Next Generation Economy, Energy and Climate Modeling

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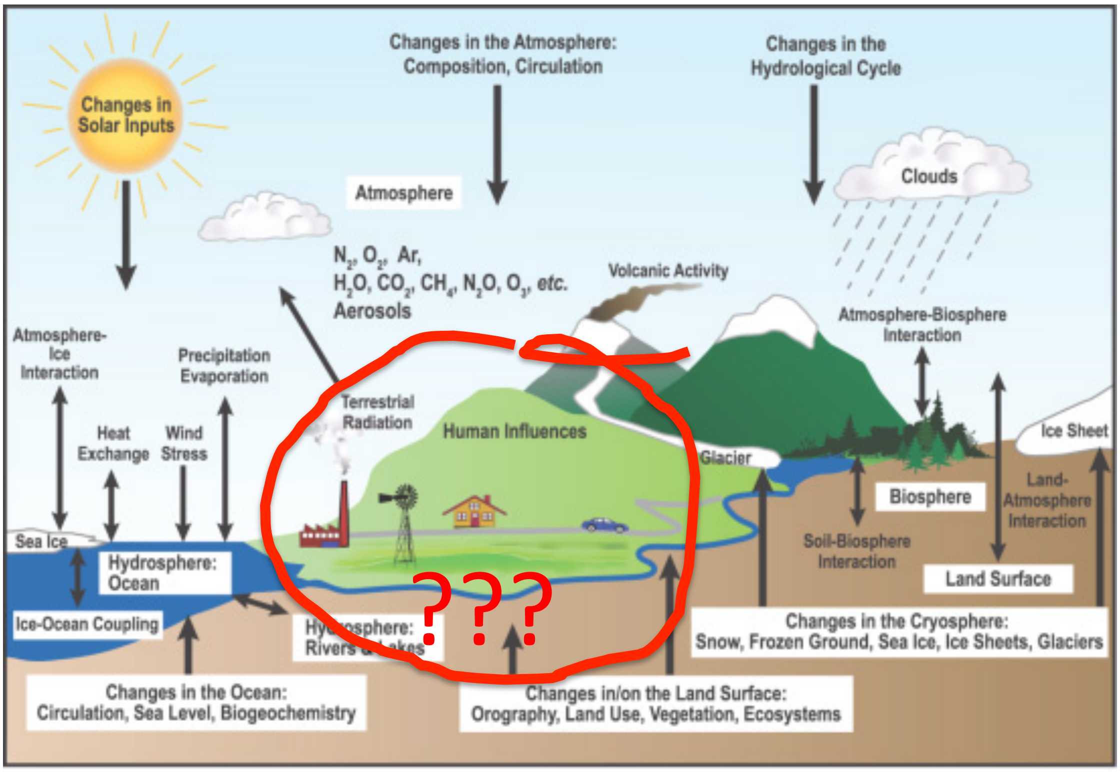

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SUMMARY

- Integrated economy-energy-climate models otherwise known as Integrated Assessment Models (IAMs), are a critical tool for understanding the likely impacts of climate change and for designing policies to mitigate those impacts; the results of analyses by these models play an important role in political debates and media reporting on climate issues.
- The greatest source of uncertainty in IAM models are scenarios for economic growth and development, and the dynamic two-way relationship between those scenarios and energy use and emissions.
- Standard economic modeling makes strong assumptions about the optimality of the current economic system, about agent rationality, our ability to forecast future risks, has difficulty modeling the distributional consequences of climate policies, and is limited in its treatment of technology progress.
- This paper identifies new approaches - many developed in response to the challenges of modeling the financial crisis - that overcome these issues and could be incorporated in IAMs; success in other fields using "agent-based models" provide an example of what might be achieved in IAM modeling.
- Such next-generation IAMs could provide significantly more realistic analyses and policy prescriptions; the authors hypothesize that the results of such analyses could have major implications for policymaking and lead to new insights and innovative approaches.

