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Economic models and frameworks to guide climate policy

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Abstract

Reaching net-zero emissions will involve a structural transformation of the global economy. The transition is complicated by deep uncertainty about the new economic configurations that will emerge, coordination challenges, and non-linear dynamics amidst shifting political winds, where nation states are actively intervening to gain comparative advantage in key technologies. Here, we consider key economic questions about the net-zero transition that are of interest to finance ministries, based on a recent survey. Specifically, this paper asks: '*What is the most effective way economic models and frameworks can help guide policy, given the complexity and uncertainty involved?*' We suggest five general criteria that models and frameworks should meet, and provide some guidance on how to select the right model for the question at hand—there is no single model to rule them all. A range of examples are offered to illustrate how models can be used and abused in the provision of economic advice to policy-makers. We conclude by noting that there are several gaps in our collective modelling capability that remain to be addressed.

Keywords: climate, economy, integrated assessment models, carbon price, carbon tax, finance ministry, climate policy.
JEL codes: Q54, Q55, Q58, C63, C68

I. Introduction

Climate change is no longer a distant threat; it is a present-day reality. The World Meteorological Organization (WMO) has confirmed that 2024 was 1.55°C hotter than pre-industrial temperatures, making it the warmest year on record, with the past 10 years all in the top 10 years on record (WMO, 2025). In addition to record-breaking disasters, a new 'category 6' has been proposed to be added to the Saffir–Simpson hurricane wind scale (Wehner and Kossin, 2024) and ice melting in Greenland and Antarctica is affecting global timekeeping by changing Earth's spin and hence the length of a day (Agnew, 2024).

At the same time, the global transition to a low-carbon economy is under way. Technological advances have rapidly lowered costs: between 2013 and 2023, prices for photovoltaic (PV) cells, wind, and batteries dropped 76, 70, and 79 per cent, respectively (RMI, 2024) and costs continue to decline. Utility-scale solar PV and onshore wind are the cheapest options for new electricity generation in a significant majority of countries worldwide (IEA, 2022). Global solar PV capacity is currently doubling every 2–3 years, with battery storage doubling every year (RMI, 2024); and before the end of this decade solar is expected to become the world's largest source of power capacity. In response, industry is increasingly investing in clean production, and governments are acting, too: the EU is putting tariffs on carbon-intensive products, and the USA and other nations have implemented significant active industrial policy support, much of which remains in place despite the change in US President. Meanwhile, concerns about air pollution and health- and productivity-related impacts from burning fossil fuels are also driving the transition globally. The invasion of Ukraine made the link between fossil fuels and threats to energy security more obvious.

The net-zero transition requires several major economic transformations, involving structural breaks (discussed in section II), such as shifts in technologies, institutions, finance, business models, and employment, as well as significant redistributions of material wealth and political power within and across nation-states (Geels, 2002; Acemoglu *et al*., 2012; Stiglitz, 2015; Stern, 2021). The transition will reshape the global economy and geopolitics, given the eventual decline in demand for fossil fuels.

The question now is not whether to act, but how to develop policy and strategy in such a complex landscape (Barbrook-Johnson *et al*., 2024). In fits and starts, with forward and backward steps, policy-makers are reforming electricity markets, modifying utility regulations, introducing feed-in tariffs, tax credits, building codes, auto emissions standards, adjusting government purchasing, providing R&D support, creating new industrial policies, and so on. Economic frameworks, models, analyses, and perspectives are not always at the heart of such decisions; while policy-makers may not be completely 'flying blind', they are certainly partially sighted. Modelling the specifics of these policies, and understanding their political feasibility (Mealy *et al*., 2025), requires a suite of models and subsequent policy packages that go beyond modelling a 'shadow' carbon price (Barbrook-Johnson *et al*., 2024).

This paper explores how economic models can better support climate policy in the face of complexity and deep uncertainty. Since the net-zero transition is a fundamental transformation of the economy, it calls for a diverse set of economic theories and analytical perspectives relevant to understanding structural transformations. Economists increasingly recognize that no single policy lever, nor any single model, can suffice. Rather, a varied policy mix supported by different types of models is needed to address multiple market failures and support coordinated transitions across sectors and regions.

We begin in section II by highlighting three challenging characteristics of the net-zero transition that make choices more difficult for governments, particularly finance ministries, in a shifting global context. In section III, we draw upon a recent survey conducted by the Coalition of Finance Ministers for Climate Action which we organize into five over-arching questions. In section IV we set out properties of a good analytical approach for answering such questions. In section V, we provide an overview of available approaches, summarizing existing models. Section VI showcases a series of examples, demonstrating the application of different models to answer key policy questions and assessing each approach in terms of our five properties described in section IV. Section VII concludes by noting key gaps in the existing analytical toolkit and outlines future research priorities.

II. Three challenging characteristics of the transition

This section highlights three important characteristics of the net-zero transition with their implications for modelling as follows. First, the transition to a net zero economy requires profound **structural transformations or breaks** in several different sectors, not least energy, agriculture, transport, and much of heavy industry. These transformations must overcome path dependencies and deliver a shift from one system to another. This is described differently across various strands of the literature as a '*shift*' between multiple '*regimes*' (e.g. Hendry, 2000; Castle and Hendry, 2019, p. 128), or as a system with '*multiple equilibria*' (e.g. Dybvig, 2023), or as crossing a 'tipping point', or as a dynamical system with multiple '*basins of attraction*' (e.g. Ott, 2006), or as one that is undergoing '*non-marginal change*' (Dietz and Hepburn, 2013). Irrespective of the language used, the point is that the future—after a structural break—is in some ways fundamentally different from the past. In other words, as new technologies, policies, or geopolitical factors emerge, long-established statistical relationships and market behaviours can shift (i.e. inducing abrupt structural changes in time-series data, invalidating prior assumptions of stable trends) (Perron, 1989). This can have the frustrating consequence that an excellent model of the current system, even one that is well calibrated on high quality and sufficient past data, may not in and of itself necessarily offer the best description of the new regime that the system is moving into. In other words, when an economy undergoes an abrupt transition, statistical relationships that once held true may unravel, complicating efforts to forecast or calibrate models based on historical data alone. The deep uncertainty about the future shape of the economy is compounded by the deep uncertainty about the future state of the climate, and the interaction between the two will be complex in the coming decades. The other key implication of the existence of structural breaks is that marginal analysis, the bread and butter of ordinary economics, may provide poor guidance (Dietz and Hepburn, 2013).

Second, in most sectors, the transition is characterized by **strategic complementarities** between multiple agents, technologies, and sectors (Cooper and John, 1988). In particular, the returns to deploying one technology often increase as usage of a complementary technology expands, especially with the right coordination policy in place (Alvarez *et al*., 2023). For instance, the payoff from the use of an electric vehicle (EV) increases the more EV charging points are installed, and the payoff from installing an EV charging point increases the more EVs are being used. More EVs implies cheaper batteries, which increases the payoff to renewables, which implies more and hence cheaper renewables. This in turn makes EVs cheaper to run and increases the uptake of EVs, and so on. These complementarities can retard progress until a tipping point is reached, when the scale-up is difficult to stop (Way *et al*., 2022).

Third, **non-linear dynamics** are a central feature of the net-zero transition. Such dynamics are found in many macroeconomic phenomena (Ashwin *et al*., 2025). Decarbonizing the global economy will involve the sort of tipping points, technology cost thresholds, investment frictions, and regulatory ceilings or floors that create non-linear dynamics. In such circumstances, traditional methods that rely on linearization or small perturbations may fail. For instance, as many clean technologies scale up, their unit costs decrease, enhancing their affordability and accelerating further adoption (Arthur, 1989; Stern, 2006; Aghion *et al*., 2014; Farmer *et al*., 2019). This positive feedback loop implies that increased adoption leads to further cost reductions and innovation, reinforcing the transition momentum (Geels, 2002; Grubb *et al*., 2014). Non-linear dynamics, including resulting from changes in climate as well as in the transition to net zero, imply that modest policy interventions at 'sensitive intervention points' can lead to significant shifts in technology adoption, emissions reductions, and even comparative advantage (Farmer and Lafond, 2016; Farmer *et al*., 2019; Alvarez *et al*., 2023; Mealy *et al*., 2023). Good policy guidance will therefore often require models that can account for such complexities. Reliance on static or comparative-statics between optimal outcomes thus risks overlooking these crucial feedback loops.

