EEIST

THE WHAT, WHY AND HOW OF NEW ECONOMIC MODELLING

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This document presents the introductory sections of the 'New economic models of energy innovation and transition: Addressing new questions and providing better answers' report, produced by the EEIST project.

To view other parts of the full report, including modelling case studies on the global energy transition, the power and industrial sectors, transport, agriculture, impacts of the transition, national decarbonisation plans and finance, go to https://eeist.co.uk/eeist-reports/new-economic-models-of-energy-innovation-and-transition/

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About

The Economics of Energy Innovation and System Transition (EEIST) project develops cutting-edge energy innovation analysis to support government decision making around low-carbon innovation and technological change.

By engaging with policymakers and stakeholders in Brazil, China, India, the UK and the EU, the project aims to contribute to the economic development of emerging nations and support sustainable development globally.

Led by the University of Exeter, EEIST brings together an international team of world-leading research institutions across Brazil, China, India, the UK and the EU.

The consortium of institutions are UK: University of Exeter, University of Oxford, University of Cambridge, University College London, Anglia Ruskin University, Cambridge Econometrics, Climate Strategies, India: The Energy and Resources Institute, World Resources Institute, China: Beijing Normal University, Tsinghua University, Energy Research Institute, Brazil: Federal University of Rio de Janeiro, University of Brasilia, Universidade Estadual de Campinas (UNICAMP) EU: Scuola Superiore di Studi Universitari e di Perfezionamento Sant'Anna.

Contributors

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Introduction

The call for change

This report represents a major effort to demonstrate and provide evidence for the value of a range of new economic modelling on specific energy topics and climate policy questions, in partnership with policy stakeholders in key countries in the global energy transition. Many researchers, policymakers and practitioners have been making the case for new economic modelling of the energy transition for some time. These calls have focused on three key areas:

1. The need for new approaches to climate policy appraisal.[2]
2. The need for better modelling of technology and innovation dynamics.[3,4]
3. The need to better model the underlying dynamics of the transition at national and global scales.[5]

These calls for new analysis are underpinned by a range of specific concerns about current analysis and decision-making frameworks, from purely technical modelling arguments to specific issues around the energy transition and how to model it appropriately, to wider arguments about how policy appraisal should be conducted and decisions made. These concerns are often overlapping and intertwined. We attempt to summarise them in Table 1. It is important to emphasise that different types of models and analysis address different subsets of these concerns; no single approach meets them all.

[2] Mercure, J-F. et al. (2021). Risk-opportunity Analysis for Transformative Policy Design and Appraisal. Global Environmental Change 70: 102359.
[3] Way, R. et al. (2022). Empirically Grounded Technology Forecasts and the Energy Transition. Joule: 6(9), 2057-2082.
[4] Peñasco, C. et al. (2021). Underestimation of the Impacts of Decarbonisation Policies on Innovation to Create Domestic Growth Opportunities. C-EENRG Working Papers, 2021-6: 1-16.
[5] Grubb, M. et al. (2021). The New Economics of Innovation and Transition: Evaluating Opportunities and Risks, EEIST report to COP26.

Table 1: Why do we need new economic modelling of the energy transition?

Theory: Energy transition domain concerns	Modelling: Conceptual and technical modelling concerns	Policy: Policy appraisal and decision-making concerns
• Marginal economic analysis is not appropriate for the transformational structural change that addressing climate change demands. • Existing theory, models and decision-making frameworks which assume equilibrium or an efficient self-optimising economy have an inbuilt bias that policy action will have costs. • Equilibrium-based theory and models often do not model structural transformation nor innovation, so assume that economic structure is static, incorrectly implying that only large price changes can prevent emissions. • We don't know the role of the private sector in the transition well, and this is often interpreted as a gap in public finance. • Real institutions should be represented.	• Models should be structurally realistic (i.e. represent the flows and relationships between economic actors as realistically as possible). • Models should capture disequilibrium[6] and path-dependent dynamics. • Models should capture feedback loops and tipping points. • Models should capture heterogeneity and interaction. • Models should capture uncertainty and 'fat-tailed' probability distributions. • Economic decision-making should be modelled using realistic individual behaviour (bounded rationality or heuristics). • Models should be empirically validated so that we can have confidence in their predictions. • Many existing models use poorly validated or arbitrary technology pathways. • Technology dynamics should be modelled endogenously. • Distributional impacts often need to be modelled.	• Decisions should be made on more than narrow 'best-guess' cost-benefit terms, to incorporate uncertainty, risks and opportunities. • A wider range of policy options needs to be considered – rather than modelling only a carbon price, we need to model the broader family of policies that are more likely to be politically feasible in the real world. This may involve implementing multiple complementary policies at the same time. • Policies should be assessed based on their likely effect on processes of change within the economy (how they affect the dynamics of innovation and structural change[7]), not just on the basis of predicted outcomes at fixed points in time. • To inform policy decisions, we need more probabilistic 'forecasting-type' models (i.e. which simulate and forecast likely futures,[8,9] as opposed to optimisation models which identify 'optimal' solutions or pathways).

In our previous EEIST reports, we have emphasised key messages on the question of how to model the energy transition. In our first flagship report, The New Economics of Innovation and Transition: Evaluating Opportunities and Risks,[10] we outlined the reasons why a new approach was needed, arguing the greatest successes achieved so far in the low-carbon transition have happened in ways that few people expected, using policy approaches that were not those recommended by standard economic analysis. If modelling for ex ante policy appraisal is to enable such successes more frequently, we need a new approach, to supplement traditional cost-benefit appraisal with new techniques, to understand the risks and opportunities of transformational changes.

[6] Here we are referring to disequilibrium as a property of complex systems, not the capability of models to be out of equilibrium or not.
[7] Peñasco, C. et al. (2021). Systematic Review of The Outcomes and Trade-Offs of Ten Types of Decarbonisation Policy Instruments. Nature Climate Change 11.3: 257-265.
[8] Meng, J. et al. (2021). Comparing Expert Elicitation and Model-Based Probabilistic Technology Cost Forecasts for the Energy Transition. Proceedings of the National Academy of Sciences 118.27: e1917165118.
[9] Farmer, J.D, and Lafond, F. (2016). How Predictable is Technological Progress? Research Policy 45.3: 647-665. 10 https://eeist.co.uk/eeist-reports/
[10] https://eeist.co.uk/eeist-reports/

In our second flagship report, Ten Principles for Policy Making in the Energy Transition,[11] we presented new evidence-based principles for policymaking in the energy transition, arguing that many of the economic principles, models and decision-making tools used by governments are designed for use within contexts of 'marginal' or incremental change, where technologies, markets and other economic structures are relatively stable. Different principles and tools are needed when, as in the energy transition, the aims and context of policy include widespread innovation and structural change.

