



DECIPHER

Holistic decision-making for climate & environment

D4.1

Understanding the limitations of existing
economic theory, methods and models

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Scope of the document	This task will identify the main shortcomings of current theory in the context of the policy decision making frameworks designed in WP5 and applied in WP6. The Task will take stock of the dedicated engagement of stakeholders in Task 1.2. It will compare these shortcomings with insights from more recent branches of economic theory, including ecological economics, behavioural economics, evolutionary economics and complexity economics. The Task will assess examples of relevant existing models and how consistent the theories' underlying assumptions are with current approaches. The task will cover a range of different impact areas from the social, economic and environmental pillars of sustainability. Examples include gender effects, unemployment and labour markets, structural change, financial risk, innovation, human



health and 'non-economic' factors that are typically excluded from models. These impact areas will be considered in the context of dynamic transition, for example including behavioural change, innovation rates, irreversibility, heavy-tailed uncertainty, and systemic risk. The main output of this task will be a description of shortcomings in current theory and models (including full descriptions of the current models used by the consortium), suggestions for advancing the theory and potential areas for developing new and existing modelling tools.



EXECUTIVE SUMMARY

Policymakers rely heavily on complex models of the environment, economy and energy sectors, as they provide economically meaningful intuition on the implications of various energy and climate policy interventions. The purpose of this study is to review and identify the main shortcomings of existing applied economic methods and models that are used for applied energy and climate policy analysis. The report reviews the existing models and associated modelling approaches and focuses specifically on two of the major models used for policy support included in the DECIPHER consortium (the GEM-E3 and the E3ME).

We focus on aspects of the models that are particularly relevant for questions usually made by the policy makers that require advancements to the modelling tools before a satisfactory answer is possible. The analysis on the shortcomings of the two models is complemented by providing suggestions for specific model improvements. These suggestions are based on already available published studies.

Decarbonisation needs to be accelerated by a factor of five to meet the targets of the Paris agreement. To achieve this, knowledge must be drawn together from a large set of sources. We review the latest developments in four recent branches of economics namely: ecological economics, behavioural economics, evolutionary economics and complexity economics, which **can provide useful insights regarding the interdependencies and adjustment of the economic system**. Ecological or biophysical economics provides insights into the biophysics limits that underpin the transition. Empirical evidence from behavioural economics can validate models, to increase the ability to model behavioural change. Evolutionary economics incorporates innovation, while complexity economics is a data-driven way of looking at the economy and its emergent behaviour.

We explore six themes that play a significant role in the low carbon energy transition: labour, behavioural change, finance, innovation, uncertainty and systems thinking. For each theme we do a literature review, drawing among wider literature on the four strands described above. For each theme, we signal possible improvements to the existing theory and models. For labour, we suggest an increased focus on the availability and creation of skills for the transition. We suggest improving the representation of behavioural change, to account better for demand-side policies, which are often modelled in inadequate detail, compared to supply-side policies. The representation of finance can benefit from a more detailed evaluation of country and technology risk. We suggest operationalising uncertainty quantification, so that the resilience of policies to shocks and other unpredictable elements of society can be better quantified. Not all dynamics can be captured well by large-scale economy-environment-energy (E3) models. For instance, the feedbacks between policies, the



support they have from the population, which impacts the robustness or long-term success of these policies. with system dynamics models or agent-based models.



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LIST OF ACRONYMS AND ABBREVIATIONS

Acronym	Long text
3E	Energy-economy-environment
CGE	Computable General Equilibrium
EROI	energy return on investment
ESMs	Earth System models
FTT	Future Technology Transformation
ILO	International Labour Organization
IO modelling	Input-output modelling
IO	Input-output
MS	Member State
NUTS	Nomenclature of territorial units for statistics (NUTS2 is regional)
OECD	Organization for Economic Cooperation and Development
OECD Stan	OECD STructural ANalysis Database
SD	Systems dynamics
SFC	Stock-flow-consistent



Introduction

To mitigate climate change, the energy system needs to be transformed drastically. This transition is a complex and challenging structural shifts.

Macroeconomic models for climate & energy policy analysis are designed to allow a transparent analysis of the wider shifts in the economy from policy, so that stakeholders can have a clear picture of the mechanisms that affect the system and ranges of possible future states of the economic system. To achieve the low carbon energy transition, a set of policies is required, including support for green innovation, carbon pricing, sustainable public procurement, and a regulated phase-out of polluting technologies. These policies affect all aspects of economic activity through multiple interconnected channels. The shift towards a low carbon / carbon neutral economy is often associated with job loss in energy-intensive sectors and job creation in green sectors. Policies crafted to target a decarbonised economy and net-zero emissions should mobilise funds and investment to support the transition. This appears to be a challenging task for policymakers since the type of instruments, the timing and the mix of recipient sectors is not a straightforward choice. Another aspect to consider is the potential distributional effects that these policies have on households, and how financial resources can be mobilised towards more sustainable innovations and investments.

The energy transition is quickly evolving, which corresponds to a change in research questions asked by policymakers. Large, coupled energy-economy models play a major role in supporting decision-making processes at the national and supranational level. For instance, they were used to justify the ambition level for energy efficiency in 2014 in the European Union. They were also used in the assessment of the European Green Deal and the EU Climate Target Plan impact assessment (Royston et al., 2023). In this review, we examine recent strands of energy transition literature and the gaps and limitations in economic models within this literature.¹ We then describe opportunities to make the models more relevant to open questions around energy policy, by incorporating insight from a broad range of disciplines.