ABOUT THE AUTHORS

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1. CURRENT GENERATION INTEGRATED ASSESSMENT MODELS

Over the past decades the economics, energy, climate science and policy communities have developed a number of Integrated Assessment Models (IAMs).[1] These models are diverse in their methods and scope but typically contain some representation of the macroeconomy, a representation of the energy sector, and a representation of the global climate system. The purpose of these models is to study the interlinkages between these three highly complex systems. A consistent theme across generations of IPCC reports has been that the greatest source of uncertainty for the future path of the climate system is the future path of human economic activity and the policies that will guide that path. IAMs enable researchers to develop and analyze scenarios for such future paths.

IAMs also play an important role in policymaking. They enable policymakers to ask "what if" questions regarding policy options and evaluate the potential impacts of policies on both the climate and economy, and help make trade-offs between policy costs and benefits. IAMs have been used extensively in the IPCC's reports, as well as the Stern Review, and by government agencies such as the EPA and DOE in the US, or DECC in the UK, or the Environment Directorate of the European Commission. The results of such analyses can play an important role in political debates over climate policy and in media reporting and public perceptions.

Examples of IAM models include the DICE model developed by William Nordhaus at Yale which combines a Ramsey-type optimal growth structure model and Cobb-Douglas production function with a stock and flow emissions model calibrated to the MAGICC physical climate model; the IGSM model developed at MIT combines a computable general equilibrium (CGE) economy model with a 2-D atmospheric and ocean model, plus a land use model; the IIASA-IAM has a detailed economy-energy model that allows regional scenarios and modules on emissions, agriculture and forestry; and the Tyndall Centre has its Community Integrated Assessment System (CIAS) which is a platform that allows researchers to mix and match from different sectoral and system models.

As noted there is a diversity of modeling approaches and scope within the IAM community. Some of the models emphasize the physical climate system with lots of detail on the climate's various sub-systems (land use, water, clouds, etc.) but then have a simpler representation of the economy. Others might emphasize the energy sector with a lot of detail on energy sources, mixes, technologies, fuel prices, and regional variations. While still others might emphasize the economy with more detail on household and firm behavior, output, employment, and the impact of policies on social welfare. Finally, some models emphasize what-if scenario building, while others are more useful for optimizing trade-offs between factors, e.g. searching for a carbon price path that optimizes the trade-off between mitigation impact and economic costs. Different models thus have different strengths and weaknesses.[2]

2. LIMITS TO CURRENT GENERATION MODELS

While these models are diverse, almost all IAMs share a common set of limitations in the way that they portray human economic activity. The models typically use conventional economic approaches to model the economy and rely on a number of strong assumptions in standard

[1] See the Integrated Assessment Modeling Consortium (IAMC) for an overview of its members and the models they have developed (www.iamconsortium.org).

[2] See for example the AMPERE project at the Potsdam Institute for Climate Change, which is comparing the output of 21 different models from 12 countries, http://ampere-project.eu/web/index.php?option=com_content&view=article&id=12:climate&catid=7&Itemid=105

economic theory. In this section we will briefly summarize those limitations and then in Section 3 we will outline new ideas from economics and other fields that could be brought into IAMs to create a more realistic and effective next generation of models.

Assumptions of Equilibrium and Optimality

Standard economics assumes that the economy is a system that naturally rests in a fixed point equilibrium, is perturbed by external shocks and then moves to a new equilibrium point. Both climate change and the potential transition to a green economy are clearly massive disequilibrium phenomena. They need to be modeled in an endogenous, interlinked, dynamic way rather than as exogenous shocks. New methods (described next section) allow the modeling of the economy as a dynamic disequilibrium system.

Cost-Benefit Framing

It is also typically assumed that the equilibrium the economy is in today provides an optimal allocation of resources. Responding to climate change is then framed as a cost-benefit trade-off problem. Policy responses and movement to a green economy are then assumed to have societal costs and those then weighed against benefits in avoided damage from climate change. There are three problems with this approach: 1) the economic arrangements we have today may not be optimal, but by *a priori* assuming they are the possibility that a green economy could be a better economy is negated, 2) it assumes we can make accurate forecasts of both the economy and climate change far into the future, and 3) the results are sensitive to both the choice of discount rate and method of discounting (see Risk below).