In the main text of this report, for clarity and brevity we focus on demonstrating the value these new principles and modelling approaches can bring in practice and do not re-tread in depth the arguments about whether new approaches are needed or not. Others have done the latter already – for example, Farmer et al. (2015)[12] outline the existing taxonomy of integrated assessment models and their economic components. They discuss four key shortcomings in detail: (i) how these models deal with uncertainty; (ii) the representation of aggregation, heterogeneity and distributional impacts; (iii) representation of technological change; and (iv) the absence of realistic damage functions for the impacts of climate change on the economy. Mercure et al. (2016)[13] identify five shortcomings in existing optimisation and equilibrium economic models: (i) their normative, optimisation-based nature, (ii) their unrealistic reliance on the full-rationality of agents, (iii) their inability to account for mutual influences among agents and capture related self-reinforcing processes, (iv) their inability to represent multiple solutions and path-dependency, and (v) their inability to properly account for agent heterogeneity. In addition, Mercure et al. (2021),[14] presenting work from the EEIST project, outline an expanded form of cost-benefit analysis, called 'risk-opportunity analysis', designed for appraising policy options where the aim or context is transformational change – as is the case for policy on low-carbon transitions. They also describe how new economic modelling is needed for this type of analysis and decision support.

The IPCC has also touched on these issues,[15] outlining the spectrum between cost-benefit analyses using early integrated assessment models, the increasing emphasis on using models which can capture dynamic, rather than static, efficiency (that is, "taking account of inertia, learning and various additional sources of 'path-dependence'[16]) through to the use of complexity and systems approaches like those in this report. Others have attempted to overview and classify the large ecosystem of climate-economy models and integrated assessment models,[17] and made calls for different types of reform, such as efforts to increase understanding and participation.[18]

Delivering on the promise of new economic modelling

Calling for change is much easier than actually developing and applying the new modelling and delivering the envisaged value (i.e. more realistic, usable and fine-grained policy advice). This report represents a major effort to demonstrate and evidence the value of a range of new economic modelling on specific topics and policy questions, in partnership with policy stakeholders in key countries in the global energy transition.

This report contains 15 case studies of applications of new economic modelling approaches in Brazil, China, India, the UK and globally. Each case study describes a recent or current project in which new economic modelling was applied to live policy questions and topics with policy stakeholders. A case study approach allows us to demonstrate and reflect on the variety in modelling methods, purposes and contexts.

Each explains the new modelling but, vitally, also explains the findings and their policy relevance. They each consider if and why the new modelling has given us new insights on existing questions, or developed insights on questions we could not address previously.

This report thus complements our other flagship reports, by providing the detailed new economic modelling and policy discussions many have been calling for.

Who this report is for – and how to read it

This report is more technical than our previous two. It is primarily intended for analysts and modellers working in government, international organisations, academia and the third sector; to allow them to see first-hand, and in detail, how new economic approaches can deliver value, what they can do and what they can't. We also hope that policy teams will find the report useful, providing insights on relevant policy topics, as well as illuminating the question of why different modelling approaches give certain answers and advice.

Alongside the modelling case studies, we reflect on the types of models showing most promise, considering how they differ, their strengths and weaknesses, and how we can evaluate, choose between and adopt them in our work.

- **For readers interested in the detail of what these models can do**, we recommend reading the case studies that are most relevant for you first (either by country or the policy topics they address). Next, it should be helpful to read the overview of different types of models.
- **For readers considering using any of the modelling approaches** presented here, we recommend reading our practical section on how to begin using these methods.

This report will not teach readers the technical details of how to use these models directly; it is not a manual in that sense. However, a core part of our mission is to develop the capabilities and capacity of organisations around the world to use these modelling approaches, demonstrate their value and advocate for the underlying philosophy of new economic modelling and policymaking. If you are interested in training or more detailed guidance, please go to https://eeist.co.uk/training/ or get in touch.[19]

What's in the rest of this report?

The next section focuses on types of policy questions and where new economic modelling can fit into these. Next, we explain what we mean exactly by 'new economic models', introducing the types of models. Then we move on to a practical exploration of how to choose and start using new economic modelling approaches. This section outlines what different types of models are appropriate for, but also how to adopt these approaches, how to get past technical and institutional constraints and how to advocate for new economic modelling. In the following section, we move on to the modelling case studies themselves. We group these by the broad policy themes they speak to – the global energy transition, power and industry sectors, transport, agriculture, impacts of the transition, national decarbonisation plans and finance. Each case study presents the modelling conducted, but also the policy context, the relevance of findings and the new value that these provide, in relation to previous work. Finally, we conclude with a discussion of what we can learn from the case studies as a whole and outline our vision for the next five years in new economic modelling for the energy transition.

[11] https://eeist.co.uk/eeist-reports/

[12] Farmer, J.D. et al. (2015). A Third Wave in the Economics of Climate Change. Environ Resource Econ 62: 329–357.

[13] Mercure, J-F. et al. (2016). Modelling Complex Systems of Heterogeneous Agents to Better Design Sustainability Transitions Policy. Global Environmental Change 37: 102-115.

[14] Mercure, J-F. et al. (2021) Risk-opportunity Analysis for Transformative Policy Design and Appraisal, Global Environmental Change 70: 102359.

[15] Grubb, M. et al. (2022): Introduction and Framing. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla. Et al (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.003 16 Ibid. page 33

[17] Nikas, A. et al. (2019). A Detailed Overview and Consistent Classification of Climate-Economy Models. In: Doukas, H. et al. (eds) Understanding Risks and Uncertainties in Energy and Climate Policy. Springer, Cham. https://doi.org/10.1007/978- 3-030-03152-7_1.

[18] Doukas, H. and Alexandros N. (2020). Decision Support Models In Climate Policy. European Journal of Operational Research 280.1: 1-24

[15] https://eeist.co.uk/contact/

Addressing the key energy and climate policy questions

Before we dive into the detail of what new economic modelling approaches are, and the applications in this report, it is important to outline the policy questions to which different approaches can be applied. Ideally, policy questions should be the driver of new economic modelling. Policy questions allow researchers to identify a topic and aim, which then in turn help us identify a suitable methodological approach (more on this below), or combination of approaches, that can provide insights on these policy questions, leading to decision-making and impact. If models are constructed or applied without policy questions as a starting point, there is a very serious risk that much time and effort may be invested without producing a tool or analysis that is useful for decision-making.

Types of policy questions

Useful analysis is rarely broad. Rather, it tends to be specific, with a narrow focus on one or all of the following: context, sector, technology, geography and policy decision. The policy decision focus can vary in scale, from macro-type questions such as, 'Will decarbonising the economy cost us money?' through to meso-level questions such as, 'Which technologies should we focus on?' or, 'Which types of policy instruments might work best?' And finally, down to micro-level questions such as, 'How should we design this specific policy instrument?' Table 2 identifies these broad types of policy questions, the relevant examples in this report and types of modelling that are well-suited to each.[20] The table is not exhaustive of all types of policy questions; there are other types, such as micro-questions about individual projects, but we do not focus on these in this report.

[20] At this stage, the types of modelling are defined on broad terms. More specific types are enumerated in the later sections.