These three key characteristics—structural breaks, strategic complementarities, and non-linear dynamics—increase the difficulty of modelling and guiding the transition. They are not the only challenges. For instance, structural transformations often generate uneven distributional outcomes, and negatively-affected actors often mobilize political resistance that impedes the adjustment process. As such, policy-makers are wise to design policies with political economy considerations in mind (Klenert *et al.*, 2018). The time horizons are long, often well beyond an electoral cycle, implying intertemporal choices between generations that raise complex considerations (e.g. Broome, 1994; Schelling, 1995; Stern, 2006; Hepburn *et al.*, 2009; Stern, 2014a; Stern, 2015). And there are many political economy issues that arise, including competitiveness and trade impacts. The United States and Europe have recently imposed tariffs on Chinese electric vehicles and solar panels, on the basis that Chinese subsidies are alleged to be distorting these markets and creating unfair competition.[1] This green protectionism may accelerate decarbonization in third countries, as tariffs reduce Chinese producer prices, but could slow the overall pace of the transition to a low-carbon economy in Europe and America.

Given the complexity and uncertainty regarding how the transition will play out, can economic frameworks and perspectives ever hope to enhance our decision-making? Our answer is a firm 'Yes', but with various qualifications. Certainly, greater circumspection is required in the use of optimization approaches based upon marginal analysis. Traditional cost–benefit analysis (CBA) is a classic example. CBA has had, and should continue to have, an important role in evaluating climate policies: policies that are economically efficient are preferable to those that are not, other things being equal.

However, the net zero transition presents challenges for CBA, because CBA can give misleading advice when evaluating non-marginal changes. CBA also faces limitations when it is difficult to determine the full effects of a policy or to construct shadow prices to account for social impacts, such as life expectancy (Dasgupta *et al.*, 1972; Drèze and Stern, 1987, 1990; Dietz and Hepburn, 2013; HM Treasury, 2022). The extensive controversy over the shadow discount rate, the shadow exchange rate, and the shadow wage rate illustrates the difficulties. Most importantly, the existence of complexities and uncertainties in the climate and economic systems means that evaluations should emphasize precautionary principles, risk management, and robust responses rather than the 'optimal' policies (Peng *et al.*, 2021). These issues are understood in many governments, but narrow or inappropriate application of CBA continues in some places, while in others (such as China) CBA is less used, in part because of these limitations (Qin *et al.*, 2024), and instead a more strategic, scenario-based approach is adopted with concomitant advantages and disadvantages. The strengths and weaknesses of several decision-making frameworks are set out in Table 1.

What are the implications of these challenges for modelling? Even a perfect model—which does not exist—could not hope to offer accurate predictions without sufficiently detailed knowledge of the initial conditions and future shocks. But this does not mean that modelling is useless, and indeed using multiple models is likely to provide more insight than relying on any single one (Page, 2018). Good modelling involves clarifying and justifying assumptions and using deductive and inductive reasoning to try to understand the system and its possible responses to interventions, as we come to in section IV. Our discussion highlights some key trade-offs in modelling: simple models can provide insights into some of the key forces, and even into principles that should guide policy, but cannot capture the complexity of the transition; but in the more complex models, we may not be able to see what is really driving any results, and there is often lack of consensus on critical relations. Economists have been notoriously unsuccessful in predicting short-term behaviour, like recessions; can we have confidence about models of the economy extending decades into the future? But before delving more deeply into such questions, we turn next to consider in a little more detail the questions that are currently on the minds of officials in finance ministries around the world.

III. Five specific climate-policy issues

The previous section emphasized that modelling and understanding the energy transition is difficult due to three key characteristics—structural breaks, strategic complementarities, and nonlinear dynamics. We nevertheless argued that models and economic thinking have a valuable role

[1] There is an obvious trade-off. On the one hand, tariffs aim to protect and develop Western green industries, addressing concerns about strategic dependencies on perceived rivals, and the risk of hollowing out domestic industries. On the other hand, countries benefit from specialization and trade, and China's low-cost manufacturing capabilities allow other countries to access affordable green technologies, accelerating their transition to renewable energy.

Table 1: Selection of decision-making frameworks.

Framework	Description	Strengths	Weaknesses	References
Cost–benefit analysis (CBA)	Evaluates the economic costs and benefits of policies or projects, often used to justify investment in climate mitigation or adaptation.	Assesses the economic efficiency of policies in the form of discounted net benefits over time. Easy comparison between different policy options.	Often poor in practice at incorporating non-monetary values, non-marginal and distributional issues.	Dasgupta *et al.* (1972); Drèze and Stern (1987, 1990); Dietz and Hepburn (2013); HM Treasury (2022).
Scenario analysis	Explores the impacts of different future scenarios, e.g. to understand potential outcomes under different policy or economic conditions.	Exploring a wide range of possible futures to identify key drivers and uncertainties. Valuable for long-term strategic planning.	Does not provide precise predictions, or short-term dynamics and transitions.	Cornelius *et al.* (2005); van Vuuren, *et al.* (2011); Kupers and Wilkinson, (2015).
Risk–opportunity Analysis	Incorporates pros and cons, like CBA, but with a focus on situations of uncertainty, heterogeneous interests, and non-marginal change where CBA breaks down.	A holistic approach to mapping system and path dependencies, risks, options, and opportunities prior to quantitative analysis. Explores distribution of outcomes more fully.	More time consuming, not established or tested at scale.	Mercure, *et al.* (2021).
Cost-effectiveness analysis (CEA)	Determines the most cost-effective way to achieve a specific goal, often used to identify least-cost mitigation strategies.	Finding least-cost pathways to meet targets, and examining costs of alternative approaches when an overall target has been agreed.	Does not question the assumed goal. In practice often misses broader impacts, including non-monetary values (as with CBA).	Garber and Phelps (1997); Ackerman and Stanton, (2012).
Multi-criteria decision analysis (MCDA)	Uses multiple criteria to evaluate and compare policy options, integrating economic, environmental, and social dimensions.	Incorporating diverse criteria and stakeholder values. Evaluating trade-offs and synergies. Balancing multiple policy goals.	Quantifying and weighting subjective criteria.	Belton and Stewart (2002).
Risk assessment	Identifies and evaluates the risks associated with climate change and mitigation policies, including probabilities and impacts of adverse events.	Identifying and prioritizing risks. Quantifying probabilities and impacts of adverse events. Informing risk management.	Non-quantifiable risks and uncertainties. Long-term systemic risks. Subjective risk perceptions.	IPCC (2014)

to play. In this section, we examine the questions that modellers are being asked to answer, building upon a survey of finance ministries, conducted by one of us between March and July 2024, for the Coalition of Finance Ministers for Climate Action in 2024 (Loni *et al.*, 2025).[2]

A broad fundamental question for governments and their finance ministries is how can governments guide the transition to net zero? In other words, how can they plan for this uncertain future, and what interventions are needed once it is recognized that markets cannot give the right guidance.

Based on the survey results, we suggest five areas of interest to finance ministries, namely: (1) carbon prices; (2) global competitiveness; (3) technological uncertainty; (4) labour and skills, and (5) tax revenues and budgeting. More detailed sub-questions are set out in Table 2. While the list is not comprehensive, it captures some of the most important issues. And while the specific questions will doubtless change over time and will look different in 2030 compared to how they do now in 2025, the underlying issues and themes are unlikely to be vastly different.

We next turn to consider properties of a good analytical approach to answering such questions, before considering the available models and frameworks to help guide policy-makers in section V.

IV. Properties of a useful analytical approach

In thinking about a future with fundamental structural and systemic change, policy-makers must be guided by more than just formal models. While models are essential tools, they should be complemented by a broader set of frameworks, analyses, and perspectives capable of grappling with complexity, uncertainty, and transformation (Stern, 2014a, b, 2015). These include:

- Theories of economic transformation (going beyond formal modelling), such as those of Schumpeter (1934) on economic development, Hayek (1935) on the role of planning, and other theories, including the idea of the big push (Rosenstein-Rodan, 1943);
- Economic history, including past examples of rapid change to provide lessons, e.g. transition from kerosene to electricity during the 1840–50s; mass production and assembly line revolution in the early 1900s, and changes in wartime economy in the UK in 1939–44;
- Detailed case studies of the key components of the transition, using a range of techniques (e.g. studies of cities, infrastructure designs, land ecosystem regeneration, circular industrial models) that can use microeconometric techniques, engineering methods, and detailed systemic sectoral models;
- Theories of intertemporal choice are also particularly important, as significant benefits often accrue over a decade or more into the future. Assumptions about discounting embedded into climate-economy models often drive the results, and yet much of the analysis of discounting has been weak. Intertemporal marginal weights (or shadow prices) depend on how well off we think we will be in the future. There is a real possibility that future generations may be worse off, implying a higher valuation of an increment in the future than now. The implication is that discount factors (i.e. weights on future increments) could be above unity, implying a negative discount rate. Most importantly, appropriate discounting is endogenous to our decisions and cannot be read off from anywhere else, such as current decisions on any market (Beckerman and Hepburn, 2007; Dietz *et al.*, 2007; Stern, 2015).

