Expanding the possible: the need for heterodox economics in integrated climate-economy modeling

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Abstract:

This paper builds the case that heterodox economists should engage with climate-economy integrated assessment modeling as a way to address the climate emergency. Climate-economy modeling is a type of formalized storytelling about the paths that are open to us in responding to climate change. Current prominent integrated assessment models, which are based on neoclassical economics, exclude, on theoretical grounds, a significant range of relevant and desirable climate futures. This paper introduces integrated assessment modeling and the climate scenarios that those models create. It then retells some of the primary storylines told by current models. Finally, the paper outlines how heterodox economics could tell more expansive stories that engage deeply with the real world and allow for a broader range of possibilities.

1. Introduction: Telling better stories about our climate futures

In late February 2020, just days before Europe and the United States joined China and much of Asia in imposing severe mobility restrictions in response to the COVID-19 pandemic, David McCollum and his colleagues published a short Nature Commentary piece calling on climate-economy modelers to “explore extremes” in their modeling (McCollum et al., 2020). Although these models, which attempt to create plausible scenarios of technological, social, economic and environmental development for the next 80 years, could fairly be described as highly formalized forms of science fiction, the plotlines investigated by these models are strikingly dull. Where, they ask, are the wars? The geopolitical realignment? The economic panics and shocks? The massive waves of structural economic changes and resulting backlash of social resistance? Where is the space for the wildcards, which are “not even on the radar” (Ibid.)? Their advice was well timed, although their extensive list of specific examples of extremes failed to include the global pandemic which had already quietly begun.

One of the primary ways economists have responded to the climate crisis has been by contributing to climate-economy integrated assessment models. These models come in a number of different shapes and sizes, but at their core they combine a vision of what is possible for our economies with an understanding of how the earth’s climate will respond to various concentrations of greenhouse gases. While the second half of this equation is the domain of climate scientists and seems to be an area of relative consensus, the question of economic possibilities encompasses essentially every debate and disagreement within our dismal discipline.

Unfortunately, this debate about which economic paths remain open is not taking place within climate-economy modeling. Virtually all of the major integrated models which are used to inform national policy, craft international treaties, and fill the Intergovernmental Panel on Climate Change (IPCC) reports, are based entirely on neoclassical economics. These models, and the scenarios they generate, take a startlingly narrow view of what is in store for the global economy over the coming century. On a formal level, they impose a state of long-term equilibrium, with economic growth happily humming away year after year at a set rate until dastardly policymakers impose productivity-killing carbon taxes. On a practical level, they foresee more of the same for the world economy, but now with windmills.

This approach to climate-economy modeling is dangerous and counterproductive. On one side, it gives us an unrealistically rosy picture of how bad things could get as temperatures rise. On the other, it artificially closes off the paths towards better worlds, formally cutting off exploration in any direction that requires a structural change to the system. Integrated assessment modeling provides a framework for holistically visualizing various paths for the future. This exercise is pointless, however, if our vision of the future is simply an endless extension of the present.

We need models that can tell better, more useful, stories. Stories in which countries can change their attitudes and adapt their reality to match. Stories in which economic growth is responsive to public policy and can rise or shrink based on our needs. Stories in which the transition to a climate-neutral economy occurs in years, not decades.

Heterodox economics can help tell these stories. With far more open theoretical frameworks, a wide range of areas of topical expertise, and a more pluralistic worldview, heterodox economics provides a better starting point for developing new climate-economy models than neoclassical general equilibrium economics. It is also an ideal field from which to make critiques of, and contributions to, the existing integrated assessment modeling literature. From the notion of government-maintained full employment to a vision of prosperity without economic growth, from an understanding of social reproduction and care to a focus on the evolution of intuitions and the development of technology, heterodox economics offers a rich range of ideas and tools that are needed to understand what policy makers can, and should, do to mitigate the climate crisis. The worlds in which many heterodox scholars would like us to live are impossible in the current integrated modeling landscape. For those worlds to have a chance of being realized, a crucial step is to show, using the prevailing methods recognized by policy makers, civil society groups, and academics outside of our discipline, that they are indeed possible.

This paper will build the case that heterodox economics have a valuable and desperately needed contribution to make in the field of integrated climate-economy modeling. Section 2 will better describe these ‘science fiction’ models which attempt to combine technological, economic, and environmental developments. Section 3 will offer examples of the kinds of stories the current models are able to tell us. Section 4 will highlight the stories that are highly relevant for addressing the climate emergency but are currently not being told, and in many cases are impossible to tell, with current assessment models. Section 5 will identify where heterodox economics has already had a hand in shaping climate-economy models and consider the prospects for further involvement.