Table 2: Types of policy question and new economic modelling applications

Nature of decision (i.e. policy hierarchy)	Scope	Example policy questions	Example case studies	Well-suited approaches[21]
Development direction and pace	Economy-wide	• Should we decarbonise or not? • How much might decarbonisation cost? • What are the macroeconomic impacts? • What are the fiscal and employment effects of phasing out fossil fuels and how should they be managed? • How fast should we transition in road transport?	• Empirically grounded energy technology cost forecasts • Decarbonising the Indian economy: policies and impacts • Socioeconomic consequences of coal phase out in China • Green complexity and competitiveness • Unstoppable renewables and marginal pricing in China, India and Brazil • Economic impacts of net zero in India	• Forecast-type models, which do not assume that the economy is self-optimising and can assess likely future outcomes in dimensions such as GDP, jobs, investment and trade. • Analytical approaches that consider the potential for a country to be competitive in emerging new technologies.
Technology choice	Within each sector	• Within the power sector, should we use solar power or coal power? • Within road transport, should we deploy electric vehicles, biofuels, hydrogen fuel cell vehicles or hybrids?	• Unstoppable renewables and marginal pricing in China, India and Brazil • Empirically grounded energy technology cost forecasts • Green complexity and competitiveness	• Forecast-type models, which can simulate the development of technologies over time and assess feasibility and likely impacts of technology choices. • Quantitative assessments of technologies' learning rates and of their compatibility with the goal of net-zero emissions. • Qualitative and quantitative assessments of the advantages and disadvantages of different technologies. • Optimisation models which can find least-cost technology mixes at fixed moments in time.

[21] See the section 'What are new economic models?' for an introduction to these types of models.

Nature of decision (i.e. policy hierarchy)	Scope	Example policy questions	Example case studies	Well-suited approaches[21]
Choice of policy	For each technology / aim	• To deploy solar, should we use tax, subsidy, technology mandate, efficiency regulation, procurement or something else? • To deploy electric vehicles, should we use efficiency regulations, EV mandates, purchase incentives, taxes or some mixture of the above?	• Decarbonising the Indian economy: policies and impacts • Activating EV tipping points	• Forecast-type models which allow detailed representation of different policy types and can simulate the effects of policies individually and in combination based on empirical evidence. • Risk-opportunity analysis[22] (as an expanded form of cost-benefit analysis).
Design of policy	For each policy	• Should a clean technology subsidy be a feed-in tariff or a contract for difference? • Should a carbon price be a tax or a cap-and-trade scheme? • How does design of electricity markets affect outcomes?	• What is the most effective form of carbon pricing? • Unstoppable renewables and marginal pricing in China, India and Brazil	• Forecast-type models which allow detailed representation of different policy designs and simulate their effects. • Qualitative models which allow us to walk through assumptions about policy design.

Where are we in the policy cycle?

Another way to think about what types of policy questions we have and where modelling approaches deliver value is to consider the policy cycle (Figure 9). We know the policy cycle is an idealised representation of the policymaking world, but it does serve a useful purpose: to break the process into different stages, which each imply different types of analysis. What it does not capture well is the iterative nature of analysis to support policy; there is often a continuous process of adjustment and improvement based on usefulness, agenda priorities and empirical data. In reality, the steps in the cycle are also not necessarily sequential – there could be arrows linking policy implementation to agenda-setting, for example. Finally, the policy cycle also obscures the importance of policy history and landscapes, where some policies can trigger others, or lock countries into certain policy paths.

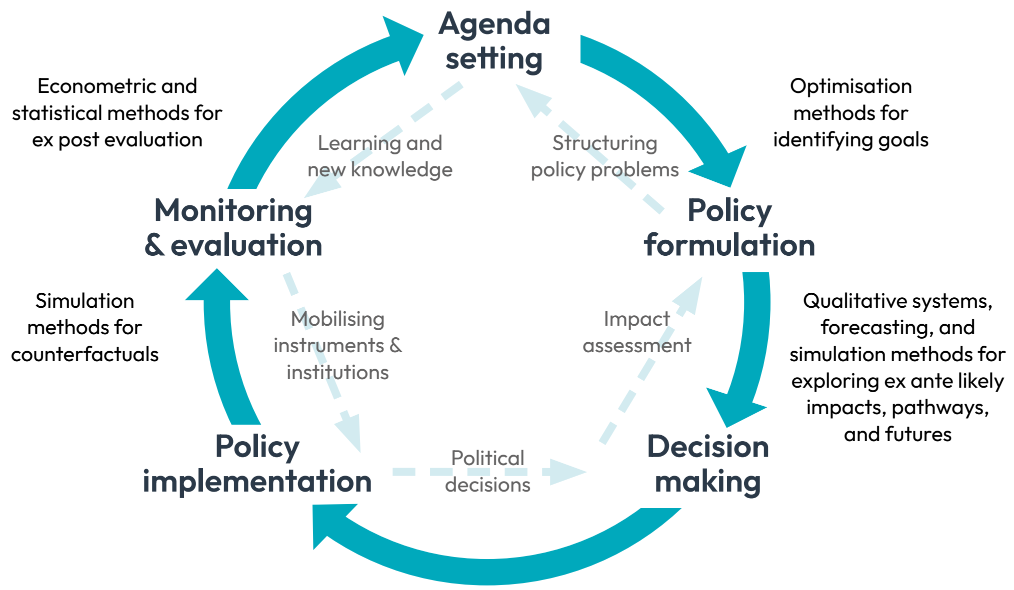
Nonetheless, the cycle helps us think about what types of analysis can be used at which stage. At the agenda-setting stage, optimisation methods (which we do not class as new economic modelling) have a role to play. Using these methods to explore what the optimal end point or goal is, in terms of costs, might be, under a set of technological constraints and assumptions, useful in setting the envelope of what we think is possible. However, as we move around the cycle, to policy formulation and decision-making, we believe new economic simulation approaches, which provide forecasts of realistic or likely futures that can result from policy actions, come to the fore. These types of models allow us to do meaningful ex-ante appraisal of policy efficacy and impacts. Importantly, they also allow us to understand the likely pathway to our goals, not just what the goal should or could be. This is simply not possible with optimisation models – it is not what they were designed for.[21]

[21] See the section 'What are new economic models?' for an introduction to these types of models.

[22] Mercure, J-F. et al. (2021). Risk-Opportunity Analysis for Transformative Policy Design and Appraisal. Global Environmental Change 70: 102359.

As we move around the cycle to policy implementation and evaluation, we begin to operate in an ex-post mode, assessing the actual impact we think a policy has had. Here, econometric and statistical methods become the most prominent, providing the data analysis techniques we need to assess impacts from real data. Econometric and statistical methods can come from new economic approaches or established approaches. A key challenge in ex-post evaluation is building a counterfactual of what might have happened without a policy. In most cases, an experimental approach with a control group to provide a counterfactual is not feasible, or ethical, for energy policy interventions. In such cases, one option is to use new economic forecast-type models to provide counterfactuals, in much the same way they assess a policy scenario in ex-ante mode.

Figure 9: The policy cycle (Adapted from Mercure, 2022[23]).