Rationality

Models typically also utilize standard economic assumptions about agent rationality. However, a large body of work in behavioral economics, psychology and cognitive science shows that real human behavior differs significantly from these assumptions. These behavioral effects can have a significant impact on policy effectiveness, for example explaining why responses to energy efficiency programs are typically lower than expected.

Risk

Standard approaches to modeling risk typically assume Gaussian distributions, linearity, time symmetry (i.e. phenomena are reversible), ergodicity, complete information, and rational discounting agents. Yet climate risks are heavily fat-tailed, are characterized by non-linear tipping points, have many irreversible phenomena (e.g. permafrost methane release), are path dependent and non-ergodic, information is incomplete and revealed over time, and real people are not time consistent in their discounting (i.e. they use hyperbolic discounting).

Heterogeneity

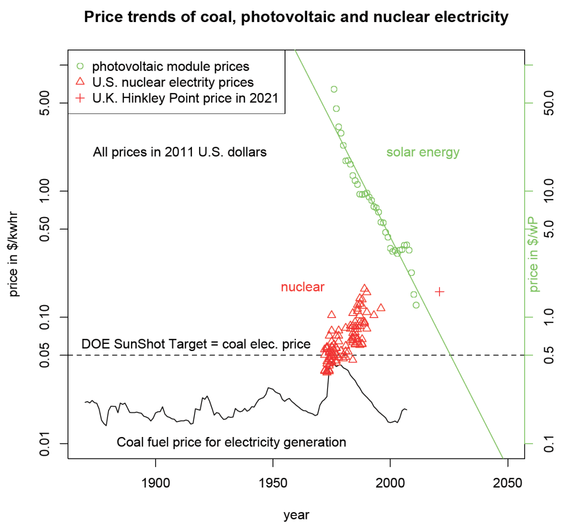
Standard models also assume that households and firms can be portrayed as a single "representative agent". This assumes away heterogeneity in these populations. Such heterogeneity is important in two ways. First, interactions between heterogeneous agents can have an important impact on policy effectiveness or technology adoption (e.g. a technology might be first adopted by one segment and then as its price drops adopted by further segments). Second, explicitly representing agent diversity is important for assessing the distributional and political economy impacts of a policy (e.g. what would be the impact of a carbon tax on the poorest households).

Networks and Geography

Industries can be thought of as networks of firms interacting in input-output relationships. Work has shown that the structure and evolution of these networks is a major determinate of patterns of economic growth. The energy sector is a key part of these interlinked networks. Standard models often handle these relationships econometrically, but this assumes the future will be much like the past and does not address structural change in these networks and relationships easily. Furthermore these networks often have a physical manifestation (e.g. industrial clusters in particular regions), and there are strong interactions between the geography of energy and transport infrastructure and the location of population centers and industrial development that are difficult to capture in standard economic models.

Technology Change

One of the most critical determinants of the future path of the economic-climate system will be technology change. Different energy technologies may be on very different trajectories (see diagram). Most IAMs model technology change as an assumed exogenous factor, e.g. as changes in total factor productivity, or as "x-factor" changes in energy technologies (unknown changes that have some assumed effect). Some models have so-called "endogenous growth" functions but these simply assume an increasing returns function to R&D investments. The transition to a green economy will require Schumpeterian waves of creative destruction and even changes on par with the Industrial Revolution = patterns of change that standard modeling techniques have difficulty capturing.



Financial Sector

Most standard macroeconomic models, including those used in IAMs, have either no or a very limited representation of the financial sector and the sector's interactions with the macroeconomy. Traditionally the sector has been assumed to merely be an efficient mechanism for allocating capital and not playing a more systemic macroeconomic role. The 2008 Financial Crisis showed how dramatically wrong this view was and there are now major efforts to re-incorporate finance in macro. The financial sector will likewise play a major role in any transition to a green economy and will be critical in determining the effectiveness of many policies.