2. Science fiction modeling: integrating climate, economy, technology and (almost) everything else

As their name suggests, integrated assessment models (IAMs) are a class of models that combine economic and climatic considerations. These models are built by combining a number of separate ‘modules’ which model different aspects of the economy-climate-environment system. IAMs typically have both an economy module, which represents economic activity, and a climate module, which projects emissions levels and their corresponding levels of warming (Cattan and McIsaac, 2021). Simple models stop here, but the most developed IAMs can add many more modules for systems such as energy, technological developments, agriculture and land use. Other physical and environmental factors such as biodiversity loss, materials use, or resource availability could theoretically be included as modules, although modeling these specific topics currently remains a largely unexplored field. While some simpler IAMs remain fairly abstract, the more complex models can provide an impressive range of projections at a very high resolution, down to the levels of an individual technology, like electric vehicles, adopted in each year. Large IAMs typically run until at least 2100, with benchmarks for 2050 also commonly used.

Due to their expansive scope and long timeframes, it is useful to think of this type of modeling as closer to an exercise in highly detailed science fiction than the short-term economic forecasting to which many of the most extensive economic models are geared. Like any work of fiction, these models start by defining what is and is not possible within their world, going question by question, topic by topic, to decide the logic by which each piece of the model will interact with the others. This sets the parameters for what can and can't happen in the world of the model. Once this world has been constructed, stories can be told. These stories can start in different places, aim at different destinations, or include critical divergences in fundamentally uncertain developments like the effectiveness of currently undeveloped technologies. By telling many possible stories, these models help us explore what lies in the dark edges of the map, uncovering one by one the worlds that may be in store for us and suggesting which actions are most relevant in the near term to reach the most desirable futures.

Heterodox economics has a chance to contribute to both levels of this storytelling exercise: by expanding the world built by the models themselves and by developing new stories, or scenarios, to be investigated by the models.

2.1 Modeling: building the world

There are two main types of IAMs that are primarily used to analyze two distinct sets of questions. The first, *optimal growth models*, analyze the expected levels of economic damages that will be caused by climate change while the second, *emission pathway models*, attempt to show various potential scenarios for future economic, technological and environmental development (Nikas et al., 2019). The emission pathway models are the real science fiction thrillers, but the optimized growth models have also been highly influential and are worth briefly discussing.

2.1.1 Optimal growth models

Optimal growth models attempt to estimate the damages which will be caused at various levels of climate change. These models are set up as cost-benefit analyses which simultaneously estimate the expected costs of climate change and the expected costs associated with mitigating climate change to produce an ‘optimal’ level of global warming at which the avoided damages of climate change match the costs of further mitigation. A pioneering example of these types of models is the Dynamic Integrated Climate-Economy (DICE) model developed by William Nordhaus (Nordhaus, 1992). Following the typology developed by Nikas et al., (2019), these models can be described as “optimal growth” models, as they maximize economic growth over the long term, given the potential for climate damages.

These models are typically relatively simple (compared to emission pathway models) and include a very limited number of additional modules beyond the core climate-economy analysis. They are often global, but can also be done at a regional or national level. Climate damages can either be estimated bottom up, by trying to add up the individual expected damages in each sector affected by climate change, or top down, by using some form of statistical inference to estimate what damages will look like in the future (Dellink et al., 2019). One popular statistical approach for calculating potential economic climate damages is to locate an optimal temperature for economic activity at which warmer or cooler average temperatures are associated with lower levels of either total GDP or GDP growth (Hsiang et al., 2017). Damages (or gains) can then be assessed by the degree to which warming projections move countries further from (or closer to) the optimal average temperature. Another statistical approach is to look at the estimates of recorded climate damages which have occurred so far at roughly 1.1 degrees of global warming and project forward to various levels of potential warming (Kahn et al., 2019).

Damages obtained from these methods are then integrated with estimates of the costs of mitigating climate change obtained from general equilibrium models which show the productivity losses resulting from the carbon taxes needed to hit a given level of warming. This produces the ‘optimal’ level of warming, at which the costs of mitigating climate change meet projected climate damages.