How clear are the policy questions?

Just as we know the policy process is not as simple as the policy cycle suggests, we know that, in practice, policy questions are not always expressed with clarity or certainty. Moreover, different groups or teams of policymakers may have different questions, and the questions may be contested.[25] Policymakers likely also have a long list of questions at any moment, and it is not always clear which are most important, or which might be most amenable to different methods of analysis. In this situation, it is useful to iterate quickly between policy teams and analysts exploring what type of questions we should focus on and how we should model them.

Systems mapping[26] is useful in this situation. It allows us to quickly describe the policy context and policy, to expose our assumptions to discussion, to start exploring our questions qualitatively, and to do all of this with other policymakers and groups. While this is useful in its own right, it is also much preferable to embarking on a significant piece of quantitative modelling only to realise halfway through that the policy questions were not clear enough, or the modellers had failed to bring along key stakeholders in the analysis. Where there is a lack of clarity on policy questions, we thus often recommend a systems mapping exercise as a stepping stone to more formal analysis.

[23] Mercure, J-F. (2022). Complexity Economics for Environmental Governance. Cambridge Studies on Environment, Energy and Natural Resources Governance.

[24] This point is further discussed in our previous report Ten Principles for Policy Making in the Energy Transition, pages 13 and 37. https://eeist.co.uk/eeist-reports/

[25] Royston, S. et al. (2023). Masters of the Machinery: The politics of economic modelling within European energy policy. Energy Policy 173, 113386

[26] Barbrook-Johnson, P. and Penn. A (2022). Systems Mapping: How to Build and Use Causal Models of Systems. Palgrave.

What are 'new economic models'?

What is 'new'?

'New economic models' could simply mean those that have been developed recently, but here the 'new' refers to models directly informed by the theory and methods of complexity economics and systems thinking. These academic disciplines are not brand new, but their application to an increasingly broad set of economic topics and the use of fine-grained data (i.e. firm level, different consumers, more granular technologies, more frequent temporal scales) is only just beginning. Together, they give us the conceptual frameworks and methodological approaches to address the issues identified in Table 1. They allow us to develop: models which capture disequilibrium,[27] path dependency,[28] self-reinforcing change and feedback loops,[29] and tipping points;[30] models which emphasise difference and interaction between economic agents; and models which allow for bounded rationality and decision-making rules of thumb.[31] These can be seen as extensions and complements to existing methods that are often dominated by assumptions of clearing markets in equilibrium, representative and homogenous agents, and perfect knowledge, rationality and optimal decision-making features.

Different types of models

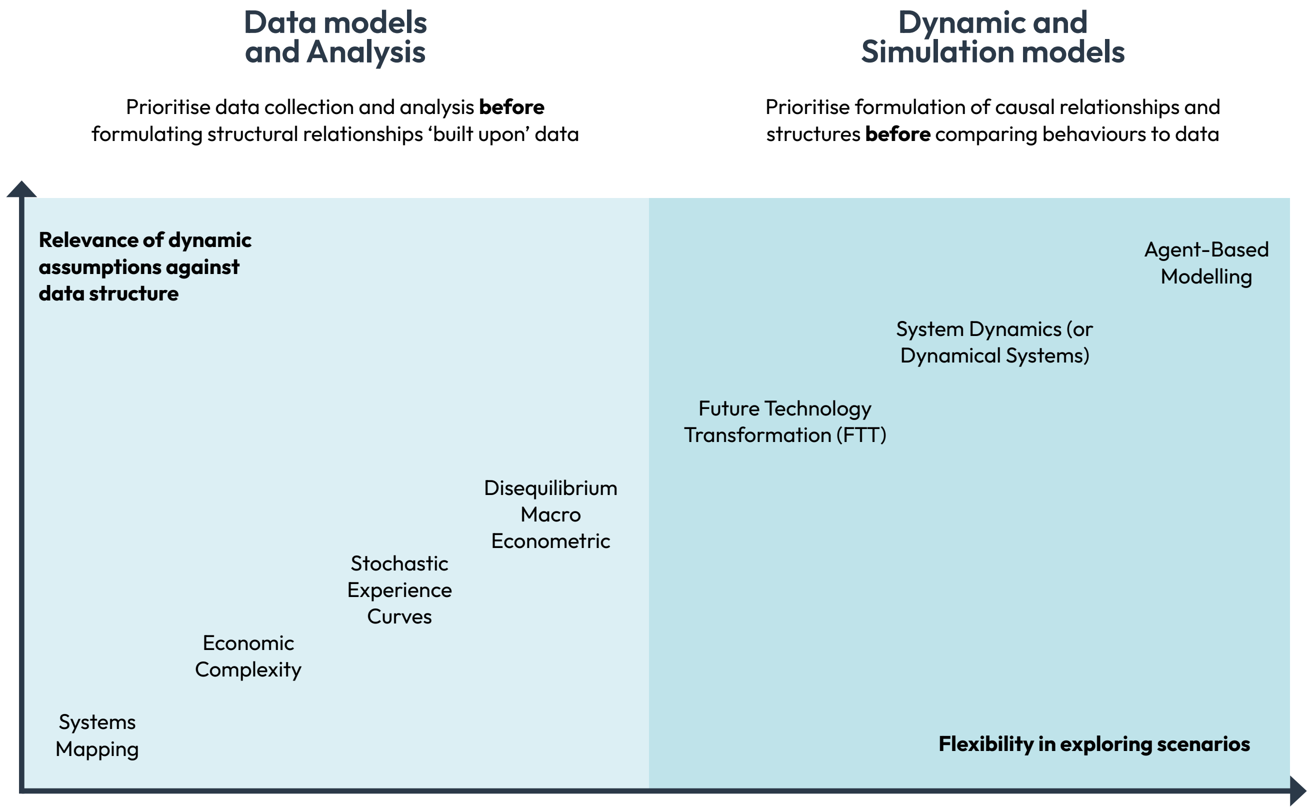
This report draws on a variety of different models that can be hard to categorise. An important distinction is between 'data' and 'models'. Put simply, 'data' are measurements from real-world indicators; they provide context to the specific case under study and provide an anchor to the description of the real-world phenomena. 'Models' represent an explanation of the behaviour of data from a conceptual perspective – an exploration of possible future performance of these data – and are often based on assumptions that are idiosyncratic to a specific methodology. The combination of models and data can provide an analysis on a case-by-case basis and, most importantly, can allow models to challenge past performance in systems, and propose predictions on future behaviours in certain conditions.

We can differentiate new economic models between those that are based directly on data (e.g. apply analytical and statistical methods on existing data to make extrapolations to the future) and those that aim to mimic the functioning of the real world via dynamic simulations (e.g. structural relationships expected to carry meaning relative to the functioning of real phenomena) and informed by and compared with data.

In most cases, models tend to be hybrids of the two, combining elements of both data analysis and simulation modelling. However, for the purposes of enumerating a list of new economic methods, we can divide them into two categories based on their preference in formulating model structures and using data – see Figure 10 and Table 3 for overviews.