Public policies are typically concerned with the consequences of the energy transition, as well as to ensure a smooth transition in terms of economic and social adjustment. It is worth noting that crucial themes in the current public debate and literature on energy transitions emphasise the impact of the transition on capital and labour markets, as well as innovation, as these areas appear to be directly affected by green policies.

¹ See the Appendix for a detailed description of the main limitations of the existing models.

The research agenda on energy transition covers a wide range of topics, including uncertainty and the behavioural changes induced by the transition. It also explores whether increasing the complexity of economic models can help answer relevant questions related to the green environmental transition. Here, we list different strands of energy transition literature. We begin with the literature that evaluates the effects of the energy transition on labour markets. We review the relevance of behavioural economics, in particular with respect to the feasibility of energy demand reductions. We also explore the role of climate finance on the energy transition, with a discussion of (induced) innovation and its role in decarbonisation. Finally, we present a broader discussion of feedbacks, uncertainty and dynamical systems.

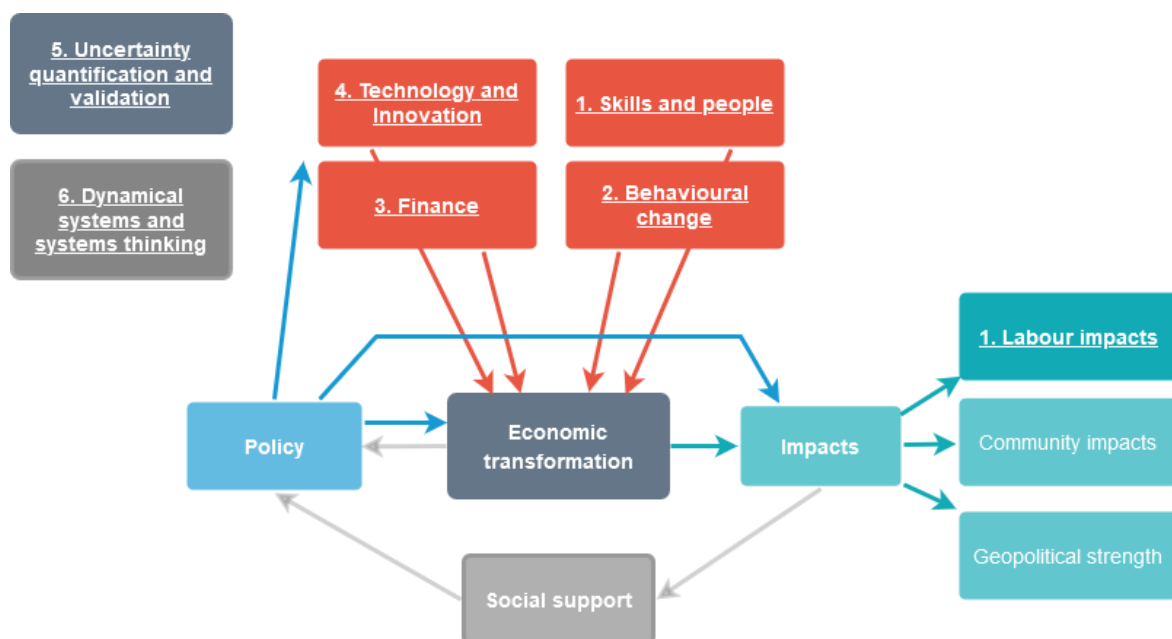


Figure 1. Connections between the thematic literature review elements. Energy policy modelling covers the decisions by policymakers, which drives economic transformation, leading to various impacts on society. We cover a set of key topics where model improvements are desirable: the impacts on the labour market, the barriers from the labour market (e.g., skills), behavioural change, finance, and technology and innovation. The last two elements of the literature review cover the modelling more broadly: the need to validate and report more systematically on (limits) to understanding, and the way in which systems thinking and dynamical systems models can complement and enhance large macro-economic models.



Types of knowledge necessary for a rapid transition

The energy transition needs to be accelerated by a factor of five to stay within the Paris goal of 1.5C (Sharpe, 2023). To do this, there is a need to use all available knowledge in the economic literature to give the best advice to policy makers. As well as improving existing methodologies, we also have to start including knowledge from recent branches of economics. We start by highlighting four branches of economic thought whose integration into policymaking can contribute to this acceleration. In the thematic literature review below, we put extra emphasis on literature from these more recent branches of economics.

Ecological economics

Ecological economics is a branch of economics that has classically looked at the biophysics of socio-ecological processes. In particular, it looked at ecosystems (which includes the economy) from a perspective of energy and entropy. Organised ecosystems have low entropy, which dissipates inevitably over time from economical processes. Later, ecological economics transformed into a branch of economics embracing pluralism. The questions formerly asked by ecological economics, were now answered by biophysical economists. Ecological economics started accepting paradigms from classical economics more, for instance by calculating the “monetary value” of ecosystems. Still, ecological, and biophysical economics are highly relevant to the question of the energy transition, especially on the analysis of EROI (energy return on investment) (Melgar-Melgar & Hall, 2020). Ecological economics also considers the questions of post-growth or degrowth, flowing from the limitation on resources made explicit in ecological economic models (Spash, 2023). A key example of an ecological model is described in Naqvi & Stockhammer (2018), which among other aspects incorporates the role of finance and financial institutions in a stock-flow consistent model of the energy transition.