Indeed, every aspect of economics—microeconomics, macroeconomics, econometrics—has important insights to offer for the climate transition (Stern, 2006, 2014b, 2015), But disciplines beyond economics are equally critical for understanding how to achieve net-zero emissions (Stern, 2014a), especially those that consider institutions, governance, social behaviour, and technological change (Stern, 2015).

[2] A total of 61 ministries of finance (MOF) participated in the survey, including from advanced, emerging, and developing economies. In addition to the survey, semi-structured interviews were conducted with 12 ministries, including the European Commission. Together the survey and interview respondents represent roughly 60 per cent of global GDP, 37 per cent of global emissions, and 33 per cent of global population. Results suggest that while there is strong awareness among MOFs about climate-related risks and opportunities, there is limited integration of these considerations into analytical frameworks. Ministries also expressed strong interest in receiving technical assistance and expanding their capabilities to better integrate climate-related considerations into their economic and policy analyses.

Table 2: Climate policy questions of finance ministries.

1. Prices and markets: How to provide appropriate carbon and other price signals to encourage more socially optimal levels of climate-friendly investment, activities, and behaviour?	
Specific questions from MOFs	• How ambitious should carbon pricing policies be, and how should they evolve over time? • What measures need to complement carbon pricing and/or taxation? • What is the ideal sequencing of climate policies (subsidies, taxes, etc.)? • Which combinations/packages of pricing, non-pricing instruments, and regulation are likely to be most effective?
2. Global competitiveness: How to capitalize on growth opportunities and minimize transition risks?	
Specific questions from MOFs	• How will my country's economic structure change due to global transitions and how can we identify optimal response strategies? • What are the impacts of the carbon border adjustment mechanism (CBAM) or other global regulation on the economy and trade balance? • What is the impact of changes in global oil and gas demand and trade disruptions on my economy? • How do global mitigation and climate policies impact my domestic economy? What are the relevant risk drivers and what are the optimal responses?
3. Technological uncertainty: How to navigate technological uncertainty and encourage sectoral decarbonization in the most cost-effective way?	
Specific questions from MOFs	• How can MOFs quantify the economic impact of net zero plans on sectors and industries? • How can synergies and potential trade-offs with other development and sector objectives be identified? • What are the trends around key technologies and how can those be leveraged to boost competitiveness and growth in key sectors? • What is the uncertainty around the cost and pace of decarbonization and energy pathways? • What is the likely uptake and diffusion of EVs in the short, medium, and long term? • What are plausible heavy-industry decarbonization and emission intensity pathways?
4. Labour and skills: How to manage the decline of sunsetting sectors while encouraging growth towards sunrise sectors?	
Specific questions from MOFs	• What is the impact of the transition on the regional labour. What are the public spending requirements for re-skilling the labour force? • What are the distributional impacts of climate change and mitigation efforts? • What is the impact of climate change and mitigation on household income distribution? • What might be the impacts on salient socioeconomic groups? How can we compensate the losers?
5. Tax revenues and budgeting: What are the budgetary implications of the transition to net-zero and how can we pay for it or benefit from it?	
Specific questions from MOFs	• How can green budgeting tools help understand public finance's role in climate and the green transition, including expenditures and taxation structure? • What is the realistic financing needed for climate nationally determined contributions (NDC) ambitions or net-zero plans? • What are the fiscal implications of stranded asset risks and public-sector contingent liabilities (e.g. legal claims, infra replacement, loan defaults, state-owned enterprise guarantees etc.) • How can carbon tax revenues be recycled and what are the macroeconomic impacts? • What is the impact of ambitious climate policies on tax revenues (including from oil and gas)? • Will we need to raise taxes to pay for decarbonization? Or will it bring along benefits that we can profit from?

This broader framing calls for moving beyond narrow policy tools focused on targeting economic efficiency by the internalization of externalities, as per Pigou (1920) or Coase (1960). The same applies to conventional decision-making frameworks. As the UK's HM Treasury (2022) Green Book acknowledges, standard cost–benefit analysis has limitations, including in non-market valuation (Annex 1) and particularly in times of transformational change (see Annex 7), and as such should be considered a complement rather than a substitute for judgement (Weitzman, 2007).

What properties should a model or theory meet in order to provide useful guidance to policy-makers grappling with the above questions? We might start with the important idea from Popper (2002 [1934]) that a good theory should be falsifiable. Stigler (1965) argued that good economic theories meet the criteria of 'generality', 'manageability', and 'congruence with reality'.

A longer list of desiderata is offered by Gabaix and Laibson (2008) who set out seven properties of good models, namely: (1) parsimony, (2) tractability, (3) conceptual insightfulness, (4) generalizability, (5) falsifiability, (6) empirical consistency, and (7) predictive precision. They note, however, that

> even highly successful models do not have all seven properties. Many of the properties are in conflict with one another. For example, generalizing a model sometimes makes a model unfalsifiable—the most general form of the theory of revealed preference cannot be rejected by behavioural data.

Here, we focus our attention on a policy-maker trying to navigate the transition to net zero. This is similar to, but different from, the quest for a general economic theory that seeks to identify a scientific insight. We adopt four of Gabaix and Laibson's seven criteria, and add an additional fifth, arguing that a framework suited for the net-zero transition should be evaluated on its: (1) parsimony, (2) tractability, (3) insightfulness, (4) empirical consistency, and (5) ability to cope with the key characteristics set out above in section II. For simplicity we subsume falsifiability and precision into empirical consistency; one of the problems in this field of research is that models are hard to test, so in most cases it is difficult to know whether the predictions of models are any good. There are relatively few counterexamples (e.g. Way *et al.*, 2022). We also drop generalizability, which is desirable, but for the purpose of supporting a policy-maker to make decisions about an unknown future in a complex world, generalizability may be unnecessary and perhaps even counterproductive.[3] We also note the importance of model robustness—results don't change when the assumptions change a little, especially in a more 'reasonable' way—which could arguably stand as its own criterion, but which we here subsume into insightfulness. A climate-economy model with perfect information, or no risk, for instance, will not be robust, and could end up potentially more misleading than insightful.

No single model can hope to capture all the appropriate dynamics in a single framework that meets all of these desiderata, and in most circumstances a much more robust approach would be to rely on a range of models. Nonetheless, while any single model may inherently fall short of representing all such dynamics, it is essential that the modeller remains informed of these complications and strives, as far as practical, to integrate and reflect them adequately within the analysis.

We summarize our desirable features of a climate-economy model in Table 3, emphasizing that not all useful models will meet all of these features.

[3] For instance, a theory that is specific but which nevertheless offers insight into a live policy question is much more valuable to a policy-maker than a *generalizable*, but highly abstract idea. *Falsifiability* is widely accepted as a central foundation of scientific methodology, explicitly since Popper (2002 [1934]), and arguably implicitly long before. However, we subsume this feature into *empirical consistency* as we acknowledge a decision-maker can sometimes need insights into possible futures, plausible scenarios, and a pedagogical framework to clarify the choice at hand, rather than a falsifiable theory *per se*. Finally, *predictive precision*—conditional on a particular policy choice being made—can often be very useful, but for simplification we incorporate it into our criteria of *empirical consistency*. We acknowledge that many of the larger, more complex IAMs are going to struggle to offer accurate and strong predictions, even conditional on a range of endogenous policy choices and exogenous shocks, but the expectation is that for models to be able to answer the questions listed in Table 2 they need to show evidence to decision-makers of their predictive value. Models need to capture the most relevant dynamics and avoid untested ad hoc assumptions or inherent biases that we believe have been hidden in plain sight in many climate models.

Table 3: Desirable features of a climate-economy model.