Optimal growth models have come under heavy criticism recently both for their simplifying assumptions about how climate change will affect the economy, and for the limited size of their ultimate estimates of the economic damages of climate change (Keen, 2020; Asefi-Najafabady et al., 2020). A good illustration of the deep limitations of these models comes from Woillez, Giraud, and Godin (2020), who take the climatic data associated with the last ice age and plug it into two standard climate damage functions (Woillez et al., 2020). In the first model, a return to the last glacial maximum, when much of the northern hemisphere was permanently covered in ice, would result in a global GDP of just 1-2% lower than the baseline. In the second model the world would actually be 36% richer, as much of the global south is cooled towards the optimal temperatures now associated with the global north and experience booms large enough to offset the declines elsewhere.

While optimal growth models are important for heterodox economics to understand and criticize due to their use in calculating social cost of carbon measures, the science regarding the impacts of climate change has clearly shown that the optimal level of global warming is as little as possible (Kikstra et al., 2021). The question of the potential damages from climate change then becomes less important for determining how much we should do to mitigate it, but rather as a key part of the world-building exercise that goes into creating emission pathway models.

2.1.2 Emission pathway models

Emission pathway models are a large range of modeling frameworks which generate plausible scenarios of possible emissions pathways given particular economic and technological developments. Instead of trying to optimize growth over a particular period, these models look to describe a coherent future by modeling the economic and technological possibilities for achieving various emissions levels. Emission pathway models can either work backwards from a set target—for example, showing various paths which could achieve 2 degrees of warming by 2100—or can simulate from a starting point forward, analyzing how various policy choices or other developments affect the environmental and economic outcomes throughout the simulation period. Policy choices and technological development can be modeled in significant detail in emission pathway modeling, although a large majority of models rely on a universal carbon price as a standin representation of all other decarbonization policies. These models can also focus specifically on individual sectors, with a large number of models focusing in particular on the energy sector.

Often the climate-economy components of the models can be combined with various other modules, resulting in extremely extensive and complex final modeling frameworks. There is an ongoing discussion about the complexity and transparency of these models, as their large scope and interconnectedness makes it difficult to isolate the causes of particular results or to explain how various assumptions or modeling decisions are reflected in results (Keppo et al., 2021). Modeling can be done at virtually any level, with global and national models being common, but also models at the regional, city and even neighborhood level (Pfenninger and Pickering, 2018).

The core economics module of each IAM can be designed in a number of different ways. Each type of modeling puts restrictions on the possible effects that the other outputs of the model (like technology adoption or decarbonization investments) will have on the overall level of economic activity generated by the model. While the results of each model will be determined to a large degree by the specific assumptions and calibrations that go into it, the choice of model structure places key limits on how growth can be affected by policy interventions.

The majority of emission pathway models, including all of the models used in the IPCC's 5th Assessment Report, use general equilibrium modeling to represent the economy (IPCC, 2014, p. 422, 2018, p. 100). Most models are computable general equilibrium models (CGE) in which the path of the entire economy is optimized, typically at a sectoral level (Matsumoto and Fujimori, 2019). A smaller number of models are partial equilibrium models in which only one sector—typically the energy system—is fully optimized while the rest of the economy is assumed to follow the status quo. In principle, these equilibrium models could be augmented by including various market imperfections and frictions which would prevent the model from achieving full capacity in the short or medium term.

A second class of emission pathway models are based on macroeconometric modeling. These models build a set of theoretical relationships within the economy and then use real-world data to econometrically calibrate the coefficients of these relationships (Lehr and Lutz, 2019). The models then simulate forward to create scenarios based on both the structural relationships of the economy embedded within the model and the inputs provided to the model to create a given scenario. Critically, unlike equilibrium models, macroeconometric models do not assume the economy operates at full capacity in the short or medium terms, but rather allow the level of economic activity to fluctuate based on the demand generated by previous periods in the model.

Finally, there are two other types of modeling that are currently used by a small number of IAMs, but have the potential to become more popular in the future. The first, systems dynamics modeling has a long tradition in modeling energy and resource use and is currently used by at least one large scale global emission pathway model (Meadows et al., 1972; Capellán-Pérez et al., 2020). The second, agent-based modeling, has quickly become more popular within economics, particularly for analyzing the financial sector and processes of innovation, and is a promising tool for creating larger emissions pathway models (Lamperti et al., 2019).