Behavioural economics

The field of behavioural economics is rapidly growing, this research area basically incorporates human psychology into the foundation of economic theories and introduces normative assumptions to explain the causes of behavioural phenomena. Behavioural economics research proposes theories that offer behavioural



explanations for empirical facts and observed irregularities in the data. It employs various research methods, such as field experiments and field data, to explain agents' behaviour. Among the most important contributions of behavioural economics to the mainstream economic field, without aiming to be exhaustive, is the emergence of expected utility as a model for agents' decision-making. The use of this theory aimed to understand what factors drive agents' choices regarding consumption, savings, and investment. Another significant contribution is the notion of preferences under uncertainty, in this context agents make choices in environments with uncertainty while assuming bounded rationality. Additionally, Bayesian updating serves as another crucial contribution, as this theory assumes that agents make judgments about the probabilities of future outcomes based on their prior knowledge. Finally, behavioural game theory also incorporates psychological elements into economic analysis (Camerer et al, 2004). All these advances in theoretical models that incorporate behavioural elements demonstrate the importance of considering behavioural aspects when designing energy policy, because they can help account for non-rational behaviour and different behavioural responses across agents. Two important examples are proposed by Rengs et al. (2020), who develop a macroeconomic multi-agent model that accounts for behavioural heterogeneity of households, and Cafferata et al. (2021), who build a switching-strategies growth model that incorporate the interaction between agents and their attitudes towards climate policies.

Evolutionary economics

Evolutionary economics deals with questions of (co)-evolution of elements of the socio-economic system. Key components of evolutionary economics, according to Safarzyńska and van den Bergh (2010), are “diversity, innovation, selection, bounded rationality, diffusion, path dependency and lock-in, coevolution, multilevel and group selection, and mechanisms of growth”. Various tools are used, such as evolutionary game theory or agent-based models (Safarzyńska and van den Bergh 2010). Within energy transition literature, evolutionary economics forms the roots of various socio-technical paradigms, such as 'technological innovation systems (TIS) studies', which deals with how new technologies are made and taken up (Cherp et al. 2018). Key examples of the application of evolutionary economics to the energy transition are the Future Technology Transformation models of competition between sectoral technologies (Mercure, 2012).

Complexity economics

Complexity economics deals with questions of emergence and coevolution. Modellers often use simplifying assumptions to make their models tractable and to be able to use data. For instance, they may assume average behaviour rather than diversity in behaviour, and equilibrium assumptions. In complexity economics, holistic tools are sought that include more diversity and complexity. For instance, it's



necessary to include agent diversity to be able to describe evolution in the system. Prime examples of the types of models in complexity economics are network dynamic models and agent-based models (Bale et al, 2015). A key example of a complexity economics ABM is the “Dystopian Schumpeter-Keynes model” (Lamperti et al 2020), which fully couples a climate model to an agent-based macroeconomic model, which is used to describe the chances of success for different transition strategies (Senra de Moura & Barbrook-Johnson, 2022).



A thematic review on shortcomings, and suggestions for advancements

Labour Market Effects and Frictions

Generally speaking, energy transition policies aim to increase the share of sustainable energy and achieve a low-carbon economy through a just energy transition (European Commission and Directorate-General for Economic and Financial Affairs, 2023). In the energy transition, high-carbon intensive industries are expected to decline while low-carbon sectors grow. Accordingly, areas with a high concentration of carbon-intensive industries employing a relatively large share of the workforce are faced with challenges, while areas with many people working in low-carbon industries are more likely to benefit from the shift towards carbon-neutrality (Chen et al., 2020). This poses challenges to labour markets, while the aggregate impact on employment remains uncertain.

Existing model-based analysis suggests that the aggregate impact of the green transition on employment is expected to be positive, with estimates for the European Union ranging somewhere between -0.3% to 1.2% (European Commission, 2021 b,a; Chatzichristou et al., 2021). The range in the aggregate results is, not least, due to varying assumptions in the modelling phase, but also hides stark differences between sectors and regions, determined by the degree of mobility of workers between sectors and occupations, on the one hand, and mobility between regions, on the other hand. The extent to which workers will require re- and up-skilling to provide them with the relevant 'green' skills will vary, as will the degree to which they need to move to different occupations, sectors or locations. Moreover, evidence suggests that, in the absence of policy action, the green transition may contribute to growing income inequality, with high-carbon jobs more concentrated in lower-income areas and lower skilled workers having more restricted labour mobility (Saussay et al., 2022). Restrictions on labour market adjustments, in particular related to lacking wage premia to compensate for skilling investments aimed at generating low-carbon skills, present additional barriers to achieve a just transition.