3. CREATING THE NEXT GENERATION OF IAMS

New Approaches Inspired by the Financial Crisis

Many of the limitations of traditional economic modeling in IAMs described above are also limitations in the models that were used by central banks, finance ministries, and multilateral institutions during the 2008 Financial Crisis. The DSGE, CGE, econometric and VAR models used by these institutions failed significantly during the crisis and policymakers lost confidence in the analytical tools at their disposal. These models could not account for the out of equilibrium dynamics of the system during the crisis, contagion effects in the financial network, the failure of standard risk models and measures, significant deviations from rational-agent behavior, the role of heterogeneity (e.g. distributions of credit quality), geography (e.g. concentrations of sub-prime in certain regions), dynamic interactions between the financial system and macroeconomy, or the important role financial innovation played in creating the conditions for the crisis. Former ECB President Jean-Claude Trichet later said, "As a policy-maker during the crisis, I found the available models of limited help. In fact, I would go further: in the face of the crisis, we felt abandoned by conventional tools."[3]

Two of the authors of this paper are principle investigators in a European Commission funded project called CRISIS (www.crisis-economics.eu) that involves ten universities and a private sector software firm working together to develop the next generation of macro-financial policy models for central banks and finance ministries to help address these issues. While the phenomena studied by IAMs differ in some important respects, we believe that many of the same ideas and tools could be helpful in creating a next generation of IAMs.

Complex Adaptive Systems and Agent-Based Modeling

A critical shift for the central banking models is to begin to view the economy not as an equilibrium system, but as a complex adaptive system. Such systems are characterized by multiple, heterogeneous, agents (e.g. households, firms) interacting in networks, where the interactions in the system are dynamic and often non-linear, and where there are endogenous processes of innovation and change. These systems are best modeled from the "bottom-up" and can include micro foundations of realistic agent behavior and important institutional detail. Such models cannot be solved analytically, but can be simulated as "agent-based models" (ABMs) on computers. Large amounts of computing power and the growing availability of "big data" mean that such simulations can become increasingly detailed and realistic - for example, one of our collaborators has successfully built a model of all 120 million private sector firms in the US economy individually modeled at 1:1 resolution. Other fields studying complex adaptive systems such as biology, ecology, and epidemiology have successfully used ABMs. There have also been applications to policymaking in defense, intelligence, public health, transport, and other areas.

What a Next Generation IAM Might Look Like

We could imagine integrating the kind of macroeconomic-financial agent-based model being built by CRISIS with a physical climate model to create a next generation IAM that would address many of the limitations outlined in Section 2. The economic section of such a model would have five sectors: firms, households, financial institutions, energy, and government.

[3] Speech at the ECB Annual Central Banking Conference, November 2010

The model could also explicitly take into account geography and endogenous technology change.

Firms

Firms would be modeled as individual agents. Each firm would have outputs of products and services, and inputs of energy, labor, materials, and capital. Each firm would then have financial variables associated with its activities (revenues, profits, balance sheet information) and CO_2 and other gas emissions also associated with its activities. Each firm could also employ a set of technologies that determine its energy and emissions impacts. The firms would then interact in a network of input-output relationships with other firms and the energy sector, as well as with the households through goods and labor markets, and with the financial sector through capital markets. Firms would also be identified with specific industry sectors and geographies. The firms would not need to be modeled at the 1:1 resolution of our colleague's model, but the largest and most significant firms for emissions could be modeled and calibrated individually, while smaller firms could be aggregated by sector. Decisions by firms could be realistically modeled as heuristics derived from the management literature and from behavioral economics, rather than assume agent rationality.

Households

A population of household agents would be created that would capture the heterogeneity of actual populations. Household agents would contain demographic information (e.g. number of people, ages), employment information, income and wealth. Other factors such as home ownership, and distributions of home styles (e.g. dense urban, suburban, rural) could also be realistically portrayed. Households would then have energy use, transport, and emissions associated with their activities (e.g. a 2 parent, 2 child household with a medium size suburban house and driving as primary transport would have a particular energy and emissions profile). The population of households could also be realistically arrayed against different energy sources (e.g. X% coal, Y% gas, etc.). Households could also be located geographically by nation, region, or even city. Households might also have a technology set associated with their activities. Finally, households would have births and deaths to introduce population dynamics. The households would also not need to be modeled at 1:1 resolution but a statistically significant population would be artificially created that captured the heterogeneity of real populations in the dimensions above. Households could also be linked in social networks to study for example the spread of new behaviors (e.g. changing energy or consumption habits) or new technologies. As with firms, household agents could be behaviorally realistic rather than assume strict rationality. The CRISIS model for example is using work from both behavioral economics and laboratory experiments to inform its portrayal of household agents.