	Models should be...	Description and rationale
1	Parsimonious	The model should capture essential features and discard the non-essential. What is essential depends on the question, hence multiple models are needed.
2	Tractable	Tractable models are easy to analyse (Gabaix and Laibson, 2008), and do not take too long to resolve to a solution. A model or framework should also be transparent, interpretable to those who did not build the model, and should not be a 'black box' where the policy-maker must blindly trust the results. Models should also avoid making ad hoc assumptions to cut down computing time or to avoid 'resolution difficulties' (Kahouli-Brahmi, 2008).
3	Insightful	Insights can be qualitative or quantitative. Many simple theory models give qualitatively useful insights for specific questions. Other questions require quantitative estimates as well (e.g. for the balance sheets of government etc.).
4	Empirically consistent	Empirical models should be based on the best available empirical evidence, with transparency about the (often deep) uncertainty involved. Model structure uncertainty should be explored, with robust scenario and sensitivity analyses to convey possible outcomes. Quantitative estimates of uncertainty are valuable, as is a track record of predictive performance and methods of validation, where the model is tested for predictive value against historical empirical counterparts.
5	Suitable (given key characteristics of the net-zero transition)	Models allow for (1) structural breaks, (2) strategic complementarities, and (3) non-linear dynamics; avoid bias by assuming that the economy is at or near some fictitious optimum, and therefore any climate action is costly.

None of these properties requires a model to be consistent with a particular theory, for instance that agents have rational beliefs. For our purposes, models simply have to be helpful to a policy-maker to make a good decision. A useful framework provides a plausible depiction of the real world from which a policy-maker can construct a simple narrative to explain their decision to themselves, and their constituents.

In an ideal world, excellent climate-economy models would generalize both old and new regimes. That is, models would fit the data in the past and help us understand which parameters have shifted as we move into the new regime. Ensuring calibration to the data that we do have, acknowledging and accounting for regime shifts, can weed out poor, ad hoc modelling assumptions that are not supported by the data. For instance, assuming 'floor costs' for solar that, based on past dynamics, were highly likely to be incorrect in prospect, and wrong in retrospect, does not make for a useful model (Farmer *et al*., 2007). Such outputs were systematically biased, in that they underrepresented the role of renewables, and overrepresented the role of carbon capture and storage (Way *et al*., 2022).

V. The menu of frameworks and models

Here we focus on the available climate-economy models, which can be thought of as formalized tools for thought experiments about future emissions and economic pathways (Ellenbeck and Lilliestam, 2019). We roughly categorize these models along two dimensions as illustrated in Figure 1:

- from small to large in terms of complexity and system coverage; and
- from theoretical to empirical in terms of methodological orientation.

Of course, many models blur these boundaries, as these are not discrete categories.

Every model is built for a specific purpose and level of aggregation or abstraction. Often models built for one purpose do not perform particularly well at other purposes (Rodrik, 2018). For

	Theoretical	Empirical
Smaller	Toy models (e.g. DICE)	Calibrated and validated simple empirical agent-based or system dynamics models (e.g. Forrester's 1971 Club of Rome World3 model)
Larger	Calibrated, more complex theoretical models for exploring plausible outcomes. (e.g. FUND)	Calibrated but sometimes difficult to validate, complex empirical models (e.g. national and global process-driven IAMs)

Figure 1: Types of models.

instance, in macroeconomic modelling, Blanchard (2018) observes that 'no model can be all things to all people'.

Models range from highly simplified theoretical models with closed-form solutions (top left of Figure 1), through to vast models simulating the entire global economy and the climate (bottom right of Figure 1). By *empirical* we mean a model that is consistent with and carefully calibrated to real data and which has, as its primary goal, to conditionally predict values of interest. By *theoretical* we mean a model whose purpose was primarily pedagogical, and which is indifferent to whether the model is '*fit to data*' or whether it is designed to predict an outcome. Such models might meet various desirable axioms (such as consistency, complete markets, etc.), but are not designed to map onto the real world.

One type of model is not in any general sense 'better' than another. Small models provide valuable insight precisely *because* they use a dramatically simplified depiction of reality. The skill in developing smaller models is deciding what to include in the model, and what to exclude. Much larger models include system models and whole-economy models with hundreds or thousands of different parameters to be calibrated.

(i) Smaller models

Smaller theory models offer sharp, pared-down explanations of a particular phenomenon. These models are highly varied, use a variety of different mathematical techniques and can offer deceptively useful insights. Simplified models can clarify important features of structural transformation with multiple equilibria (Vines and Wills, 2020), illuminate and reconcile sources of disagreement between competing theories or larger models (Luk and Vines, 2025), to provide more reliable forecasts for key dynamics and identify sources of systemic bias in larger models (Way *et al.*, 2022), identify likely game theoretic responses to carbon border adjustment mechanisms (Helm *et al.*, 2012), and capture the idea that support for the clean economy might need only be temporary: Acemoglu *et al.* (2012), van der Ploeg and Venables (2025, this issue) and Dhar (2025, this issue).

Such models make no claim to model the entire economy and are unabashed about omitting vast amounts of reality. Such models may not be 'realistic', but of course this does not mean they cannot be immensely useful to shape ideas and to influence the direction of policy. They need not be tested and validated.

Smaller empirical models comprise two quite different sub-categories of models: first, econometric models of specific climate-economy phenomena, and second, computational agent-based models (ABMs) of a limited number of climate-economy interactions (Czupryna *et al.*, 2020; Gerst *et al.*, 2013; Lamperti *et al.*, 2019). These empirical models, as with their theoretical equivalents, can be relatively easily interrogated to identify the key drivers of the economic phenomena that are of interest to the researcher. These models are less complex than vast dynamic computational general equilibrium (CGE) and the dynamic stochastic computable general equilibrium (DSGE) models, or the even more complex process-based integrated assessment models (IAMs).

Both classes of smaller models can offer an excellent way of communicating an economic concept or an economic framework for thinking about a particular policy problem (Blanchard, 2018). One can think of these models as a series of maps, of increasing detail. When discrepancies arise between results obtained from smaller models and those from larger models, such inconsistencies may indicate the presence of complex interactions that the smaller model may have failed to capture, or, alternatively, may suggest potential flaws in the more comprehensive model's formulation.

While ignoring key elements of reality is a feature, not a bug, of simplified models, it does, however, imply limitations to their use. Such models tend not to be able to provide specific or quantitative policy advice. Moreover, they can be viewed with suspicion by policy-makers who fear their simplicity represents a lack of sophistication or reliability. When systems are complex and interactions matter, simplified models might not be able to capture essential features of the policy context. The results of smaller models are, obviously, sensitive to the assumptions—or simplifications—made, reflecting choices about what is included and what is left out. With the 'wrong' simplifications, the results will not provide good guidance but can still provide value by generating debate about such simplifications and assumptions (e.g. the Nordhaus and Stern discount rate debate; see Nordhaus, 2007; Weitzman, 2007; Stern, 2022). This is valuable, because the larger models, despite their greater detail and complexity, often also embed similar sorts of simplifications that get obfuscated in the model's greater complexity. For instance, macroeconomic models with many sectors that still assume perfect capital markets, could be as flawed as a one-sector model making the same assumption. The same is true of climate-economy models. Although, even with small, stylized models, researchers must be careful about how the insights are being interpreted and applied to policy questions and wider media debates. While some policy-makers and actors might be suspicious of these models, others might latch onto their insights to promote a message or policy that the model does not encourage.

(ii) Larger models

Larger models examine climate-economy interactions at a higher degree of granularity, often with significantly more moving parts, assumptions, and data requirements, but offer enhanced realism and more precise quantitative forecasts and parameter estimates. Bigger models can also provide useful and detailed guidance on policy design and implementation. Some policy-makers may feel uncomfortable taking major decisions without at least attempting to use a larger model to test their proposals. While the pursuit of enhanced realism may motivate some researchers to model a significant part of the global economy (such as an entire country, entire sector, or even the entire global economic system), this approach can introduce as many complications as it resolves. Larger models typically require additional assumptions to drive behaviour, as well as substantially more data to initialize, calibrate, and empirically validate. These requirements need to be balanced against the demands of the policy question at hand and the sometimes steep trade-offs associated with pursuing an even larger model.

Larger models come in many varieties, as shown in Table 4. They include energy systems models (ESMs), CGE models, DSGE models, macroeconometric models, post-Keynesian models, system dynamics models, and ABMs. Such larger models differ from smaller models discussed above not only in their complexity but also in their purpose (Table 3).