A recent work by Hanson (2023) investigates the consequences of the post-1980 decline of coal industry in the US on the local labour market given that the fossil fuel-



intensive industries are spatially agglomerated. Using the local projections approach, Hanson (2023) measures the projected employment changes in local markets after the contraction in coal mining from 1980 to 2019.² Other studies contributed to our understanding of the relationship between energy transition and employment. For instance, Popp et al. (2022b), focus on the impact of green fiscal push on employment by investigating the impact of the green American Recovery and Reinvestment Act on job creation using an event study model, finding a positive effect in the long run that is highly heterogeneous across workers, sectors and communities. Additionally, Kahn and Mansur (2013) explore the implication of local energy regulation on spatial concentration of employment by exploiting within county variation using a reduced form econometric model. They find a larger heterogeneity in the employment effects between large and small counties. Del Rio-Chanona et al. (2021) focus on the network of mobility in the labour markets. This paper focuses on the effect of automation, showing indirect job losses as well as direct job losses. A paper about the effect of climate policy based on the same network is in the works.³

Moreover, the employment effect of environmental policies has been widely discussed in the literature, including the work by Hafstead and Williams (2018) who focus on the sectoral shift of employment. They develop a two-sector general-equilibrium model of environmental policy and find that a constraint on pollution has larger effects on employment whereas a pollution tax has a much smaller impact. The shift of employment is interpreted as a job loss in polluting sectors and a gain in non-polluting sectors. Vona et al. (2019) analyse the procyclicality of green employment by exploiting a quasi-experimental study and find the green American Recovery and Reinvestment Act stimulus is positively correlated with job creation in both green and non-green sectors. Bretschger and Jo (2021) study the substitutability between production input and demonstrate that energy prices have a negative impact on employment, in particular the effects appear to be larger among high-flexibility firms. Using firm level data, they identify two channels through which market-based policy instruments that increase energy prices affect employment, which depends on the degree of substitutability between labour and energy. This work serves as an example of the relevance of accounting for firm heterogeneity that itself can generate differential effects on labour. Finally, Curtis and Marinescu (2022) investigate the distributional implications of the transition for workers and find that the growth of renewable energy leads to relatively high-paying job opportunities. However, the impact of energy transition policies may depend on the space and the time of implementing these policies. Identifying worker exposure to such a policy is

² The local projection method proposed by Jordà (2005) computes the impulse responses by a sequence of projections of the endogenous variables for each forecast horizon.

³ See also Beckfield (2020) who describes the existing literature on energy transition and discusses the social impacts of the transition towards a green economy in the US.



not straightforward. The effects could be more significant on workers in specific sectors, such as those working in energy-intensive sectors or industries.

As policymakers need to account for the extent to which adjustment processes affect labour markets, the costs and benefits of the transition depend on the extent of mobility between sectors and regions, and potential restrictions to it (Kruse et al., 2017). Regional labour market characteristics, in particular the composition of the workforce in terms of skills, qualifications and occupations, but also sectors, offer insights into whether the green transition will likely be a smooth adjustment process or a difficult, lengthy period characterised by rising unemployment, declining economic activity and reliance on supportive policy action. Detailed assessments surrounding restrictions on labour mobility between sectors and regions are therefore of high relevance for policy making, in particular in the context of the just transition. Effective support requires an informed view on above-mentioned characteristics at a detailed level of spatial granularity, as most policy action primarily takes place at subnational level.

In recent analyses of labour market features needed for the transition, some uncertainties can be identified. First, there is no clear, universally accepted definition of green jobs and skills. While attempts have been made to derive a taxonomy (Vona et al., 2021; European Commission and Directorate-General for Education, Youth, Sport and Culture, 2023), this area remains work in progress. Moreover, the identification of green jobs and their proximity to non-green jobs in terms of skills remains a challenge which fuels uncertainty, though some evidence exists, based on, for example, online job vacancy data (Saussay et al., 2022). It is also uncertain how the requirements for green jobs, or the jobs themselves, might change in the future, and how this might impact the demand for skills. Another uncertainty relates to frictions and how imperfect labour markets might affect the speed of a just green transition (European Commission and Directorate-General for Economic and Financial Affairs, 2023). Current analyses provide a decent view on the type of sectors and occupations likely to decline or grow (using either top-down or bottom-up approaches to quantifying employment). But uncertainties exist when it comes to more detailed spatial analyses and the impacts of restricted labour mobility. Existing estimates of net employment effects typically depend on labour mobility as a key factor (García-García et al., 2020). With a substantial number of workers employed in declining industries, there will be an adjustment period with workers changing jobs, occupations, and geographies. Well-functioning labour markets with the capacity to absorb workers in transition face a smoother process than regions in which a declining industry is centralised and a major source of jobs (Kruse et al., 2017). A recent work by Berryman et al. (2023) analyses the implications of total factor productivity on occupation-level unemployment in Brazil using data-driven occupational mobility network model, a model developed by Del Rio-Chanona et al. (2021) that accounts for frictional labour mobility. They derive these frictions from historical movements between occupations, and show that the response of labour demand to an increase in manufacturing productivity depends on how adaptive workers are.