[27] In an economic context, it is simplest to think of this as models not characterised by return to equilibrium states, or using market clearing assumptions.
[28] Path dependency is often encapsulated by stating 'history matters'. That is, where a system has been and where it is now, constrain future directions and possibilities.
[29] Feedback loops, where an increase (or decrease) in one factor increases (decreases) another, which in turn increases (decreases) the original factor, create reinforcing or 'runaway' change.
[30] Owing to the proximity to a tipping point, small changes in a system or model can produce large or qualitatively different outcomes.
[31] Any individual model may not explicitly try to include all these aspects. This can make a model unmanageable or difficult to understand, though these trade-offs are becoming less pronounced with advances in methods.

Figure 10: Broad types of new economic models: As we move from left to right, we move from approaches which are based on looking for structure or patterns in data, through to approaches based on building structures in simulations and testing these against data. The vertical axis emphasises the importance of assumptions and theory used in approaches, which also increases as we move from left to right.



These two categories are:

1. **Models that prioritise the analysis and understanding of data before the attempt of developing model structures to explain those data.** Here, we include 'data models', often constrained by static assumptions (i.e. assumptions which do not change, or which are based on snapshots in time) – distributed on the left side of Figure 9 – and the 'disequilibrium macro-econometric' models, which, despite prioritising the analysis of data to build formal relationships, can also integrate new dynamic assumptions of real-world systems linked to non-linearity of future performance of systems.
2. **Models that prioritise the formulation of model structures to explain past events and data.** We can refer to these more generally as 'dynamic and simulation models' comprising the families of dynamical systems modelling, system dynamics models and agent-based models. The logic of these models implies that the awareness of data patterns of the past can help in identifying causal structures (of often difficult-to-quantify variables, e.g. social behaviours) that can then also be informed directly by data (i.e. parameterisation) and compared to existing time series via simulations (i.e. validation). It is worth noting that all models and methods that are built to have impact on real-world policies make use of existing data.

Table 3 further describes these classes of approaches, specifying individual modelling methods and their advantages and disadvantages.

Table 3: Specific examples of new economic models.[32]

Type Data models/analysis

Name	Description	Advantages	Disadvantages	Example case studies
Systems mapping	Uses networks to represent and analyse causal influence between factors in a system. Often used in stakeholder engagement activities.	Intuitive and accessible way of representing a range of relationships and influences in systems. Useful for identifying the dynamic effects of policies, such as differentiating between those that will be self-amplifying and those that will be self-limiting. Can utilise many sources of evidence and data. Less resource-intensive than building a simulation, but can also inform the development of dynamic models.	Though the model tries to capture feedbacks and dynamics, the model itself is static (i.e. does not explore how structure might change, or how the dynamics play out). Large maps can become unwieldy and hard to understand.	Qualitative systems mapping of ETS and carbon tax in China Data-driven systems mapping of SDGs and the energy transition in Brazil
Economic complexity[33]	Uses trade data and the economic structure it reveals to understand the direction in which an economy may be able to develop comparative advantage.	Helps understand an economy's current position and 'adjacent possible' (i.e. plausible product transition pathways). Can be used to inform industrial strategy or development strategy.	Suggests where a country could develop competitive advantage, but does not suggest how. Only based on export data, so internal consumption is missed..	Green complexity measures used to understand Chinese green technology exports
Stochastic experience curves	Uses Wright's and Moore's laws to make forecasts of energy technology costs based on past trend in deployment (or time) and costs.	Produces empirically validated probabilistic forecasts of energy technology costs. Method well-tested on a wide range of technologies and compared with expert forecasting methods.	Currently only implemented at global level. Provides no insights on why these changes are happening.	Empirically Grounded Energy Technology Cost Forecasts uses this method and plugs results into a simple energy system model.
Disequilibrium macro-econometric - E3ME[34]	Represents relationships between different economic variables and sectors as a set of equations, based on historical data patterns. Econometric model.	Can be used to identify likely macroeconomic outcomes of low-carbon transitions. Unlike CGE and DSGE[35] models, is unconstrained by restrictive assumptions such as optimal allocation of resources and full employment. Well used and documented.	A relatively aggregated model. It is not suitable to model dynamics emerging from interaction of individual heterogeneous agents. While it is not constrained by restrictive assumptions, it does not include a restriction per se on accessibility of finance, which in reality can be a constraint. Heavily dependent on data and data quality. It is not able to simulate sudden systematic change.	All E3ME-FTT case studies.

Type Dynamic and simulation models

Name	Description	Advantages	Disadvantages	Example case studies
Future technology transformations (FTT)	Uses equations that describe the S-curve of technology uptake with Wright's law. Makes forecasts of energy technology diffusion and costs, taking into account the self-reinforcing feedbacks between deployment and costs.	Can be used to simulate and predict the dynamic effects of policies – for example on technology diffusion and costs. Can test a variety of policy options and can show which policy combinations achieve more than the sum of their parts, and which achieve less.	Has limited between-sector interactions, and limited interaction between demand-side policies (in E3ME) and supply-side policies (in the FTT models)	All E3ME-FTT case studies.
System dynamics modelling (and dynamical systems modelling)	Simulation approaches which represent multiple components and structural dynamics of a system. Can simulate disequilibrium behaviour via reinforcing loops and non-linear relationships. Can capture tipping points.	Represent non-linear and disequilibrium aggregate dynamics of systems. Useful for distinguishing between policy approaches that are self-amplifying vs self-limiting, and for identifying trade-offs and synergies between policies in different sectors, or between economy, society and environment. Well-established community with norms around methodology.	Aggregated model - it is not suitable to model dynamics emerging from interaction of heterogeneous agents. Requires the dynamic structure of the system of interest to be known in advance.	System dynamics model of energy transition in India Green finance model in UK
Agent-based modelling (ABM)	Simulation method representing individual agents, their interaction with each other and their environment. Can generate emergent properties in complex systems.	'Best-in-class' structurally realistic representation of complex systems. Can show how agents such as different types of consumers, firms or investors may act in response to policy. Can be used to discover the dynamic structure of an economic system when this is not known in advance (identifying system behaviours that emerge from the interactions of different economic actors and policies). This can help to inform choices of market design.	Data-hungry (i.e. requires fine-grain data for setup, and time series data for validation), sometimes computationally heavy (i.e. slow to run). Technically difficult and time consuming to develop (e.g. difficult to trace causes and consequences of emergent phenomena).	Labour market ABM models workers as agents moving around the Brazilian labour market. Macroeconomic ABM used in Policy Options for Rapid, Smooth Decarbonisation and Sustainable Growth China carbon pricing ABM of the power sector.

[32] Most of the case studies in this report fall neatly into one of the categories in this table or are a hybrid or combination of categories. However, one does not. Modelling Sector Coupling of Hydrogen and Ammonia in India presents a 'complexity-extended' traditional energy system model, which we do not give its own category here.