An important category of larger models includes IAMs, which can come in the form of a policy-optimization or process-driven framework. Policy-optimization IAMs are generally smaller single models that combine the major elements of the economic, energy, and climate system and are employed to estimate an optimal warming for the planet, based on projections of human population and economic growth and the trade-offs between the economic benefits and costs, including climate damages, that are embodied in their equations (Rennert *et al.*, 2022). Process-driven IAMs combine or 'integrate' models from multiple disciplines including economics, energy, climate, and land-use. This group of IAMs are designed to provide global assessments of available climate change mitigation processes in terms of current and future developments in emission reduction and mitigation efforts, and to provide an assessment of national climate pledges in relation to long-term emissions goals (IPCC, 2022).

Table 4: Types of climate-economy models.

Modelling approaches	Description
'Policy-optimization' integrated assessment models (IAMs)	'Policy-optimization' or 'cost–benefit' IAMs are designed to calculate the 'optimal' social cost of carbon, or the marginal social cost of emitting one more tonne of carbon into the global atmosphere. They are 'integrated' models in that they bring together knowledge from different disciplines including climatology and economics. Examples include DICE, FUND, and PAGE. See Nordhaus and Yang (1996) and Böhringer and Löschel (2006).
'Policy-evaluation' integrated assessment models (IAMs)	'Policy-evaluation' or 'process-driven' IAMs are generally much larger 'integrated' climate-economy models that can also include energy system and land-use modules. They are designed to provide assessments of climate change mitigation pathways in terms of current and future developments in emission reduction and mitigation efforts, and to provide an assessment of national climate pledges in relation to long-term emissions goals (IPCC, 2022). Examples of the dominant models include GCAM (Calvin *et al.*, 2019), IMAGE (Stehfest *et al.*, 2014), MESSAGE (Huppmann *et al.*, 2019) and REMIND (Luderer *et al.*, 2012).
Energy system models	Models of the physical energy systems that generally use scenarios to understand how different investment strategies and future technical and economic conditions might contribute to energy system operations, future energy mixes, engineering design, or energy policy development. One example is the MARKAL/TIMES model. See Loulou *et al.*, (2004).
CGE models	CGE models work in 'general equilibrium' to simulate how the whole of the economy responds to changes in climate policy, technology, and other external factors. The policy-optimization IAMs discussed above are examples
DSGE models	DSGE models analyse the dynamic behaviour of the whole economy by incorporating microeconomic foundations, in order to allow for the fact that any change in the policy framework is likely to change the microeconomic behaviour of individual economic actors. EMuSe from the Deutsche Bundesbank is an example. See Hinterlang *et al.*, (2023).
Sector-specific models	Sector-specific models focus exclusively on particular segments of the economy, allowing detailed analysis of specific industries or activities. Examples include MOVES, which estimates emissions from on-road vehicles and evaluates the impacts of different transportation policies [see US Environmental Protection Agency (EPA) 2014] and GLEAM, which assesses the environmental impacts of livestock production and identifies mitigation strategies (see Gerber *et al.*, 2013).
Agent-based Models	National or global ABMs are computational simulations representing heterogeneous agents and their interactions. These models simulate actors' adaptive behaviours and decision-making processes in response to external shocks, including climate policy interventions or climate-induced economic damages. See Poledna *et al.*, (2023).
System dynamics models	System dynamics models are computational frameworks that use interconnected feedback loops, stocks, and flows to simulate complex interactions within economic and environmental systems over time. An example is EN-ROADs, which is an interactive system dynamics model that allows users to explore the impacts of various climate policies and scenarios on global temperature change. See Siegel *et al.* (2018).
Hybrid models	Connection of several different types of models (e.g. CGE, plus an energy system model and a sector-specific model).

Process-driven IAMs and other large models have been used by economists and policy-makers for decades to think about, develop, and guide climate mitigation policies (Krey *et al.*, 2019; Fiedler *et al.*, 2021; Ives *et al.*, 2021). These models are also used to explore different targets, government plans, policies, and strategies for international negotiations (Hermeling *et al.*, 2013; UNEP, 2015; UNFCCC, 2015; van den Berg *et al.*, 2020; NGFS, 2022; Weitzel *et al.*, 2023), and to undertake stocktakes of progress against the Paris Agreement goals (Grassi *et al.*, 2018). At the national level, many countries have introduced legislation, including nationally determined contributions, influenced by modelled climate mitigation scenarios (Nachmany *et al.*, 2017).

Such models have played a role in persuading over 80 countries to implement some form of carbon pricing, although political constraints have meant that carbon price levels are almost universally well below the level recommended by IAMs (Klenert *et al.*, 2018; Mattauch *et al.*, 2020).

Key actors in finance, business, civil society, and media also use the outputs of various IAMs. Investors and financial institutions such as Goldman Sachs, JP Morgan, S&P Global, and BlackRock have drawn on the results of such models to evaluate business and financial risks from the company's transition progress towards the Paris Agreement 'net-zero' goal—including the climate scenarios put forth by the Network of Central Banks and Supervisors for Greening the Financial System (NGFS), as well as those developed by the Science-Based Targets initiative (SBTi) (Battiston *et al.*, 2021; Rekker *et al.*, 2022). Most major companies now use such scenarios to try to understand their exposure to climate-related physical, transition, reputational, and litigation risks, and to develop their climate risk disclosures (Fiedler *et al.*, 2021). The release of the IPCC reports that contain the outputs of IAMs are also widely publicized by the global media. The scientists that publish works based on these models are very heavily cited.[4]

While these models have been very influential, it is not clear that they have always provided useful advice. For example, they have typically and systematically overestimated the future costs of renewables and underestimated their rate of deployment (Way *et al.*, 2022). This is problematic given that producing insights on the costs of mitigation options is considered one of the core purposes of 'policy evaluation' IAMs (Weyant, 2017), but also because such skewed results may have damped past investment in renewables.

IAMs have proven challenging to validate, and can be unreliable, with results not robust and changing markedly when more realistic assumptions are employed (Wilson *et al.*, 2021). In practice, users tend to exercise discretion rather than strictly adhering to the findings and implicit recommendations provided by the models. Decisions are often taken based on a wide range of factors, including heuristic 'rules of thumb' and mental models that policy-makers have internalized. Decision-makers are influenced by their experiences and have adaptive expectations and preferences that incorporate many social factors (e.g. what their competitors and other peers do), and often have multiple goals and time horizons (Dhami, 2016). Most policy-makers are relatively savvy about the limitations of economic modelling in general and can be highly sceptical of their findings. Much has been written about the various, sometimes manipulative, ways in which policy-makers use economic modelling and how they enter into the political economy of climate policy (Barbrook-Johnson *et al.*, 2024). Models provide, at best, a guide, but are only one source of information.

VI. Example applications and evaluation

This section presents a series of examples where climate-economy models have been applied to inform key policy questions, following the groupings of questions of interest to MOFs from section III above. We consider each example in terms of our five desirable properties set out in section IV (Table 3): (1) parsimony, (2) tractability, (3) conceptual insightfulness, (4) empirical consistency, and (5) suitability. The primary purpose of Table 5 is to bring much of the previous discussion together. The columns in Table 5 reflect ideas set out in Tables 2–4 above. Overall, Table 5 provides a variety of assessments of the advantages and disadvantages of specific models for specific questions. Note that larger, empirical, process-driven IAMs are being used for most of the research questions examined here—demonstrating their flexibility in providing outputs—but it also raises concerns about the appropriateness of using them in contexts beyond their original design scope (i.e. applying them to questions that they were not designed to answer).

[4] Listed in the Clarivate Highly Cited Researchers database (https://clarivate.com/highly-cited-researchers/) generally under the Social Sciences or Cross-Field award categories.

Table 5: Example application of climate economic models.

Question (see Table 2)	Specific question	Relevant type of model (see Table 4)	Key findings	Assessment according to the five criteria (see Table 3)
Transforming markets: How to provide appropriate price signals to encourage more socially optimal levels of climate-friendly investment, activities, and behaviour?	How ambitious should carbon pricing policies be? That is: what is the social cost of carbon?	Simplified policy-optimizing IAM (DICE) Nordhaus (2017)	Initial estimate of SCC using DICE was \$6/tCO_2, revised to \$41/tCO_2 (2025\$US) in 2015 with optimal warming at 3.5°C above pre-industrial levels.	1. Parsimonious: very simple model 2. Tractable: Open to analysis, transparent, and interpretable. Can be easily altered to demonstrate the implications of important dynamics that have not originally been included—this has led DICE to be highly cited and used. 3. Insightful: Helpful initial framing of the problem, but misleading in its assumptions, approach to risk, and abstraction from reality. 4. Empirically consistent: Minimal calibration/validation of the empirical data (Keen, 2022). Not tested for reliability and misleading about levels of uncertainty. 5. Suitable: Useful as a toy model but not appropriate for examining structural transformation. Highly criticized for not correctly characterizing risks or including important non-linear dynamics and structural breaks (e.g. Cai *et al.*, 2015 ; Stern and Stiglitz, 2021 ; Keen, 2022.