The remainder of this paper will refer primarily to emission pathway models and the stories they tell.

2.2 Scenarios: telling the story

Once you've built a world, you need to tell a story. In the context of an emission pathway model, the story, or scenario, is a tool for understanding the various coherent ways in which different emissions outcomes can be achieved. They are intended to show a range of plausible futures and to provide insights into the most important components for achieving a desired emissions pathway. These stories are not forecasts or predictions of what is most likely to happen, but rather coherent sets of things which *could* happen. Very often the stories being told by these models center around hitting various emissions goals by certain dates, such as net-zero emissions by 2050, or 2 degrees of global warming over pre-industrial averages by 2100. In this context, the scenarios can be presented as roadmaps that detail the path a country, or the world, could take to achieve their climate goals. The integrated nature of these models also allows many IAMs to consider non-energy related sources of emissions, providing a proper to-do list of the steps that could be taken to transition to a fully emissions-free economy.

Climate-economy models can also be used to analyze more topical questions by changing key assumptions, inputs, or policy responses to see how the model responds. For example, many models now estimate the various ways decarbonization technology could develop going forward to better understand what the transition will look like if things like renewable energy, nuclear energy or carbon capture and sequestration are either much cheaper or much more expensive than normally projected (Larson, et al., 2020). Scenarios have also been created for various levels of resource availability to analyze how the climate-economy system could develop with either very high or very low levels of fossil fuel availability (Capellán-Pérez et al., 2019; Samsó et al., 2020). Different decarbonizing policy measures can also be compared via scenario analysis to see which paths are opened and closed by measures such as carbon taxes or state-directed industrial policy. There are also a number of sector or industry-specific uses for these models, as they allow for very detailed questions to be answered in the context of the larger decarbonization transition.

Their all-inclusive approach makes emission pathways scenarios highly influential in policy. They are the primary source for the socioeconomic portions of the IPCC's reporting framework, particularly the Working Group III on mitigation of climate change, and are used by governments, businesses and nongovernmental organizations to plan for decarbonization (Süsser et al., 2021). When politicians and activists began saying that we have 'twelve years to save the world', they were citing the emission pathway scenarios reviewed by the IPCC for their 2018 report which projected that global emissions would need to decrease substantially by 2030 and hit net-zero by 2050 to achieve the 1.5 degree target (IPCC, 2018, p. 13).

3. The stories we tell

3.1 A general narrative: getting to 1.5 degrees

There are dozens of large scale IAMs, and hundreds of scenarios produced by them. Luckily, the IPCC has taken on the gargantuan task of summarizing the findings from the main global IAMs and their scenarios which are consistent with either the 2- or 1.5-degree goals. The story these scenarios tell of how we could reach the 1.5-degree goal goes something like this:

> Starting immediately, the countries of the world impose a universal emissions tax. This tax starts at a modest level and is progressively increased as the century goes on. By 2030, it is somewhere between $135 and $6,050 per ton of CO_2 equivalent (IPCC, 2018, p. 152). The tax makes the deployment of a series of decarbonizing technologies—renewable energy generation, nuclear energy, electrification of energy end uses, low-carbon industrial and agricultural techniques, carbon capture and sequestration—cheaper compared to the more carbon-intensive alternatives. As these technologies are increasingly adopted, they progressively drop in unit costs, becoming much cheaper by the end of the century.
>
> In response, greenhouse gas emissions decline sharply, with a global peak reached sometime in the mid-2020s, a global halving of emissions by the early 2030s, and net-zero global emissions achieved around 2050. The ‘net’ in net-zero is important however, as the rapid decarbonization is not rapid enough, and carbon dioxide will need to be sucked out of the atmosphere to either maintain 1.5 degrees, or to bring us back down to it by 2100 if we have already overshot our target (IPCC, 2018, p. 13). This drawdown of emissions will be both feasible and cost effective due to large declines in the costs of carbon capture technology and techniques by around 2050. Due to cheap carbon capture, a not-insignificant amount of fossil fuels will remain in use, either with emissions directly captured on site, or offset elsewhere.

> The cost of our rapid decarbonization is enormous. To hit 1.5 degrees, the carbon tax may eventually be set as high as $30,100 (IPCC, 2018, p. 152). Over the century, this tax will have the effect of distorting the global economy away from what otherwise would have been its preferred investment path. As a result, global GDP will be roughly 2–4% smaller by mid-century than it otherwise would have been, and 4–9% smaller by 2100 (IPCC, 2014, p. 450). Curiously, there will be no economic damages from climate change during this same period (IPCC, 2018, p. 109).