[33] 'Economic complexity' here refers to the specific stream of literature on using trade data to understand the sophistication of different national economies. It is an unhelpful term because it is so generic and often confused with 'complexity economics', but it is the recognised term for this work, so we use it.

[34] Technically, E3ME and FTT are specific models, not classes of models. However, owing to their central position in the EEIST project, and new economic modelling more broadly, we give it its own category here.

[35] Computable General Equilibrium and Dynamic Stochastic General Equilibrium models. We do not introduce these well-known approaches here. For an introduction see Burfisher, M. E. (2011). Introduction to Computable General Equilibrium Models. Cambridge University Press and Wickens, M. (2012). Macroeconomic Theory: A Dynamic General Equilibrium Approach. Princeton University Press.

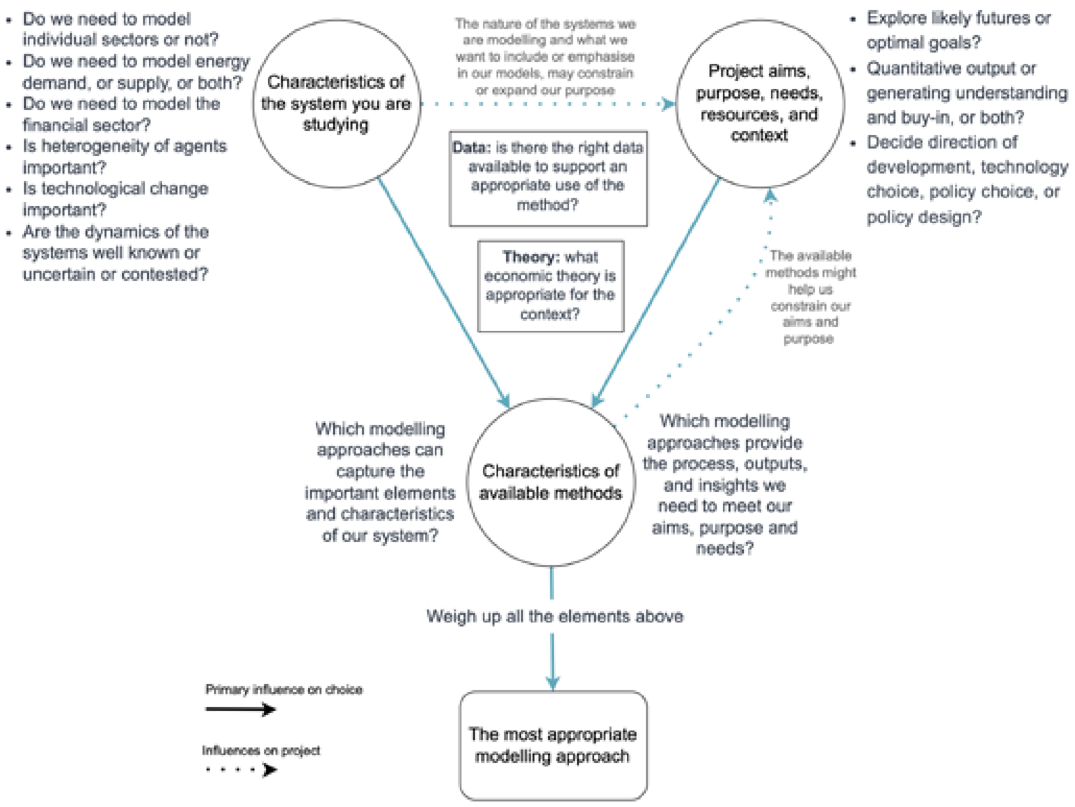
How to choose and use new economic models

Now we have a sense of what new economic models are and the types of policy questions they can be put to, in this section we outline how we can begin to make choices about which methods to use and how to start using them in practice. These choices need to be made with all methods, new or not, but since the approaches we outline in this report are less well established than others, it is worth considering these issues in detail.

Choosing the most appropriate modelling approach

There is rarely a simple best-worst choice when selecting modelling approaches to use. There will be methods that are inappropriate given specific questions and purpose, and among appropriate choices, there will be pros and cons that differ in different contexts. The trick is to find the most 'appropriate' approach given the purpose, aims, resources, data available and context – and given the characteristics of the economic and energy systems being represented. Even when taking all of those into account, there may not be an obvious choice. Where time and resources allow, it is often beneficial to deploy or combine multiple methods. This has the additional benefit of providing an indication of the robustness of results – i.e. are they the same across different methods?

Figure 11: Aspects to consider when choosing the most appropriate modelling approach.



Project purpose and aims (summarised in Table 4): These can be very different from one project to the next, and purpose can also evolve through time or be seen differently by different actors. Nonetheless, at their core, all energy transition modelling projects need to be clear on a variety of purpose questions. For example:

1. Are we trying to identify a desirable end state for the transition, given some constraints, or are we trying to identify policies that will help us get there?
2. Which do we value more: (i) a quantitative output, (ii) generating stakeholder understanding and buy-in, or (iii) both equally?
3. Are we most interested in informing development direction, technology choice, policy choice or policy design?

Beyond the immediate purpose, there is also the project resources and contexts, the needs and objectives of other stakeholders, and the availability and quality of data. These all interact with our intentions for the purpose of the project, constraining or augmenting it in different ways.

For example, the stage we are at in the policy process may affect choices. If a policy is in the early stages of being designed or discussed, we may have a more 'exploratory' purpose, which opens up more options and allows us to experiment with new methods. Whereas, if a policy design is set, and we want to appraise it in detail, or we want to understand what impacts an existing policy might have in the coming years, we will have a narrower purpose focused on exploring likely futures in detail. This will mean we are much more likely to want a tried-and-tested approach.

A key resource is data. Many modelling approaches are data-hungry and rely on the right data being available. The usefulness of models for different purposes often goes up and down with the quantity and quality of data we have to initiate and validate models. However, some methods are better suited to working in low-data contexts. When we do have data, overfitting of models (i.e. producing a model or analysis that corresponds to one particular dataset well, but not to others, or performs badly in forecasts) is a common problem to both new and traditional methods. This can happen when there are specific problems with the methods themselves being susceptible to overfitting. It can also occur where there is insufficiently developed understanding of the underlying social phenomena, leading to limited (or no) generalisability in contexts where social and economic relations are somewhat different.

Table 4: How aspects around project purpose shape the most appropriate modelling method.

Aspect	Potential situation	Most appropriate method/model
Purpose and aims	Explore likely effects of policies	Bottom-up or structurally realistic models, such as E3ME, ABMs, energy system models.
	Optimal outcomes	Process-based integrated assessment models.[36]
	Understanding, policy choice and buy-in	Simpler or qualitative models, such as systems mapping.
	Detailed policy analysis	Models which can represent different policies in precise and meaningfully different ways, such as FTT or very applied ABMs.
	Broad system behaviour	Simpler models, such as System Dynamics models, or relatively simple energy system models.
Time and money resources	High resources	Larger models such as E3ME or ABMs.
	Low resources	Relatively simpler models such as System Dynamics, systems mapping, or larger models which already fit needs closely.
Data available	Data-rich	Data-hungry models such as applied ABMs, data-driven systems mapping.
	Data-poor	Qualitative models such as systems mapping.
Context	Early in policy cycle	More scope for different methods and those less well-established; value in models that increase understanding of the behaviour of the system.
	Late in policy cycle	Pressure to use tried-and-tested models and those with quantitative outputs; greater need for specificity in policy options to be tested.
	Contested policy area	Methods which allow us to question assumptions and build buy-in, such as systems mapping; value in use of a range of models, to compare outputs with different assumptions.