Table 5: Continued

Question (see Table 2)	Specific question	Relevant type of model (see Table 4)	Key findings	Assessment according to the five criteria (see Table 3)
	How ambitious should carbon pricing policies be? That is: what is the social cost of carbon?	Estimates are based on expert evaluation but are likely to have been informed by modelled results. Stern and Stiglitz (2017)	Recommends that SCC would need to be in the \$51–\$104/tCO_2e (2025\$US) range by 2020 to meet the Paris Accord temperature goals. Along with Stern and Stiglitz (2021) the analysis is accompanied by a highly detailed criticism of estimates of SCC from policy-optimization IAMs, that fail to consider many important risks and costs and deep uncertainty.	1. Parsimonious: based on deliberations of a large group of experts. 2. Tractable: Not tractable in the sense that all the assumptions the authors employ in their estimates are made available for scrutiny. 3. Insightful: Qualitative perspective but provides and justifies SCC estimates for use by major global organizations like the World Bank. 4. Empirically consistent: The social cost of carbon estimates are not based on any tested modelling or predictions but are provided as an expert evaluation of a large group of experts. 5. Suitable: Embodies the estimation of two leading climate economists. Transparent in the sense that the SCC estimates are explained. Lower bounds on SCC are what authors consider sufficient to promote action and provide a clear signal to investors and consumers. Upper bounds are based on more pessimistic assumptions regarding the pace of technological change and the impact of socioeconomic trends. Authors' expertise includes an understanding of the potential for structural breaks, market failings, and non-linear dynamics.

Table 5: Continued

Question (see Table 2)	Specific question	Relevant type of model (see Table 4)	Key findings	Assessment according to the five criteria (see Table 3)
	How ambitious should carbon pricing policies be? That is: what is the social cost of carbon?	Built on a DSGE with non-linear climate damage feedbacks. Van den Bremer *et al.*, (2023)	Rule-based estimates of optimal SCC of $188 (2025$US) with 2% discount rate and including total factor productivity damages, climate disasters, and tipping points.	1. Parsimonious: Provides an easy-to-interpret rule for calculating the optimal risk-adjusted social cost of carbon. 2. Tractable: Built on a reasonably complex model employing general equilibrium, so likely requires constraints and scientific expertise to understand and interpret. However, it is translated into a tractable, relatively simple rule for decision-makers. 3. Insightful: Produces SCC estimates in the range of more complex modelling efforts. 4. Empirically consistent: Rules are calibrated and tested against a more complex market-based model. Explicitly incorporates major sources of uncertainty and debate, particularly around climate damages and discount rates. 5. Suitable: Utilizes an appropriately detailed model including the potential for structural breaks and non-linear dynamics.

Table 5: Continued

Question (see Table 2)	Specific question	Relevant type of model (see Table 4)	Key findings	Assessment according to the five criteria (see Table 3)
	How ambitious should carbon pricing policies be? That is: what is the social cost of carbon?	Employs a policy optimizing IAM to estimate the SCC Rennert *et al.* (2022)	Provides a preferred mean value for the optimal SCC at 2% discount rate of \$227/tCO_2e (2025\$US) with a range of \$54–506/tCO_2e (2025\$US).	1. Parsimonious: medium complex model specifically designed for this research question. 2. Tractable: The code base is not simple but open to analysis and made more tractable by the modular structure that facilitates assumptions testing and the addition of new components such as new damage sectors. Transparent in that all assumptions are based on peer reviewed literature and open source. 3. Insightful: Model built specifically for estimating the SCC that deals with most of the problems associated with smaller models like DICE. 4. Empirically consistent: Calibrated based on recent peer-reviewed research on socioeconomic projections, climate modelling, climate, impact assessments, and economic discounting. Explicitly incorporates uncertainty in all estimates. 5. Suitable: Provides an appropriately detailed model appropriate for driving structural transformation. Estimates incorporate recent scientific advances unaccounted for by the previous IAMs used in regulatory analysis, including the potential for structural breaks, strategic complementarities, and non-linear dynamics.

Table 5: Continued

Question (see Table 2)	Specific question	Relevant type of model (see Table 4)	Key findings	Assessment according to the five criteria (see Table 3)
	How ambitious should carbon pricing policies be? That is: what is the social cost of carbon?	NT2NZ approach involving the selection of emissions target based on best available science and economics, and application of a process-driven IAM (GCAM-USA) to calculate carbon prices consistent with the emissions pathway. Kaufman *et al.* (2020)	NT2NZ carbon price is \$43–81/tCO_2 (in 2018\$US) in 2025 and \$97–\$US157 in 2030 for consistency with a 2050 net zero target. • SCC estimates derived from a highly complex process driven IAM GCAM which is highly complex but available with a reasonable amount of documentation and a code base that is publicly available.	1. Parsimonious: not parsimonious—large complex model not specifically designed for this research question. 2. Tractable: Not particularly tractable—GCAM utilizes general equilibrium and optimization and so likely employs constraints, and requires an expert team to use. 3. Empirically consistent: Model calibrated to US historical national income accounts and energy balances (Bond-Lamberty *et al.*, 2024). Honest about most uncertainty—key assumptions such as oil and gas prices etc. are informed by data, and wide range sensitivity analyses undertaken. However, technology cost projections for renewables are conservative compared to historical trends resulting in lower renewable energy adoption and higher costs of transition than other US models. Hence, their cost estimates for the transition are not necessarily consistent with other US net zero modelling efforts (see Nasta and Wissmiller (2023) for a meta-analysis). 4. Insightful: This approach provides useful insights but is sensitive to the attributes and performance underlying energy-economic model chosen. 5. Suitable: GCAM was not specifically designed to answer this research question and so may provide misleading insights. Does not necessarily incorporate the potential for structural breaks, strategic complementarities, and non-linear dynamics.

Table 5: Continued

Question (see Table 2)	Specific question	Relevant type of model (see Table 4)	Key findings	Assessment according to the five criteria (see Table 3)
Transforming landscape of global competitiveness: How to capitalize on growth opportunities and minimize transition risks?	What is the impact of changes in global oil and gas demand and trade disruptions on my economy?	Process-driven IAM (MESSAGE) McCollum *et al.* (2016)	Sustained low or high oil prices could have a major impact on the global energy system over the next several decades with the potential for significant carbon-dioxide consequences	1. Parsimonious: large complex model but arguably employed to understand the potential of major factors to influence economic and carbon impacts. 2. Tractable: Not particularly tractable—requires an expert team with years of expertise using the MESSAGE model. 3. Empirically consistent: Utilizes empirically grounded parameter estimates but uses a highly complex model with thousands of underlying data points making it difficult to analyse, validate, or test. Transparent in the sense that the code base is available but unlikely the parameterization used for this study could be replicated. 4. Insightful: provides useful insights about the impacts of long-term oil prices on economic activity and decarbonization efforts. 5. Suitable: MESSAGE was built for other purposes. Similar insights could potentially be derived through the use of a simpler empirical model designed specifically for this research question.

Table 5: Continued

Question (see Table 2)	Specific question	Relevant type of model (see Table 4)	Key findings	Assessment according to the five criteria (see Table 3)
	What is the impact of changes in global oil and gas demand and trade disruptions on my economy?	Integrated energy-economy carbon-cycle climate model—process-driven IAM (E3ME-FTT-GENIE) Mercure *et al.* (2018)	Losses from stranded fossil fuel assets could be US$1–4 trillion, with important distributional impacts: winners include China, or the EU, and losers include Russia, the US, and Canada.	1. Parsimonious: large complex model modelling a complex global system and question but has many free parameters. 2. Tractable: Not particularly tractable—E3ME is a large and complex model that utilizes optimization and employs constraints and requires considerable training to operate. Code base not available except under licence. 3. Empirically consistent: Utilizes empirically grounded parameter estimates but with thousands of free parameters so high potential for being overfit. Transparent in the sense that the code base and assumptions can be examined, but highly complex with thousands of underlying data points making it difficult to validate. 4. Insightful: provides an alternative perspective to traditional CGE-based IAMs with useful quantitative and qualitative insights about the losses associated with stranding and about countries that will be most adversely impacted by the transition. 5. Suitable: Appropriate for providing input into questions around structural transformation and importantly it provides an alternative perspective to mainstream CGE-based models. Can be used to explore some structural breaks, strategic complementarities, and non-linear dynamics that are problematic for other CGE-based IAMs.