3.2 A common starting point: the Shared Socioeconomic Pathways

Key features of this world, like the rate of economic growth or the global population, were intentionally left out of the story. These demographic and economic factors are instead treated as variable input data which provides a set of baselines from which each scenario can start and then compare itself back to. These background assumptions add a necessary level of restrictions to what is going on outside of the immediate scope of the model, but come with the risk of directly eliminating some feasible realities before the story even gets going.

To enable easier comparison across models, the IAM modeling community has collaborated to create a set of common starting points, called the Shared Socioeconomic Pathways (SSPs) (Riahi et al., 2017). The SSPs provide specific background assumptions for population, urbanization, education and GDP growth for five different global scenarios. The scenarios are categorized by their ease of mitigating climate change on one hand and their ease of adapting to climate damages on the other hand. This creates five numbered SSPs, with SSP1 representing a world with low adaptation and low mitigation challenges, SSP3 representing a world with high adaptation and high mitigation challenges, and SSP4 and SSP5 representing the diagonals where one challenge is difficult and the other is easy (Ibid.). SSP2 represents a middle road between the extremes of the other scenarios.

These SSP scenarios are intended to represent possible trends in a world without climate change. This allows modelers to add climate change to each scenario via their IAM. The differences between the results of different SSPs from the same IAM can then be used to analyze how different background assumptions make mitigating climate change easier or harder, while differences between an SSP with and without climate change can be used to measure the total costs (or benefits) of climate change mitigation.

For a sense of scale, the baseline growth rate in SSP2, which is often used as representation of current trends, shows global growth rates falling from roughly 3% a year to 1.7% a year by mid-century where they stabilize until the end of the model in 2100 (Dellink et al., 2017). The other SSPs follow a similar trend, with growth rates somewhere between 2–4% between now and mid-century, and falling closer to 1% by the end of the century (Ibid.). The main exception is SSP5, which forecasts very high levels of growth (between 4–5%) until 2040, leaving world income per capita at almost $140,000 by 2100 (Ibid.). None of the SSPs represent negative economic growth at any point in the century. The result of this growth is a striking fall in global inequality, with global Gini coefficients falling from around 0.6 today to between 0.1 and 0.2 by 2100 in the three scenarios with the fastest growth (Ibid.). Population ranges from a low of 7 billion people in 2100 to a high of 12.6 billion, with 9.4 billion in the middle SSP2 scenario (Riahi et al., 2017).

Separately, the modeling community has also adopted a common set of Representative Concentration Pathways (RCPs) which show significantly different levels of emissions concentration ranging from very low (RCP 1.9) to very high (RCP 8.5). Each RCP is labeled after the amount of radiative forcing (in W/m^2) generated by the given emissions level (van Vuuren et al., 2011). A common framework is to pair the SSPs with the RCPs to see the climate possibilities given various demographic and economic baselines. In concrete terms, a modeler will pick a starting SSP and use it to try to find paths to achieve a particular RCP. A key insight to come from this modeling is that some sets of socioeconomic inputs are incompatible with some RCPs, as the models are unable to find paths to the very high or very low emissions concentrations from the more extreme SSPs (Riahi et al., 2017).

4. The stories we are not (yet) telling

New stories need to be told—stories with the depth of detail and theoretical openness offered by heterodox economics. Heterodox economics has an inherently expansive view of the possible, with much brighter, and also much darker, futures possible than in the calm and stable world described by neoclassical economics. It also tends to get its hands dirtier with real world details that don't fit neatly into a general equilibrium. The remainder of this paper will describe some of the potential stories that heterodox economists are distinctly suited to tell.

4.1 Decarbonization could cause growth—growth we might not want

Despite its centrality in economic policy, economic growth plays a fairly unnuanced role in integrated assessment modeling, as it is typically generated simply by subtracting the costs of decarbonization from the level of baseline-growth originally inputted into the model (typically form the SSPs). This is problematic, as it leaves little room for either sustained economic booms driven by increased levels of investment or changes in income distribution, as would be possible in a post-Keynesian framework, or a shift away from targeting continual GDP gains, as is advocated by degrowth proponents and modeled seriously in the ecological economics community. Growth is an important detail for these models to get right, as it simultaneously determines the scale of decarbonization needed and the overall economic cost to society of that decarbonization.