[32] 36 These are the more detailed cohort of IAMs, such as AIM-Enduse, GCAM, IMACLIM, IMAGE, MESSAGE-GLOBIOM, and REMIND. For a discussion of these models, see: Wilson, C. et al. (2021). Evaluating Process-based Integrated Assessment Models of Climate Change Mitigation. Climatic Change. 166.3.

System characteristics: the energy transition is impacted by, and itself impacts, many different economic, social, ecological and technological systems. We rarely need to model all of them, and when we do, we will model some in more detail than others. We may also want to model them in different ways (i.e. representing different elements in different ways, or emphasising some parts over others) depending on our aims and how important we think specific characteristics of the systems are to our questions and purpose.

There are several sets of structural questions we should regularly ask ourselves when deciding which things to model in the energy transition:

1. Do we need to be modelling individual institutions, technologies or economic sectors, or can we aggregate them? Relatedly, is technological change important? Do we need to separately consider knowledge or technology developments outside the energy sector? Do we want to model scenarios or policies with sector-specific changes, or do we want to understand sector-specific impacts? If yes, include sectors, if not, we may be fine simplifying them away.
2. In how much detail do we need to model energy demand and energy supply? Or put another way, in how much detail do we need to model the energy system and the economy? It is likely we want to focus on one or the other, and we should not be afraid of using a simple model of one, when our focus is really the other.
3. Do we need to model the financial system? Do we believe the process of acquiring credit, or investment, is important in system behaviour? Can we do useful modelling without including the financial system?

There is also a second set of grouped questions, about how we model the systems we want to cover:

1. Do we need to model heterogeneity and interaction between actors such as consumers, firms and investors, or can we aggregate their behaviour within each of these groups? If yes, then we should probably model them, if not then we may be fine to simplify them away.
2. Do we want to model a (sub)system endogenously or exogenously? Put another way, do we want to model the internal dynamics of a (sub)system and how it is affected by other things in the model, or can we simplify it away, or treat it as static? For example, do we want to model technology innovation? Key issues here include whether we have good data and understanding of a sub-system, and how important it is to our questions or important in system behaviour. We may want to represent it endogenously and capture feedbacks between it and other parts of our model.
3. How do we want to model human behaviour and decision-making: using rational expectations, or with bounded rationality or other social rules or decision-making heuristics? Do we believe a rational expectations model of decision-making is appropriate to our context, or does it systematically miss important decisions/dynamics?
4. Which behavioural characteristics of systems – i.e. path dependency, emergent behaviour, technology complementarities and dependencies, tipping points or feedbacks – do we want to capture? Are there particular concepts we think are driving behaviour in the system and we want to understand in detail? For example, path dependency, feedbacks or tipping points.
5. How should we capture uncertainty? For many contexts, 'model structure uncertainty' can be more important than 'parameter uncertainty', so choosing a modelling approach that can represent and incorporate the former can be important. Sensitivity analysis then becomes a key tool for exploring model structure uncertainty.

Finally, it is often vital to keep in mind whether the dynamics of the system in question is well known, uncertain or contested. This can have implications for the methods that are most appropriate. Where the dynamics are contested, we might want to use a more qualitative or participatory method to help resolve open questions with stakeholders, whereas where dynamics are well agreed, we are much more likely to be able to use a quantitative simulation method successfully. Project purpose plays a big role here and should ideally always be cognisant of the status of perceptions of system dynamics and behaviour.

Reflecting on prediction, forecasting and empirical validation

In many contexts, modellers and policymakers are interested in using models to forecast how policies will affect outcomes. Having a clear understanding about expectations on forecasting and prediction is vital – users can often have different expectations about whether models can or should be used in this way. Before we can discuss this, we need to define our terms and acknowledge that they are often used in different ways. By prediction, we mean an attempt to reduce randomness by narrowing down the possible states of the world. A prediction is a statement about the likelihood of different states; it need not be about the future. For example, the ideal gas law allows us to predict the pressure of a container of gas at a given point in time if we know the volume at that same point in time. A forecast is specifically a prediction of the future.

Empirical validation can refer to many different approaches to testing if a model is giving good predictions or forecasts. We can do this by ensuring the design of the model makes sense, given some data or theory we have about the mechanisms and structure of the system. We can also validate by testing the model outputs against real data, to understand how well it forecast or predicted them. The balance between these two types of validation is often debated.

Predictions are valuable only insofar as they are accurate. This means that empirical validation is essential. Until we validate a model by using it to make predictions and testing their quality, we have no idea if it is of any use. It is essential to test against obvious benchmarks, such as random guesses, and it is surprising how many economic models fail to beat simple null models.

Models are useful for more than predictions. In many cases we may want to use a model to understand the logic of a given system. How does each part of the system affect the other parts? Sometimes qualitative models provide a good way to get started. But as modelling develops, we often want to make our models more quantitative and to make them more reliable. The key role of empirical validation is that it helps tell us whether a model has any realism – where realism is claimed, we should be suspicious of analysis based on models that do not make good predictions.

From this perspective it is important to distinguish how well a model fits data in-sample from how well it predicts data out-of-sample. By 'in-sample' we mean data that was available when the model was built and that was used to estimate its parameters. In contrast, 'out-of-sample' refers to new data that was not available when the model was built. Overfitting is the situation in which a model fits data well in-sample but produces poor predictions out of sample. From this point of view, it is often the case that a simpler model is better, it is less likely to be overfitted because it has fewer parameters to fit.

Overfitting is not just about prediction. For policy evaluation, it is always tempting to assume that complicated models that fit the available data well are more realistic, and therefore should provide better answers. However, a measure of a model's realism should not only be its design, but also the quality of its predictions. With this in mind, simple models are often more reliable, even for policy analysis.

Economic modelling is hard, so we should expect that making good predictions will require a great deal of time and effort. We are unfortunately often forced to make important decisions based on inadequate models. Our philosophy is to test models extensively where appropriate and be clear about their accuracy, managing expectations so that the user understands what a model is intended for and how reliable it is.

How to begin using these approaches

Our intention is that economists, analysts and policymakers in national governments, multilateral organisations, the private sector and civil society make more use of the modelling approaches presented in this report. There are great opportunities to develop new and timely analysis, and a growing demand for this work.

There are also potential conceptual, practical and institutional constraints that may be encountered. We have encountered these ourselves, along with our collaborators and have begun to think seriously about how to overcome them on more than just an ad-hoc basis. In this section, we consider what the barriers might be and how we can overcome them, to apply new economic modelling to generate the most value in the right settings.