Table 5: Continued

Question (see Table 2)	Specific question	Relevant type of model (see Table 4)	Key findings	Assessment according to the five criteria (see Table 3)
	How do global mitigation and climate policies impact my domestic economy? What are the relevant risk drivers and what are the optimal responses?	Theoretical analysis supported by empirical evidence D'Orazio (2025)	Suggests developing economics undergo fossil fuel subsidies reform, provide renewable energy support, incorporate climate risks into fiscal policy frameworks, diversify revenue sources, and increase institutional capacity.	1. Parsimonious: theoretical arguments based on the author's understanding supported by cited publications. 2. Tractable: Provides arguments in a consistent risk and opportunities framework using standard economic language that would appeal to political actors. 3. Insightful: Qualitative perspective providing useful advice for developing economies. 4. Empirically consistent: Qualitative approach but supported by cited publications some of which involve modelling. 5. Suitable: Provides analysis for emerging and developing economies that shows awareness of their more specific challenges in a risk and opportunity framework.

Table 5: Continued

Question (see Table 2)	Specific question	Relevant type of model (see Table 4)	Key findings	Assessment according to the five criteria (see Table 3)
	How do global mitigation and climate policies impact my domestic economy? What are the relevant risk drivers and what are the optimal responses?	Energy model coupled with partial equilibrium economic model and climate emulator for wind and solar Cesaro *et al.* (2025)	A renewables-based energy system coupled with ammonia off-take sectors could dramatically reduce India's GHG emissions, reduce requirements for expensive long-duration energy storage, reduce renewable curtailment, provide short-duration and long-duration load-shifting, system resilience to inter-annual weather variations, and replace tens of billions of USD in ammonia and fuel imports each year.	1. Parsimonious: parsimonious for the task—a medium complexity model. 2. Tractable: Utilizes optimization and so employs constraints to ensure solutions, requires an expert team to use the model but is based on open-source software. 3. Empirically consistent: models India's national infrastructure network using 10 years of weather data and other data. Utilizes empirically grounded parameter estimates and is calibrated to infrastructure capacities but conditional predictions are not validated or tested. Code base not currently available. 4. Insightful: provides useful quantitative and qualitative insights on an announced government policy utilizing multiple meaningful performance metrics including system costs, levelized costs of hydrogen and ammonia, land-use, energy security, labour effects, and stranded assets. 5. Suitable: Appropriate for providing input into questions around structural transformation and utilizes a risk and opportunity framework (Mercure *et al.*, 2021) in capturing uncertainty in future climate change and technology costs, non-linear dynamics in learning rates, and exploring complementary cross-sectoral strategies.

Table 5: Continued

Question (see Table 2)	Specific question	Relevant type of model (see Table 4)	Key findings	Assessment according to the five criteria (see Table 3)
Transforming sectors and technologies: How to navigate technological uncertainty and encourage sectoral decarbonization in the most cost-effective way?	What is the uncertainty around the cost and pace of decarbonization and energy pathways?	Applies a process-driven IAM (REMIND) to alternate scenarios of solar PV deployment and related cost decline Creutzig *et al.* (2017)	Concludes past IAM outputs have grossly underestimated the role that solar PV is likely to play in reducing emissions and the cost of the energy transition.	1. Parsimonious: utilizes the findings of large complex model that are difficult to validate or test. 2. Tractable: Not very tractable—the REMIND model is large and difficult to manage, utilizes optimization and so employs constraints to ensure solutions, and usually requires a well-funded team of experts. 3. Insightful: a complex model but used appropriately to explore the problems with other IAMs to test assumptions around the potential of clean energy technologies with consistently declining costs. 4. Empirically consistent: Utilizes empirically grounded parameter estimates. Transparent in that the code base is open source. 5. Suitable: Appropriate for providing input into questions around structural transformation, although using a type of model that has struggled to incorporate structural breaks and non-linear dynamics.

Table 5: Continued

Question (see Table 2)	Specific question	Relevant type of model (see Table 4)	Key findings	Assessment according to the five criteria (see Table 3)
	What is the uncertainty around the cost and pace of decarbonization and energy pathways?	Time series models for technological forecasting + a simplified global energy model Way *et al.* (2022)	A rapid transition to a green energy system is likely to be cheaper than a future based on the existing fossil fuel system	1. Parsimonious: Relatively simple model that captures the essential and simplifies or discards the non-essential. 2. Tractable: Open to analysis, as complicated as it needs to be, transparent, and interpretable. Bespoke model focused specifically on answering the question of the cost of the global transition to a green energy system. Only uses optimization to fit learning curves. Code base available on request. 3. Empirically consistent: Designed specifically for prediction using empirically grounded learning curves on all energy technologies. Well-validated and tested, yielding empirically grounded, more reliable answers. Honest about uncertainty. 4. Insightful: at the global level, though less so at the country level 5. Suitable: Appropriate for advising on driving global structural transformation. Built to focus on some important strategic complementarities (EVs, VRE, and grid storage), and non-linear dynamics (endogenous technological learning).

Table 5: Continued

Question (see Table 2)	Specific question	Relevant type of model (see Table 4)	Key findings	Assessment according to the five criteria (see Table 3)
	What is the uncertainty around the cost and pace of decarbonization and energy pathways?	Process-driven IAMs IPCC (2011)	The annual averages of investment necessary in a global green energy system is less than 1 per cent of the world's gross domestic product (GDP).	1. Parsimonious: Relies on the outputs of three extremely complex process-driven IAMs that were designed to explore plausible scenarios and not necessarily provide reliable estimates of the costs of the transition. 2. Tractable: Not tractable, utilizes optimization, and employs constraints to ensure solutions (Kahouli-Brahmi, 2008) and relies on teams of experts to run each IAM. 3. Empirically consistent: Model outputs relied upon are not overly transparent due to the size and complexity of the models. Lack of validation—glaring problems in some models' projections not matching actuals. 4. Insightful: Provides a measure of the cost of the global energy system based on the outputs of three models—exploring model structure uncertainty. However, outputs of models have been highly criticized for sacrificing important non-linear processes for optimization tractability. 5. Suitable: The IPCC publication undergoes extensive review, but the IPCC report is relying less on the modelled outputs due to criticisms and inconsistency with the report's literature review and its own qualitative conclusions. The majority of IAMs have struggled to incorporate structural breaks, strategic complementarities, and non-linear dynamics.

Table 5: Continued

Question (see Table 2)	Specific question	Relevant type of model (see Table 4)	Key findings	Assessment according to the five criteria (see Table 3)
	What is the uncertainty around the cost and pace of decarbonization and energy pathways?	Agent-based process-driven IAM (DSK) Lamperti *et al.* (2020)	Shows an equilibrium from the transition to green energy technologies has higher GDP growth and lower unemployment than one with a carbon-intensive lock-in. However, for green transition to emerge carbon taxes need to be coupled with command-and-control regulation and monitoring.	1. Parsimonious: a high complexity agent-based micro-founded model but employed for the specific purpose of showing contrast with traditional IAMs. 2. Tractable: Not particularly tractable—difficult to analyse, requires an expert team to use the model, and code base does not appear to be publicly available. 3. Empirically consistent: Indirect calibration and selected variables evaluated against historical empirical counterparts subject to data availability. 4. Insightful: provides contrasting insights regarding the cost of decarbonization and the efficacy of mainstream climate policies. 5. Suitable: Appropriate for providing contrast to traditional IAMs, addressing model-structure uncertainty and allowing economic and climatic variables to co-evolve interacting non-linearly, with multiple feedbacks, and emerging tipping points.