Macroeconomic models of different natures and theoretical underpinnings are popular methods for modelling environmental policy impacts (European Commission, 2020; Auffhammer, 2018). The impact across economic sectors of the transition is well-covered in most existing macroeconomic models that have an IO framework, including E3ME and GEM-E3, even if the level of detail differs across models. E3ME includes 70 sectors, while GEM-E3 includes 68 activities, aligned with classifications in Eurostat National Accounts and OECD STAN. However, the dimension of heterogeneity also concerns the skill and spatial heterogeneity, and effective support requires an informed view on above-mentioned characteristics at a detailed level of spatial granularity, as most policy action primarily takes place at subnational level. In the absence of such representation, macroeconomic models tend to assume a smooth and instantaneous transition of employment across sectors, with limited frictions in the adjustment process

The E3ME and GEM-E3 models treat differently the supply of qualifications and skills in the labour market, with E3ME applying an off-model estimation using fixed-share or linear-logistic trend-extrapolated coefficients (estimated results by occupation are derived in a similar way and serve as a proxy for skills supply). Skills demand is derived from model results for sectoral employment, off-model occupation estimations, and qualification trends. GEM-E3 includes an endogenous human capital formation mechanism and a distinction between eight different occupation categories with endogenous unemployment rates – driven by empirically estimated labour supply curves. Some techniques have also been applied to provide more detailed results (e.g., at NUTS2 level). E3ME has a regionalised and sectoral version (E3ME-ERR) which uses dynamic shift-share decomposition with ARIMAX techniques. A shortcoming of this static approach is the assumption that regional structures remain stable over time. GEM-E3--R is soft linked with a regional satellite module that transposes national results to NUTS-2 detail using a mix of gravitational and optimisation modelling approach.

Disregarding frictions limits the use of macro models for evaluating the energy transition, particularly in the short- to medium term, and it is therefore important that macroeconomic models are further developed to better answer questions, such as: Which subnational regions are at a disadvantage in implementing the green transition? How will the distribution of the workforce across regions change as a response to the green transition? How large is the green skills mismatch and the need for skilling?

Looking at future modelling of the interlinkages between labour market features and environmental policy, macroeconomic models would therefore benefit from improved representation of the spatial and skills dimension. Learning from the aforementioned papers that propose different frameworks to identify the effects of the energy transition on labour markets is important for the improvement of the two climate-economy models (E3M and GEM-E3) discussed in this report. Those papers can serve as benchmarks to compare and validate the model results.



Suggested advancements

We suggest two key advancements of the models regarding the way labour heterogeneity is modelled and the effect of the transition on the labour market is estimated.

1. Frictions for skill limitations in the models, for instance using data-driven network models of mobility across occupations. This mobility data reflects how transferable skills are across different jobs. Model improvements like this can give us more confidence on which parts of the energy transition can be realistically accelerated, and where there are more risks of delays.
 - a. In specific, improve existing methods to account for changes in regional economic structure, for instance with dynamic input-output modelling
2. Labour heterogeneity needs to be better quantified. While large macro-models of the energy transition typically account for some heterogeneity, models need to be expanded to generate heterogeneous effects on labour demand and supply based on skill, age, gender, and occupation categories. Explicit age cohorts representation and endogenous representation (empirically validated) of the population participation.

Behavioural change

In recent years, a number of heterogeneous agents models have emerged to explain differences in consumption, earnings, and wealth among agents. These models account for preference heterogeneity and are capable of underpinning and matching the irregularities observed in micro-data. Given the importance of understanding the macroeconomic implications of energy transition, it is deemed crucial to incorporate behavioural elements into macroeconomic models. Such models can deliver heterogeneous responses across agents to climate change mitigation policies and can provide well founded policy insights.

Furthermore, to meet the objective of the energy transition, public policies must align with observed household behaviour and support behaviour change through education, infrastructure, and financial incentives. Behavioural change is a key element of various decarbonisation scenarios, such as the Shared Socio-economic Pathway (SSP1) scenario (Riahi et al., 2022) and the Low-Energy Demand (LED) scenario (Grubler et al., 2018). These scenarios suggest the possibility of highly rapid social changes. The behavioural changes assumed in the model include a shift in transport towards active transportation methods and dietary changes. In the IEA Net-Zero Emissions scenario, these behavioural changes in transport are the single biggest measure to reduce transport emissions (IEA, 2022). Furthermore, the design and implementation of green policies aimed at behaviour changes comes with economic, legal and societal incentives (Creutzig, et al., 2022). These demand-side mitigation strategies are typically classified into Avoid-Shift-Improve (ASI) options



and take into account social and cultural norms to achieve sustainable transformation. Large macroeconomic models of the energy transition typically model the supply-side in much more detail than the demand-side. This may lead to biases: Edelenbosch et al. (2020) find that behavioural choices around investment in insulation and modal shifts in transport are typically underestimated in decarbonisation scenarios.

Carmichael (2019) identifies strategies for the UK government to facilitate much greater behavioural and societal change towards net-zero emissions scenarios in different sectors, for example, the decarbonisation of the transport and power sector, the transition to low-carbon aviation technology, the shift to lower greenhouse gas emissions agriculture.⁴ Niamir et al. (2018) presents an Agent-Based Model that tracks the aggregated impacts of behavioural changes among heterogeneous households. They show that incorporating household heterogeneity significantly increases the diffusion of energy-related actions, and that the top income households are more inclined to invest in solar panels rather than conserve and switch to a green supplier. Mander and Minas (2019) reviews different models and frameworks that explain public responses to low carbon technologies (LCTs). Based on insights from literature, they highlight the need for a multidimensional perspective to understand the complexities surrounding public acceptance or opposition to LCTs. They also propose two key solutions for how public responses can be better accommodated in a way that engenders support from the public: by integrating social and values-based aspects in planning, and by ensuring procedural justice in technology deployment. Reflecting on these, these policy options might contribute to delivering better approaches in engaging the public in the low carbon transition.⁵