On a technical level, general equilibrium IAMs work by assuming that the economy starts in a state of optimized equilibrium and consistently operates at full capacity throughout the scenario. In the absence of policy interventions, the economy is assumed to reach its full potential, as defined by the inputs to the model. In this framework, new investments in emissions mitigating technology are fully offset by reductions of investment and consumption elsewhere in the economy, meaning they can have no direct positive impact on short term growth. Investments made due to the impact of new policies (typically a carbon tax) are also assumed to decrease the long-term productivity of the economy, as they are not the optimized investment decisions that would have been made without policy intervention. This leads to long-term reductions in growth, particularly when the carbon tax reaches extremely high levels in the second half of the century. This unbalanced growth effect, in which investments can have negative effects on the supply side of the economy but no corresponding positive effects on the demand side, means CGE models will by definition treat decarbonization as an overall economic cost in terms of GDP. In the 2014 IPCC report, all but one of the scenarios reviewed have positive costs of decarbonization, with the only scenario containing negative costs (benefits) occurring in 2100 with the highest level of emissions modeled (IPCC, 2014, p. 450).

As mentioned in the section on model design, it is conceptually possible to allow for market imperfections within equilibrium models such that some amount of decarbonization can actually help the economy operate more efficiently and boost growth in the short run. A similar method was employed by the International Energy Agency in their recent *Net Zero by 2050* report in which they took the investment outputs from their climate-economy model and used them in the IMF's Global Integrated Monetary and Fiscal (GIMF) dynamic stochastic general equilibrium model to see the short-term effects of decarbonization on growth (IEA, 2021). The results show gains to annual growth rates of between 0.3 and 0.5 until the year 2030 due to increases in government and private investment (IEA, 2021, p. 156). The report does not provide estimates past 2030, which is describes as the "medium-term", but given the long-run tendency towards full capacity embedded within general equilibrium modeling, it seems very likely that the reported gains fade out and reverse after 2030.

Much larger gains can be obtained in macroeconometric modeling where there is no optimizing mechanism. The recent *Global Renewables Outlook 2020* of the International Renewable Energy Association, which is based on the macroeconometric E3ME model, shows large positive growth effects (between 1 and 2.5 percent a year above the baseline) until 2050 (IRENA, 2020, p. 109). Initially the growth is driven by increased investments due to the energy transition, but by the mid-2020s growth is led by increases in consumption created by a revenue-neutral carbon tax which is reimbursed back to households (Ibid.). In the longer term however, growth in macroeconometric models tends to reverse itself and returns back to the long run trend, following what can be conceptualized as a “debt repayment phase” (Mercure et al., 2019, p. 1028).

One model that is able to show persistent, long run growth effects from decarbonization is the post-Keynesian MEDEAS system dynamics model (Capellán-Pérez et al., 2020; Nieto et al., 2020a; Samsó et al., 2020). In an effort to explore the effect of limits to energy availability, MEDEAS was used to create a scenario representing a large increase in investments in decarbonization and energy transition (Nieto et al., 2020b). This “green growth” scenario managed to gradually increase global economic growth from a baseline of 2.55% to approximately 4% per year by 2050. This result is quite different from the persistent GDP declines projected by equilibrium models for a similar set of policy interventions.

The divergence comes from the split between neoclassical economic theory, which assumes the economy operates up to its full productive capacity, at least in the long run, and post-Keynesian economic theory, in which economic activity can fail to utilize all its resources, even in the long run, if demand for goods and services is insufficient. Therefore, in the neoclassical framework, the transition can only create growth if it can somehow increase the productive capacity of the economy faster than the status quo, while in the post-Keynesian framework, the act of transition itself can have direct growth effects if it manages to increase demand by boosting total levels of either private investment, government spending, consumption, or, in the national context, net-exports.

It's an open question which of these assumptions make more sense, especially in very long run. But if we are trying to really understand everything that is possible for the coming century, at a minimum we should investigate scenarios where the post-Keynesians are right about growth, and a wave of Green New Deals have significant and compounding growth effects well into the second half of the century. Understanding what could happen with growth is critical because of the dual role it plays within the energy transition. On one hand, faster growth makes the needed investments in decarbonizing infrastructure appear less costly, as they will be paid for by a richer society and can be financed out of a larger overall economic pie. On the other hand, until economic growth is fully decoupled from greenhouse gas emissions, faster growth will also increase the size of the problem which needs to be solved, as more economic activity drives more emissions and places other pressures on the earth's ecosystem.