Table 5: Continued

Question (see Table 2)	Specific question	Relevant type of model (see Table 4)	Key findings	Assessment according to the five criteria (see Table 3)
Transforming demand for sectors and skills: How to manage the decline of sunsetting sectors while encouraging growth towards sunrise sectors?	What is the impact of the transition on the regional labour. What are the public spending requirements for re-skilling the labour force?	Empirical analysis Vona *et al.* (2018)	Environmental regulation has no impact on overall employment but creates significant, if modest, gaps in the demand for some green skills, especially those related to technical and engineering work tasks.	1. Parsimonious: Relatively simple empirical analysis but is aware that it does not provide a complete picture of all dynamics. 2. Tractable: Open to analysis, repeatable, transparent, and interpretable. Uses publicly available data. 3. Empirically consistent: Empirical data analysis, designed for prediction, shows awareness of some major sources of uncertainty even if they remain unaddressed. 4. Insightful: over the short term and at the country level. 5. Suitable: Appropriate for advising on short-term skills requirements for the green transition. Examines the complex interactions between new skill requirements for employees and employers with environmental regulation but does not address non-linearities or structural breaks, such as the end of major green transitions

Table 5: Continued

Question (see Table 2)	Specific question	Relevant type of model (see Table 4)	Key findings	Assessment according to the five criteria (see Table 3)
	What is the impact of the transition on the regional labour. What are the public spending requirements for re-skilling the labour force?	Input–output model running an energy-economy modelled scenario coupled with an occupational mobility network model Xie *et al.* (2023)	Decarbonization brings consistent job growth and heightens the need for investment in human capital and supply chain restructuring. Major fossil fuel-producing states must prepare for fewer mining jobs, so other opportunities should be created or seized.	1. Parsimonious: Model complexity suitable to the task. 2. Tractable: Model is open to analysis but requires a team of experts to operate; is relatively transparent (code base available) and repeatable. 3. Empirically consistent: Model calibrated to US, using models designed specifically for this national context. Examines many plausible scenarios to explore uncertainty, but admits the JEDI I/O method needs regular validation against *ex post* empirical employment analyses. 4. Insightful: Provides an understanding of the regional employment and distribution effects of the energy transition and the relative size of the employment effects of the energy transition compared to past transitions. 5. Suitable: Looks at scenarios with non-marginal change and structural breaks. Does not account for labour mobility and might under-represent sectoral unemployment effects. Suitable for policy analysis.

Table 5: Continued

Question (see Table 2)	Specific question	Relevant type of model (see Table 4)	Key findings	Assessment according to the five criteria (see Table 3)
	What is the impact of the transition on the regional labour? What are the public spending requirements for re-skilling the labour force?	Input–output model coupled with an occupational mobility network model running against an energy-economy modelled scenario Bücker *et al.* (2025)	A rapid transition of the power sector in the US could entail significant skill shortages in the scale-up phase, and significant layoffs in the scale-down phase—underscoring the importance of careful planning and labour market policies to support the energy transition.	1. Parsimonious: Reasonably complex modelling but incorporates a methodological framework that enables flexibility. 2. Tractable: Is open to analysis, does not employ optimization, is repeatable, and can be applied to any energy transition scenario but requires experts to operate. 3. Empirically consistent: Calibrated against US national power sector capacities and detailed US input–output model. Reliable and honest about uncertainty and includes a sensitivity analysis on key variables and assumptions including alternate realizations of the input–output structure of the economy. Shows awareness of some major sources of uncertainty that it does not address. 4. Insightful: Captures complicated labour mobility dynamics based on real world data, provides qualitative and quantitative insights about the likely demand of specific types of labour and potential skill mismatches in a fast energy transition. 5. Suitable: Bespoke model specifically designed to capture the micro-foundation dynamics of labour markets. Built specifically to incorporate non-linear labour market dynamics, the non-marginal structural change to the economy, and the ensuing complex interactions between job-seeking agents and skill-seeking industries. Appropriate for driving structural transformation

Table 5: Continued

Question (see Table 2)	Specific question	Relevant type of model (see Table 4)	Key findings	Assessment according to the five criteria (see Table 3)
Transforming tax revenues and fiscal balance sheets: What are the budgetary implications of the transition to net-zero and how can we pay for it?	How should governments optimally design carbon taxes when they must simultaneously raise revenues using distortionary income taxes?	Does not use a model but provides answers based on theoretical arguments supported by publications, some of which involve modelling. Marron and Morris (2016)	Recommends that governments use some revenue to reduce other taxes on lower-income households, fossil fuel workers and their communities; to not use revenues for further emissions reductions but instead use some to maintain support for carbon tax.	1. Parsimonious: Theoretical arguments supported by cited publications, some of which involve modelling. 2. Tractable: Provides arguments in a consistent standard economic framework using mostly plain non-academic language that would appeal to political actors. 3. Insightful: Provides useful insights and reveals important interactions between carbon taxes, other taxes, economic actors, and potential distortions, but does not support arguments with any modelling. 4. Empirically consistent: little provided in the way of empirical evidence. 5. Suitable: Considers some non-linearities, but does not consider strategic complementarities, or structural breaks.

Table 5: Continued

Question (see Table 2)	Specific question	Relevant type of model (see Table 4)	Key findings	Assessment according to the five criteria (see Table 3)
	How should governments optimally design carbon taxes when they must simultaneously raise revenues using distortionary income taxes?	Dynamic CGE, merged with an optimal Ramsey-type taxation framework and DICE Barrage (2020)	Incorporating real-world distortionary taxes into a dynamic climate-economy model leads to an optimal carbon tax somewhat below the Pigouvian rate—especially under positive capital taxation—while careful policy design can deliver substantial welfare gains.	1. Parsimonious: Mostly theoretical with majority of key features but uses a DICE-based climate-economy feedback, lacks technological change dynamics which could lead to misleading results (e.g. cost reductions from learning in renewable energy deployment could allow government to achieve emissions targets with a lower carbon tax and thus even fewer distortions). 2. Tractable: utilizes general equilibrium optimization with constraints to ensure solutions but uses standard functional forms and linear tax structure and the relatively simple DICE framework. 3. Insightful: Reveals important interactions between carbon pricing and pre-existing tax distortion. 4. Empirically consistent: detailed empirical calibration but very little evidence of validation or out-of-sample testing of the model. Relies on a number of Nordhaus assumptions that have been criticized (Keen, 2022). 5. Suitable: Does incorporate some non-linearities and to some extent strategic complementarities, but no commentary on structural breaks.

VII. Conclusion

Economic models, frameworks, analyses, and perspectives are important, but not decisive, inputs into climate policy-making. The experts who build the models, and to a lesser extent the decision-makers who use them, are often aware of their limitations and tend to combine model analyses with other inputs, influences, and domain knowledge to try to reach wise policy interventions. Nonetheless, the results generated by climate-economy models do influence decisions-makers, sometimes by justifying pre-existing biases and maintaining the status quo, but often in shaping the narrative around particular questions (e.g. 'the transition will be costly').

This paper has examined how economic models, frameworks, analyses, and perspectives can help guide climate policy, given the complexity and uncertainty involved. We characterized the net-zero transition as involving three challenging, but important features, namely: structural breaks, strategic complementarities, and non-linear dynamics (see section II). Then, based on a survey of finance ministries, we identified five issues of climate policy interest, namely: prices and markets; global competitiveness; technological uncertainty; labour and skills; and tax revenues and budgeting (see section III). We described the properties of a good model (see section IV) and set out the categories of models available to help policy-makers (see section V) before considering a range of examples where models have been used to attempt to answer the questions that finance ministries are currently asking (section VI).

Although this paper has covered a broad range of issues, it has only scratched the surface of this topic. We deliberately limited our analysis to the transition towards net-zero emissions, and did not, for instance, explore the significant challenge of assessing how physical climate impacts could harm national fiscal positions, and how countries can adapt and respond to inevitable climate damages.

Three key conclusions from this review stand out. The first is that there are many different climate-economy models, each providing a different function for policy-makers. Choosing the right model for the right question is absolutely crucial, but not straightforward. Sections V and VI offer guidance and examples. The second key conclusion is that no single model can ever hope to fully encompass all the vital elements of a transition (see section II), nor can it flawlessly integrate every desirable feature into a single analytical framework (see section IV). And while modellers should make every effort to aim for these features—and to openly disclose inevitable limitations—the more critical imperative is to employ multiple models to provide policy-makers with more robust and reliable answers to complex policy questions. The third key conclusion is that some of the critiques made of the current suite of climate-economy models suggests useful directions for further research and development. These include better representing specific policies, more accurate representation of non-linear dynamics, uncertainty, and distributional concerns, greater sensitivity analysis, improved evaluation of empirical models, and a more thoughtful approach to discounting and intertemporal choice. Despite these challenges, for most relevant policy questions, there is often at least one model or economic framework that can help provide insight. A major part of the challenge for policy-makers is identifying which model or group of models to turn to for the question at hand; we hope this paper makes meeting that challenge a little easier.

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