Accounting for behavioural heterogeneity by incorporating differences in consumer preferences or in savings behaviour is important for our understanding of household income and wealth distribution. Several models have been developed to account for household heterogeneity consistent with observed survey data that represent an ideal source of disaggregation. The literature on quantitative models with heterogeneous agents has attracted a lot of attention, recent example in this literature are Druedahl and Martinello (2022), who focuses on the implications of long-run saving and consumption dynamics, while Achdou et al. (2022) develops

⁴ Nikas et al. (2020) proposes a holistic and transdisciplinary perspective on the role of human choices and behaviours in influencing the low-carbon transition, starting from the desires of individuals and communities, and analysing how these interact with the energy and economic landscape, leading to systemic change at the macro-level.

⁵ Crow et al. (2021) reviews the effect that behavioural changes have on International Energy Agency's Net Zero Emissions by 2050 scenario. These changes operate in three ways: cutting emissions from existing carbon intensive assets, cutting emissions in sectors where other options for doing so are scarce, and reducing energy demand, taking pressure off new sources of low-carbon electricity and helping to keep biofuels production within sustainable limits.



tools for solving heterogeneous agent models. Moreover, Parra-Alvarez et al. (2023) identify and estimate the structural parameters of heterogeneous agent models using a likelihood approach and microeconomic data, and Nuno and Thomas (2019) analyses the redistributive effects of optimal monetary policy in environments with heterogeneous agents.

Because the effects of the energy transition could vary greatly across households, we require a model with heterogeneous agents, where consumption and saving decisions vary with different income levels. The approach to model heterogeneity in household behaviour is probably best described in the work of Parra-Alvarez et al. (2023). One way to account for behavioural heterogeneity is to assume that propensity to consume differs across income distribution in order to generate model simulation in line with the data.

Suggested advancements

As a macro econometric model, E3ME assumes behaviour going forward will match the behaviour observed historically. It currently cannot endogenously consider how behaviour might change in the future. (e.g., diets, recycling etc., modal shift). Exogenous inputs can be used to proxy the impact of behavioural change. In GEM-E3 agents are rational and optimise their behaviour given their preferences and any constraints that may apply (both monetary and behavioural). Suggestions to model behavioural change are summarised in two key points:

1. Identification and empirical validation of key drivers for behavioural change so that they can be represented in macroeconomic models
2. Provide a better balance between supply and demand-side policies by incorporating more behavioural change dynamics in the models. For instance, ensure that modal shifts and insulation are properly accounted for.
3. Allowing for changes in the marginal propensity to consume across the income distribution so that the model can generate consistent results with the data.

Finance

In recent years, we have witnessed an upward trend of climate finance, which refers to financial resources allocated to support actions aimed at mitigating the effects of climate change. A recent report from the World Bank reveals a record \$31.7 billion to finance climate related actions globally in 2022.

Climate finance has emerged as an important topic that has been discussed in a number of recent papers. For example, Bhandary et al. (2021) discussed the effectiveness of different climate finance policies, including target lending, green bond policy, loan guarantee programmes, weather indexed insurance, feed-in-tariffs, tax credits, national development banks, disclosure policies and national climate



funds. They highlighted the lack of a common international standard for green bonds and the need to account for the interaction between these policies as it influences the mobilisation of financial resources for climate mitigation actions. Moreover, Mazzucato and Semieniuk (2017) have highlighted the role of public finances in supporting renewable energy innovation and in targeting the development of specific technologies in line with government agenda aimed at mitigating climate change. Furthermore, Lamperti et al. (2019) have emphasised that the energy transition policy mix must account for climate damages that can reduce the effectiveness of policy instruments such as financial regulation, fiscal instruments, and public-private co-funding schemes.⁶ Battiston et al. (2017) have used a network approach to show that there is a significant exposure of investors from sectors impacted by climate policy, especially pensions and investments. They have stressed the importance of policy timing as a smooth transition can reduce stranded assets.

Developing countries face higher costs of finance than developed countries, which is a significant barrier to gaining sufficient climate finance. Large changes are needed to enable flows of finance toward greentech in the Global South, as discussed in Ameli et al. (2021). Most often, countries that encounter challenges in financing the energy transition are those with a minimal degree of economic diversification, and a large dependence on the energy sector, as well as low-income countries with less access to capital flows. There are several studies that account for financial constraints at firm and national level, including Rosenzweig and Wolpin (1993), Rajan and Zingales (1998), Ayyagari et al. (2008), Fritz-Morgenthal et al. (2009), Ekholm et al. (2013), and Fauceglia (2014). Recognizing financially constrained agents in macroeconomic models is relevant for a better understanding of the mechanisms at work. Macroeconomic models could be enriched by accounting for financial markets that includes both financially constrained and unconstrained agents. In fact, the central idea of macroeconomic models with financial accelerators is to explain how financial shocks propagate through the investment channel. Augmenting a model with such a feature will help explain the funding mismatch that slows down the transition to a green economy (European Commission and Directorate-General for Energy and Hoogland, et al., 2022). Additionally, it can provide consistent guidance for policymakers, on how to direct investments towards a successful energy transition, how to assess financial stability risk, and how to implement public policies that guarantee sustainable green investments.

