicted in the early 2010s, when the pathways were decided on, that most nations would sign off on the Paris Agreement, nor that renewables would be widely deployed. So no RCP was considered to be more probable than the next. "Because we simply don't know the fundamental decisions that are going to be made, we can't assign real probabilities," says van Vuuren of PBL. "We really want to emphasize that there's not a single business-as-usual case."

The researchers next began work on more detailed storylines that complement RCPs and can be used by IAM, climate modelers, and the climate impacts community. Researchers developed five storylines, called shared socioeconomic pathways (SSPs), which describe plausible futures (3). For example, SSP5 portrays a world of high fossil fuel use. SSP4 describes a world dominated by inequality, in which rich nations contribute knowledge and skills whereas poor nations embrace labor-intensive economies. SSP3 is a world of regional rivalry, and SSP1 envisages a sustainable world. SSP2 is a compromise between these four, a "middle-of-the-road" storyline. Economic and demographic modelers can translate these storylines into projections of gross domestic product (GDP) and population, which drive the growth in demand for transportation, heating, and other services.

To highlight what these stories might mean for mitigating climate change, IAMs come into play again. First, modelers run their IAM for each SSP, to see what would happen if no efforts are made to mitigate—this is the baseline scenario. Then they run it again with constrained emissions, corresponding to some of the RCPs, to see what policies and technologies would be needed to meet those emission pathways with the lowest cost.

IAM Complex

Most process-based IAMs have at least three internal stages, or blocks. The first block simulates the energy demand of transportation, industry, buildings, agriculture, and a few other sectors. This depends on socioeconomic factors such as population and GDP. A second block simulates greenhouse gas emissions, by representing energy generating hardware, from nuclear power through to wind farms, furnaces, vehicles, and boilers. Inputs include cost of new units, efficiency, lifetime, and performance of technologies in various parts of the world. For example, one IAM represents three kinds of wind technology, each with a different capital cost assumption for 15 world regions every year till 2100. Finally, a climate block has a rudimentary climate model, which uses emissions to project future warming and other climate effects. The blocks talk back and forth with one another—a shift in energy system might feed back to GDP, etc. IAMs may also include land use and agricultural models, and greenhouse gases other than carbon dioxide.

The blocks can have parameters embedded in them that can affect their behavior. For example, the energy block might have a parameter that explains the link between the price of energy and demand for energy. Historically, when price increases, demand goes down—but by how much? The IAM teams may estimate the parameter value using historical data or studies by energy experts. And they may also make a judgment on how the parameter might change in the future.

The models typically assume that the preferred mitigation option is the lowest cost option. To calculate the lowest cost, some IAMs compare the present value cost of a low-carbon energy system with a business-as-usual energy system over a stated period of time. Other IAMs use a more detailed approach using macroeconomic models to simulate knock-on effects of shifts in the energy system. The underlying assumptions, and resulting trade-offs and feedbacks, some say, can be difficult to unravel and understand.

IAM modelers say the complexity is simply a reflection of society and the economy. "The world is complicated; models will be too," O'Neill says.

Careful Critique

Today, some researchers charge that many IAMs effectively remain a black box, with the underlying computer code, thousands of input assumptions, and millions of data points not publicly available (4). "Many assumptions around things like costs haven't really been published in accompanying material or scientific papers," says Ajay Gambhir, senior research fellow at Imperial College London in the United Kingdom. "That can create a lack of trust in the model results and outputs."

O'Neill disagrees, pointing at an IAM run by his institute where the code and documentation are available online. "There is definitely more that we can do, but I think it's not a true characterization of the field to say you can' find what the numbers are or where they came from," he says.

The model structures can be opaque, says Steven Pye, an associate professor at University College London's Energy Institute in the United Kingdom. For instance, most IAMs find that large amounts of bioenergy with carbon capture and sequestration (BECCS) will be necessary in the future to limit emissions to the RCP2.6 pathway. This puzzled researchers because BECCS is a high-cost option (see Core Concept: Can bioenergy with carbon capture and storage make an impact?), and the assumptions baked into the BECCS choice were not obvious. It turns out the IAM assumed that all mitigation options, including BECCS, were discounted over the long run at a high rate. BECCS had an edge over solar, wind, and other sources of energy because it not only reduces emissions but also removes carbon dioxide from the air. But a steady discount rate is a value judgment on the future, Schmidt says. "A lot of the value statements in economics get buried so deep into the mathematics that people think it is mathematics and not values," he says.

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O'Neill, though, notes that the aim of IAMs is not to be value-free but rather to make judgments explicit and give researchers a way to test them to see how they affect results. Judgments such as discount rates are loudly debated in literature, he says.

Some IAM models do not include all potential mitigation options and so depend on the offsets from BECCS to curb emissions. Pye's own IAM, for instance, has an iron and steel sector that cannot eliminate coal use. "That's not to say there isn't an option for getting rid of the coal in the real world," he cautions. For example, green hydrogen created with surplus renewable electricity could do the job.

There are dozens of IAMs in existence, each having unique structure, different data sources, and varied assumptions. For example, Pye says that most IAMs assume that rising population and GDP will cause energy demand to grow, but factors such as a circular economy and teleworking could make energy demand fall instead.

Finally, IAMs don't account for extreme events—wars, extreme weather, technological innovation, pandemics, and swings in political ideology—which could establish new status quos around energy systems, Gambhir says (5). Many IAMs also don't incorporate "damage functions" to balance the costs of mitigation against the costs of damage to people, the Earth, and the economy, experts say.

Model Transparency

The IAM community is responding to criticisms and moving toward greater transparency. For decades, the community has had inter-comparison projects where they study models with differing specifications to understand their strengths and weaknesses—and to make improvements. The Integrated Assessment Modeling Consortium has been promoting standardized documentation of IAM models.

But some researchers outside the community question whether this will be enough. "A transparency movement in energy modeling is welcome and will help with research integrity long-term," says Ritchie. "However, because IAMs are so complex and funding for transparency efforts is limited, this is difficult to pull off." He says modelers should, at the very least, reveal all the cost assumptions for technologies in a public repository. Schmidt is more circumspect, saying that having open source codes will not necessarily reveal all the value judgments inherent in the models.

Still, researchers say IAMs have their place in a hierarchy of models and are especially useful at the regional scale. IAMs can also be used to study pathways to hit biodiversity and sustainable development goals. At the global policy level, researchers say that IAMs could be combined with other approaches, including regional policy models, expert workshops, scenario analysis, and climate damage models to integrate diverse perspectives on low-carbon pathways.

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