Potential constraints:

The central conceptual constraint is likely to be a perception that new economic models are in direct competition with existing approaches. Existing economic approaches have been successful in many domains and are valued for their clarity and apparent quantitative rigour. Economics holds an extremely influential position in policymaking, relative to other social sciences. It also has an established set of principles and tools embedded in training and education, so has many proponents in treasury ministries, government departments and international organisations.

What matters is choosing the economic theory, models and decision-making frameworks that are appropriate for a given purpose and context. Rather than setting up different economic approaches as competitors or rivals, it is more productive to see them as complements, to be used in different contexts, depending on our purpose and how appropriate they are as theoretical lenses, or analytical tools, to the questions at hand.

Nonetheless, people advocating for new economic models are likely to encounter pushback from some economists and (more broadly) modellers, and should be ready to engage in detailed conversations about the pros and cons of using these approaches and how they sit together. In Table 5, we attempt to outline these and some of the potential constructive responses.

Practical constraints are normally more important to the quality of work we can do with new economic models than conceptual constraints. The primary practical constraint is often data. The modelling approaches presented here, especially ABMs, are data-hungry; that is, they require a lot of data, often disaggregated and through time, with which to initialise, calibrate and validate. The appendix outlines the exact data requirements of many of the case studies in this report, which we hope is useful to get a precise sense of what we mean by 'data-hungry'. Even where models are not data-hungry, they may require different data to other models, which are not immediately accessible.

Table 5: Common pushback on new economic modelling.

Pushback	How to respond and generate a constructive discussion
New economic modelling critiques a 'straw man' of economics and many of the criticisms have been addressed in recent work (i.e. critiques are made on outdated vision of mainstream economics).	This is the most important pushback to address. In whatever specific context or issue this is raised, attempt to dig deeper, to understand what the recent work is and whether it does address the critiques that new economic modelling makes. A common issue is confusion about the purpose of individual modelling projects, which clouds the discussion. Many debates can be diffused by making clear that the purpose of new economic modelling is often different to existing approaches. It is also common for misunderstandings to arise here, around terminology or use of concepts, so digging deeper and comparing approaches carefully is a vital first step. It is also often the first step to new approaches being used.
Existing economic assumptions and frameworks have been valuable so we should not get rid of them.	We are not advocating for the abolition of existing work, rather for selecting approaches that are appropriate to the contexts in which we use them. In contexts where transformational (i.e. whole-system) or structural change is needed or under way, analysis which relies upon assumptions of marginality (i.e. interventions will not affect technological capabilities, market structures or the wider economy) are not appropriate. Thus, when we are modelling the energy transition, which represents one of the primary examples of transformational change, we should be extremely careful about using marginal approaches.
New economic models are not well tested or trusted.	The complexity economics and systems approaches we present in this report have been well-tested over the last 10 years in a range of policy domains. However, it is fair to say many of the techniques we are advocating for are not well established in energy and climate change policy. However, there is a clear need for policy to make faster progress on low-carbon transitions, the limitations of currently dominant approaches are well documented, and there are strong theoretical reasons to believe that these new approaches will have significant advantages. The influence of these approaches in decision-making and the number of proponents working in national governments and international organisations is increasing. This report provides examples of these approaches being used with policymakers in important contexts. Major organisations making use of new economic models include: the UN, the OECD, the EU, the World Bank, China's Energy Research Institute, the World Resources Institute, the Bank of England, and the UK government's business and energy department.

Beyond data, new economic models may not produce the same types or precision of outputs that organisations are used to (e.g. estimates of particular indicators or variables, or plots). However, some of the precision from established methods can be illusory. New economic models are often stochastic and/or systemic in their approach and favour exploring uncertainty, so will provide ranges and estimates of outputs, not point predictions. This in turn requires a more probabilistic approach to further analysis. Before using a new method, check what outputs it produces and in what form, and think about how these might be used in organisational workflow.

Institutional constraints are a combination of practical and conceptual constraints that apply to specific organisations. Some institutions are inherently risk averse and may avoid using methods which are perceived as untested or which may be less efficient than using a method already used or well understood. Organisations may favour 'multi-purpose' models with wide applicability, since they are easier to keep and maintain than specialist models where resources and skills to maintain them, or commission when needed, will be rarer.

Organisational cultures, training and structures may also be built around an existing method or model; there may be infrastructure built up to enable its use (e.g. team structures, training, job roles dedicated to parts of models, regular reports and events organised around analysis timetables). There may also be many modelling efforts being run in parallel which are later brought together (for example, running economic forecasts at short, medium and long-term timescales). Swapping in new approaches for one of these strands may make them incompatible. These can be very serious barriers, which no method could overcome if they are seen as a direct replacement. In these situations, working in parallel is often the only way forward, but can be seen as unnecessary additional work.

How to proceed?

Given the clear opportunities, and the potential constraints, how can we proceed with adopting and using new economic modelling approaches? Here is a tentative list of suggestions based on our learning:

1. Start small and ramp up. Use pilot studies and small projects focused on specific policy questions of interest to show how new economic models can add value. This will allow organisations to learn and incrementally build up.
2. Systems mapping as an entry point.[37] Use systems mapping, an intuitive and easy-to-start method for exploring topics, to analyse the dynamics of a policy problem. This can open people's eyes to the complexity of a topic and how to think about it differently. Systems mapping, when well executed, can (i) inform policy directly, without needing a quantitative model to be built, (ii) show why disequilibrium models may be useful and (iii) be the first step in moving to a quantitative new economic model.
3. Become an advocate. Build a coalition of advocates (or users) in and around your organisation, connecting likeminded people. Practice and get used to articulating the value and complementarity of these approaches on terms that make sense to others, not just existing supporters. Build legitimacy and credibility around these methods, through pilots and partnerships with external groups who use them. Gather examples from elsewhere, of where these methods have generated value (this report, for instance).
4. Build capacity and expertise. Organisations working on the transition need people who can use these methods. Think about the training and capacity building they need to do this and how organisations can provide or access it. Consider how to fine-tune hiring or procurement processes to encourage people interested in these methods.
5. Develop bespoke guidance. There is already generic guidance out there, but bespoke guidance for individual organisations will be useful too. In particular, we recommend developing guidance for policy analysis that distinguishes between principles and tools appropriate for marginal change, and those appropriate for non-marginal (including transformational) change.

[37] Here, we are referring to the specific method 'systems mapping' (see Barbrook-Johnson, P. and Penn, A. 2022. Systems Mapping. Palgrave), but this could also apply to systems thinking more widely. For an introduction for civil servants, see https://www.gov.uk/government/publications/systems-thinking-for-civil-servants

EEIST

Economics of Energy Innovation and System Transition

The Economics of Energy Innovation and System Transition (EEIST) project develops cutting-edge energy innovation analysis to support government decision making around low-carbon innovation and technological change. By engaging with policymakers and stakeholders in Brazil, China, India, the UK and the EU, the project aims to contribute to the economic development of emerging nations and support sustainable development globally.

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