The energy transition has implications for financial stability as well, which may not be fully captured by macro models. The transition risk includes aspects of sudden asset depreciation, defaults on debt, and the formation of bubbles in rising industries

⁶ There is a growing literature that takes a step linking monetary policy with climate policy. For instance, McKibbin et al. (2017) have contributed to the debate and discussed the challenges of accounting for policies aimed at reducing emissions in setting monetary policy.



(Semieniuk, et al., 2020). Recent advances in stock-flow consistent (SFC) modelling may provide a systemic way to study these instabilities, consistent with many schools of economic thought. Simply said, stock-flow consistent models contain a full balance sheet for each agent in an economy. They have proved successful in predicting the 2007–2008 financial crisis (Nikiforos and Zezza, 2018). Jackson and Jackson (2018) and Jacques et al. (2023) contain examples of biophysical energy models with stock-flow consistent modelling. The high data requirements pose a challenge for integrating these models with existing macro-models.

The recent report published by the European Commission Directorate-General for Energy and Hoogland, et al., (2022) presents several challenges that face the energy transition which are relevant for policy makers. Specifically, the report addresses the issue of final investment decisions for new energy assets, whether they are made under a project financing structure or a corporate financing structure. Additionally, the report highlights the impact of public policies, such as carbon taxes and tariffs, on the assessment of risks and returns associated with investments in the green economy. Furthermore, the issue of low investment in renewable energy sectors is explained by high-risk exposure and lower returns in these sectors, which substantially impact the financing conditions in sustainable and unsustainable sectors. The report makes three key suggestions for model improvements: (1) include a country and technology-dependent risk factor, for instance in the discount, to represent differences in risk perceived by investors (2) Apply lower average sales prices for intermittent energy sources, to reflect periods of overproduction and (3) incorporate financial learning. The weighted cost of capital decreases when a technology matures, which is not yet included in the major models.

Deep thinking is required to account for financial risk of climate policies that target the reduction of GHG emissions. Battiston et al., (2017) developed a new approach to estimate the expected losses and gains for climate policies using a network analysis of the exposure of financial actors. It is worth noting that application of this method in the E3ME model can be useful in assessing the direct exposure of financial actors.

Suggested advancements

E3ME-FTT, beyond assuming that policies are funded and repaid, currently does not account for the difference in financial risk premiums either between regions, technologies or asset classes. GEM-E3 includes a separate representation of the financial sector where banks provide the necessary financial instruments to meet economic agents requirements (savings/investments), however financial flows are treated in a bottom up way masking important insights regarding potential financial bottlenecks that are visible at the bottom up level.

There are three key suggestions for the advancement of the models.



1. Improving country and technology risk representations of finance, to explore barriers for the Global South, and barriers to new technologies in general.
2. Incorporating financial markets that include both financially constrained and unconstrained agents into the model can help explain the funding mismatch that represents one of the main barriers to the energy transition.
3. Increase the detail of financial transactions and economic instruments so as to better reflect the risks at a firm/agent level.
4. Exploring the integration of SFC models with larger macro-economic models, or models of the energy system.

Innovation

Innovation is key for the transition towards clean energy. In general, models have done a poor job in predicting price declines for technologies. In particular, the rapid price declines in solar and to a lesser extent (offshore) wind were not foreseen by the major big models (Way et al., 2022). The question remains open whether modelling has improved sufficiently.

There is a rich literature about innovation, both for green technologies and technology more broadly. The literature focuses on a few key ideas. There is literature on induced innovation, which sees an important role for policy makers in driving innovation. A separate strand of literature looks at the crossovers between technology innovation, and how there could be multiple paradigms of technologies that work well together and co-develop, or there could be cascading tipping points in socio-technological innovation. Finally, there is a rich literature on the multi-level perspective on innovation (Geels, 2011), rooted in a social science perspective on transitions.

One element often excluded from models is induced innovation. . The main idea of induced innovation is that prices or policies accelerate innovation in specific technologies. For instance, an increase in the price of oil would stimulate innovation in energy efficiency. Grubb et al. (2021) provides an overview of the empirical literature on this topic. They conclude that (a) demand-pull factors (such as energy prices and targeted policy to build markets) increase the rate of patenting in most cases. (b) The costs of technologies go down with cumulative investments for a large majority of technologies studies. There are lines of evidence pointing to a causal relationship. (c) Innovation is cumulative and self-reinforcing. In other words, it is path dependent. One of the main disagreements around induced innovation is the question of causation (Lafond et al., 2022). Does deployment reduce costs or is this mainly related to time (and the general technological progress of society). Normally, this cannot be answered due to problems with collinearity, as technologies increase exponentially, and the time-trend and log of the deployment are collinear. Lafond et al. (2022) showed that in the case of technological progress in World War 2, a distinction could be made, and this class of war technologies saw about a 50-50 split between cost



declines due to time and cumulative production. This is a key finding to be included in models. This endogenous innovation is difficult to include mathematically in optimisation models, but it is possible. Kim et al. (2020) study how to implement endogenous learning-by-doing in an optimisation model using “mixed integer programming-based formulation and iterative approaches”.