To better see the importance of getting growth right, we can turn back to the MEDEAS Green Growth scenario referenced above. The slowly accelerating growth rate achieved by the scenario was only reached *without* energy limits imposed by the model (Nieto et al., 2020b). In effect, the model allowed all demand to be met, whether the system was actually capable of producing enough energy to meet that demand. When energy limits are included, the picture is much different, with the relatively high rate of growth in the first decade driving a demand for energy which cannot be fully met by the expansion of renewables. To keep up, the scenario relies on fossil fuels, leaving it well short of its emission targets and creating a resource scarcity issue which tightly constrain growth after 2030 (Ibid.).

Now this is a different story from what we heard earlier! And a story worth telling, as the same inputs in a general equilibrium model would have likely shown a substantial decrease in growth, leading to more manageable emission levels.

Finally, apart from the internal world-building of how the models treat growth, there's the question of what levels of growth the people within the models actually want. The countries in the various worlds represented by the SSPs are all trying to maximize their GDP, even if in some cases they do not do a particularly good job. The possibility for a post-growth world, in which at least some countries drop the pursuit of ever-increasing energy and material use, is not considered in the models that feed into the IPCC's story.

Again, as with the question of how growth behaves in the long run, it is an open question of whether actively disregarding economic growth is the best way to respond to the climate emergency. But it is certainly possible some countries will choose this path, particularly when thinking eighty years in the future. This leaves a space, and indeed a responsibility, for heterodox economists to help fill in the details of what may lay along these post-growth paths.

4.2 The transition could be really fast

The scientific evidence is clear that the climate crisis should be dealt with as quickly as possible (IPCC, 2021). A task for heterodox economics then is to determine exactly how quickly decarbonization could happen.

In the standard story recounted above of how we get to1.5 degrees, the transition happens very quickly compared to current trends, but slow enough to still require large amounts of carbon sequestration in the second half of the century. One key mechanism that leads to this result is cost optimization. Within each scenario in a general equilibrium framework, the model is typically working to create the most cost-effective pathway given the starting inputs and other variables inserted into the story. This creates a tricky tradeoff for the models, which must balance the urgency of reducing emissions immediately and the knowledge that future technology will be both cheaper and easier to finance, as the economy will be bigger. The caricature of this problem would be a scenario showing absolutely no climate action until the year 2099, when the world is fabulously wealthy and technology is dirt cheap, and then a century worth of decarbonization undertaken in twelve months. Real models obviously are not so dramatic, but the traces of this tradeoff can be seen in the ambitious wagers placed by many models on currently unproven technologies which, if they were able to follow similar sharply declining cost curves as renewable energy has in the past, could appear a cheaper long-term solution than immediate action. This problem of delayed decarbonization is also compounded by the way most IAMs treat economic growth, because if the transition will necessarily hurt growth, it is cheaper to put off these costs as long as possible so they have less time to compound before 2100.

Instead of finding the cheapest transition, heterodox modelers could look for the fastest. There are already some models which use a ‘cheap enough’ approach that approximates the concept of satisficing from behavioral economics, and allows the model to pick options that fall into an acceptable cost range but are not necessarily the cheapest (Larson, et al., 2020). This allows the models the flexibility to optimize other virtues, such as speed.

This approach could be complimented nicely by the Doughnut framework proposed by Kate Raworth, in which our economy must meet certain human needs while staying within planetary boundaries (Raworth, 2017). In a modeling context, scenarios could attempt to maximize decarbonization without breeching a certain set of social and ecological limits imposed on the model. The issue could also be conceptualized as a kind of democratic feedback, with decarbonization policies stalling or reversing if they negatively affect human wellbeing past a certain threshold.

There are also critical issues about the physical limits associated with decarbonization, such as rare earth materials or land use, which must be better understood and modeled to know where and when we can expect bottlenecks in the transition (Galbraith, 2020). Finally, there is the question of the overall productive capacity of the economy which could introduce another bottleneck for the transition if decarbonization were to push against the limit of potential economic output (Fontanari et al., 2020).