Financial Sector

The financial sector would not need to be modeled in as much detail as the CRISIS central banking model, but it would still be important to include the sector. A network of bank agents would take savings from and provide loans to households and firms. Capital markets for other assets such as stocks could also be introduced. Certain aspects of the financial sector might be modeled in more detail such as the provision of capital to the energy, industrial, buildings, and transport sectors, or venture capital for new energy technologies. Again these could be specific to particular geographies.

Energy Sector

The energy sector would naturally be modeled in more detail than other sectors. Individual power plants with their specific economics and operating characteristics could be modeled as agents if that was important, as well as the transmission network. The sector would have both new-build and plant retirement and a mix of fuels (coal, gas, oil) and technologies (e.g. CCGT, super critical coal). Renewables could be affiliated with households (roof-top solar), firms or specific geographies (e.g. wind farms). The energy sector would provide inputs into the network of firms, and would be part of household consumption.

Government

The government sector would provide basic economic policy management (e.g. monetary and fiscal policy) and then more detailed policies relating specifically to energy and climate change. This module would be created as flexibly as possible to enable a broad array of policy options to be modeled and tested. These could include carbon prices, carbon taxes, direct regulation of emissions, energy efficiency standards, vehicle standards, sectoral regulations, sectoral subsidies, government R&D spending, tax policies, and so on.

Geography

Numerous agent-based models incorporate realistic representations of geography, e.g. epidemiology models, road traffic models, and military models. Economic agents of firms and households could be arrayed on a realistic geography to provide more direct connections with 2D and 3D physical models for land use, atmosphere, and oceans (e.g. concentrations of economic activity and emissions in cities could be represented, or geographies with rural economies). Other geographic considerations such as electricity and transport networks, or distance between renewable sources (e.g. windy, sunny places) and energy demand could also be taken into account.

Technology Change

Such a model could draw on existing agent-based models with endogenous, Schumpeterian technology change. Such models view innovation as an evolutionary search process through a space of possibilities. The model could also draw on new work that two of the authors and a set of collaborators are doing for the US Department of Energy that looks at interconnections between technologies in "technology ecosystems" and the impact of the evolution of such ecosystems on experience curves and innovation in the renewables sector.

The agent-based economic model outlined above would then be integrated with a physical climate model (or set of physical modules, e.g. atmosphere, land use, water). The linkages between the economy model and the physical model would mirror those of the real world - household agents and firms would use resources and create emissions based on their activities. Those resource uses and emissions would then feed into the physical climate model to produce outcomes for warming, sea level rises, weather patterns, impacts on forestry, agriculture, and other factors of interest.

Analyzing a Next Generation Model

The net effect of such a model would be that the emissions path of CO_2 (and other gases) would emerge bottom-up out of the activities of the households and firms. Other factors such as GDP, energy use and mix, sectoral growth rates, investment, and employment would also emerge bottom-up as the model evolves and unfolds over time. A key step in making such a model useful for policy analysis and research would be to calibrate it against data and initialize the model to a set of specific countries (or regions) at a specific point in time. While there are inherent limits to forecasting in a system as complex as the economy-energy-climate system, the model could be used to make contingent, scenario-based forecasts (e.g. under the following conditions we would expect the following range of outcomes).

Such a model could also be used to run and test a broad array of policy scenarios as outlined above in the Government section. The model would not only enable analysis of the broad economic and climate outcomes, but also distributional, regional, and political economy effects - key to understanding the likely politics associated with policy options.

Complex agent-based models typically do not have single optimal states as they are dynamic and do not have fixed point equilibriums. However, such a model could be used to assess possible paths towards a policy goal (e.g. possible paths to 2 degrees), rule out certain states (e.g. under the following conditions 2 degrees is not possible), and test system robustness (e.g. under these conditions the system is robust against shocks and uncertainty, under these conditions it is more fragile). Agent-based models do not *a priori* assume Gaussian distributions rather risk distributions emerge bottom-up from the model and so may be fat-tailed. Likewise irreversibilities, non-rational agent discounting behavior, and other factors to realistically model system risk can be incorporated. Finally, non-linear dynamic systems such as the climate-energy-economy system often have a handful of particularly sensitive variables. Parameter sweeps of the model can help identify such variables which may be helpful to emissions mitigation efforts (e.g. sensitive points where policy intervention might have an outsized positive impact) or might be harmful (e.g. tipping points that lock the system into a negative path).

4. POTENTIAL SO-WHATS FOR POLICY

Creating such an ambitious model would require major investments of time by the research community and significant funding support. One would need to be confident that the effort would be worthwhile and lead to understanding, insights, and ideas that are different from and not possible with the current generation of models.

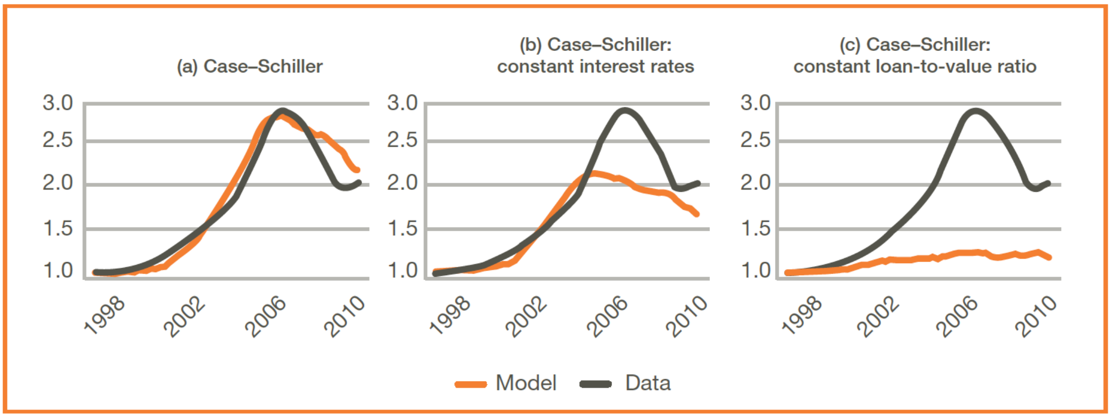
A good analogy is the case of the development of epidemiology over the past decades. Prior to 9/11 the models used by epidemiologists were very similar to the economic models used by IAMs today. They were aggregate, top-down models based on differential equations and came with a strict set of *a priori* assumptions. Physicians tracking the spread of disease in the field and doing empirical work knew that these models were highly inaccurate and even produced misleading results. But policymakers relied on the models to provide analysis and support in vaccination and other public health programs.

After 9/11 US policymakers began examining the potential impacts of a bio-terrorism attack. The standard models said that if smallpox was released in a major city such as New York that this would require vaccination of the entire city and shutting down all transport in and out of the city. Not only would this be expensive and logistically challenging (e.g. storing and distributing 20 million vaccine doses for New York, closing all roads, trains and airports) but there would be a major human cost as 1 in 10,000 people would have a reaction to the vaccine resulting in severe illness, permanent disfigurement, or death.

White House officials and other policymakers asked if there was a better way. This led to a $50 million effort to develop a next-generation set of epidemiological models based on the agent-based approach outlined above. The models revolutionized not only epidemiological research and public health, but also had significant policy implications. The policy for bio-terrorism response was changed from mass vaccination to one focused tightly on isolating and vaccinating the infected population, tracing and vaccinating their social networks and contact points, and vaccinating first responders. The models, supported by field evidence, showed that such a response would be both more effective, less economic costs, and have far lower human costs in terms of side-effects.