4.3 Climate change could change everything

Current climate-economy models explore a world in which the technology that underlays our economy changes dramatically, but the fundamentals of the economy, and the broader society it supports, remain essentially the same. Not only is this not the only possibility, it seems a fairly unlikely one. The expected impacts associated with climate change, even at relatively low levels, are shocking. The task of rapidly transforming our economy into something which can absorb as much carbon as it emits, all while adapting to the warming to which we have already committed, is likewise humbling. Neoclassical economics is designed to efficiently manage the system we have. It is less useful when it comes to imagining significant structural changes to the system itself. Here, again, heterodox economics has a valuable contribution to make in helping to detail the broader range of possibilities, both hopeful and haunting, in store for us. The heterodox schools of thought can also help to pinpoint things missing from current models that are critical to the functioning of our economy and have important interactions with the other systems represented in integrated assessment modeling.

The potential for heterodox contributions to integrated assessment modeling is huge, but here are a few short indicative examples of what the project could look like.

Post-Keynesians can further develop the role of money and finance in the models, exploring how governments, central banks and the private sector can best work together to manage the massive investments needed for decarbonization. They can also start to think through how investments in some countries will affect the rate of transition in other countries, as interest and exchange rates add an important layer of complication to the story of global decarbonization. The role of fundamental uncertainty in Keynesian economics can also be applied to climate scenario analysis itself, helping to contextualize the large range of possible futures before us.

Feminist economists can strengthen the reality of the overall modeling framework by introducing social reproduction, ensuring that the huge investment projects depicted by the models do not come at the expense of a large increase in unpaid and unmodeled care work. Similarly, they will likely have key insights into how the damages of climate change will be shared within communities and households. As economic activity begins to shift to less carbon-intensive sectors like education and health, feminist economists will also have a critical story to tell about the limits of potential productivity gains for in-person services and the so called ‘cost disease’ (Baumol and De Ferranti, 2012).

Institutional economists are needed to understand how the transition will interact with democracy and law. In particular, they could play a key role in exploring the potential effectiveness of various international legal frameworks for managing climate change. Institutional economics also offers a window into some of our worst-case scenarios in which key pillars of our social systems collapse under the weight of climate extremes.

The Marxists can help us operationalize an understanding of power, both within countries and between them, in order to see how different decarbonization paths could either build or erode the coalitions needed to push for more radical measures. Along with co-operative economics, they also have a wealth of thinking about how production and work could be structured in ways which are both liberating and sustainable. Evolutionary approaches can contribute a notion of deep path dependence, for both technological and social developments, within any given scenario.

Finally, ecological economists have a central role to play in providing an alternative framework that can accommodate and coordinate the various insights and tools held by the heterodoxy. The ecological concept of embeddedness, in which the economy is a subsystem of the earth's larger ecology and thus subject to hard bio-physical limits, is a key starting place for any larger heterodox modeling project (Spash and Asara, 2018). Likewise, many of the tools developed within ecological economics which allow focus to shift from GDP to physical measures like material or energy use, can be integrated nicely with the work of the other schools.

5. Conclusions: How heterodox economics can help tell better stories

Heterodox economists have already contributed substantially to both integrated climate-economy modeling and the larger project of conducting economic research which addresses the climate emergency. A key development here has been the creation of the subfield of ecological macroeconomics, which has created a suite of models which combine the methodologies and theoretical foundations of post-Keynesian and Ecological economics (Hardt and O'Neill, 2017; Rezai and Stagl, 2016; Svartzman et al., 2019). There have also been a number of global IAMs developed with heterodox foundations including the MEDEAS system dynamics model, the Cambridge Econometrics E3ME, and Agence Française de Développement GEMMES macroeconometric models, and a climate extension of the agent-based "Schumpeter meeting Keynes" evolutionary model (Capellán-Pérez et al., 2020; Mercure et al., 2018; Bovari et al., 2018; Lamperti et al., 2020).There is more work to be done, both in using and further developing the models that already exist, and in creating new heterodox IAMs.

Integrated assessment modeling provides an exciting opportunity for heterodox economists to work directly with hard scientists, engineers and other social scientists who likely do not have a personal or professional investment in tying their modeling to the limitations of neoclassical economics. The heterodoxy can tell stories other economists can't, and modelers who want to represent as many paths as possible will want to hear what we have to say. If we can successfully make the case that our stories are important and find ways to integrate our ideas into the formal frameworks of assessment modeling, we can tell more plausible stories about the coming century and in so doing better prepare those who are in a position to lead us into it.

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