Our work on financial systems modeling is still in its early stages but is similarly yielding new insights that are significantly different from traditional modeling. For example, one of us (Farmer) and colleagues have built a detailed agent-based model of the housing market parameterized with real-world data. Not only does this model replicate actual housing bubble

Agent-based model of the Washington, DC housing market
1 = Case-Schiller house price index in 1998



dynamics well (see diagram, panel *a*) but also points to a different policy response. Traditional modeling recommends that the best policies for preventing the formation of housing bubbles are to raise interest rates or to increase bank capital reserves. Both policies have significant side-effects and could potentially slow overall economic growth and create unemployment. Farmer and his colleagues ran counter-factual scenarios for the Washington DC housing market and showed that if interest rates had been held constant instead of declined the bubble would indeed have been less severe (panel *b*), but with the consequence of lower overall economic output. However, the model highlighted that if regulators had prevented a decline in loan-to-value ratios (i.e. maintained standards for borrowers' down-payments) it would have been more effective in preventing the bubble (panel *c*) and had far fewer negative side-effects for the rest of the economy. As in the smallpox case, a more targeted policy was found that was both more effective and less costly.

What specific policy insights an agent-based IAM would yield are difficult to predict. However, one can hypothesize there would be several areas of difference with conventional models:

- Green growth - by assuming that the current economy is optimal, traditional models necessitate that any transition to a green economy results in a lower output path and welfare losses. Yet historically periods of major investment and technology change have resulted in higher growth, productivity, and welfare increases. An ABM approach that does not assume equilibrium could give insight into how a green growth path might be achieved.

- Employment - likewise, by assuming full-employment equilibrium, traditional models necessitate negative employment effects from a green transition. An ABM could explore the sectoral employment dynamics and both job destruction and job creation of such a transition and provide a more realistic picture of likely employment impacts.

- Risk - as noted, traditional assessments of risk depend on discount rate assumptions within a cost-benefit framework and forecasts. A next-generation approach would take into account fat-tails, irreversibilities, and tipping points, thus likely creating an even stronger case for action. And rather than rely on forecasts, an ABM approach would highlight system sensitivities and support the design of strategies that are robust agains future uncertainty.

- Energy mix dynamics - the relationships between energy demand, mix, technology and prices is quite complex with two way feedbacks and time delays. For example steep declines in gas prices due to fracking is having a significant impact on the economics of coal, oil and renewables. This will feedback both to the economy, and eventually back to gas economics. A bottom-up ABM is well suited to analyzing these feedbacks and possible scenarios.

- Technology - a next-generation approach would endogenously model dynamic feedbacks between policies, technologies, economic activities, and emissions; for example dynamics between R&D investments, technology adoption, experience curves, and costs. Such an approach may yield more targeted and effective green innovation policies.

These are just a few examples. As experience has shown from other domains, our intuition about highly complex systems is not always right. This is why tools such as ABMs are so valuable - they can take a large volume of facts and data into account, keep track of complex and dynamic relationships, and sometimes surprise us with the results. They do not replace policymaker judgement, but they can very helpfully augment it.

5. CONCLUSION

The current generation of IAMs have played a very important role in both research and policymaking. The physical climate models incorporated in them are highly sophisticated, based on sound science and incorporate significant amounts of data. The empirical accuracy and detail of these physical climate models has advanced significantly over the past decades.

Unfortunately the economic models that these physical climate models are attached to are not nearly as sophisticated or empirically sound. They typically model the economy as a highly aggregate, top-down system, with strict and empirically questionable assumptions about economic optimality, market efficiency, and agent rationality. This is problematic as the greatest source of uncertainty in the future path of the Earth's climate system is human economic activity. It is also problematic as these models may in some cases be misleading or erroneous in their conclusions for policy design. They are also insufficiently helpful in generating new ideas for innovative solutions.

The program outlined here is highly ambitious. Building a next generation of IAMs would take years of effort and have risks. But the experience of the climate science community shows it can be done. Decades ago physical climate models were also very crude. But with significant investments in modeling methodology, data, and underlying science, that community has built today's highly sophisticated and impactful models. The challenge of climate change deserves no less of an effort from the economics community.