Innovation in one technology is often essential for innovation in the next technology. Many key technologies are similar within or across sectors. For instance, improvements in onshore wind allowed the offshore wind industry to become large. Similarly, innovations in batteries for electric vehicles are making short-term storage in the power sector much cheaper. The literature on cascading tipping points in green technology innovation is quite new. A report by Meldrum et al. (2023) identified a set of linkages in 10 green technologies, but from a qualitative perspective. Quantifying the strength of the linkages is challenging, as this problem also suffers from collinearity; many of the technologies are developing concurrently.

Within the social sciences, there are multiple theories to describe socio-technical transitions. Large economic models often focus on the techno-economical dimension of transitions, for instance in the form of evolutionary economics (Freeman, 2021). Techno-economic paradigm (TEP) shifts reflect on transitions from a whole-economy perspective, and investigates the science, technology, economy, politics and culture of a transition (Geels, 2011). The multi-level perspective focuses more on specific transitions in for instance oil and electricity. While these perspectives cannot be easily translated to model worlds, they do complement modelling insights, especially on the social aspects.

Additionally, Mercure et al. (2019) provide a review of the treatment of technology and innovation in modern low-carbon transition models. They find that these models belong to two broad families (i.e., supply-led and demand-led) often resulting in opposing predictions. Shayegh et al. (2017) show that curve-following R&D (accelerating learning-by-doing) is less effective than curve-shifting R&D (cost declines that would not have happened from learning-by-doing), especially for technologies with a lower learning rate. Zhou et al. (2022) investigate the relation between economic policy uncertainty and firms’ green innovation, and find that it has an inverted U shape, i.e., uncertainty has a positive effect on green innovation up to a certain point. Some of the literature on innovation does not fall in any of the above categories. Cherp et al. (2021) for instance looked at the maximum growth rate for newer technology, when they are in the mid-part of their transition. They concluded that scenarios of the energy transition compatible with 1.5C are typically incompatible with historical rates of technology diffusion.

Most macroeconomic models simplify the role of innovation by assuming it is exogenous, rather than endogenous. However, directed technical change models offer a more comprehensive approach by explicitly modelling endogenous innovation. These models have been extensively developed and discussed in the



literature, see Hemous⁷ and Olsen (2021) for a discussion of these models. Prior studies have relied on patent data to measure innovation. However, firms typically invest in research and development to create new products and processes. In this context, induced innovation is interpreted as input augmenting technology, and the degree of substitution between inputs can significantly impact the model results.

Suggested advancements

To improve the coverage of learning in theory and models, drawing on the shortcomings as described in Appendix Part B, we suggest:

1. Including endogenous learning that takes into account both learning-by-doing (Wright's law) and learning-by-research
2. To better represent first-mover effects it is essential to better represent learning at a firm level accounting for potential spillovers and monopoly rents realisation
3. Use insights from social sciences, such as multi-level perspective, to complement large macroeconomic models of innovation. These models provide information on the first steps of innovations (niches) that large models cannot capture well; and on the social aspects of innovation

Uncertainty in Economic Modelling

When evaluating the outcomes of complex systems, there will always be uncertainty inherent in evaluating expected outcomes. This is especially true for complex macroeconomic models where emergent phenomena cannot be exhaustively quantified due to the excess levels of knowledge required to understand every potential linkage and their interactions (Mercure, 2022).

The precise definition of uncertainty differs across the literature. Walker et al. (2003) defines uncertainty as 'any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system'. This covers a broad range of uncertainty types based on differing levels of available knowledge ranging from 'know' to 'not know' and 'not know that we do not know'. Knight (1921) defines uncertainty as "an immeasurable lack of knowledge" in contrast to risk which is measurable via probability of known possible outcomes.

Beyond the broad definition of uncertainty, there is the consideration of the various dimensions/locations that uncertainty presents itself this includes:

Parameter uncertainty – Uncertainty in individual parameters, assumptions, or other input data. A good example of this is uncertainty in the costs of low carbon technologies (both those that are known or are unknown). These uncertainties are to some extent quantifiable within bounds between costs reported today as the upper



bound and find the costs of somewhat similar mature technologies providing an indication of the lower bound.

Structural uncertainty – Considers uncertainty inherent in choosing a structure and implementation for a model. Given that models are an abstraction of reality, there will always be uncertainty resulting from an incomplete understanding of the system dynamics being modelled.

Due to the complexity inherent in macroeconomic modelling, uncertainty will always have implications for how well the modelled outcomes will reflect reality. It is important in modelling exercises to consider where and how such uncertainties may have implications for the conclusion that can be drawn from modelling exercises.

A particularly important case where uncertainty can have substantial implications for modelling outcomes is where you have heavy tailed uncertainty. Heavy tailed uncertainty occurs where there is considerable likelihood in the extremes of the distribution in contrast to a normal distribution. Heavy tailed uncertainty occurs in systems with at least a moderate degree of complexity and where positive/self-reinforcing feedbacks can occur. This is commonly seen in the concept of tipping points in which small changes in a system can escalate into large outcomes such as the role of incentives in Wind and Solar reaching a tipping point of cost parity leading to acceleration in deployment (Farmer et al., 2019) or tipping points in the climate system where temperature increases GHG could lead to release of trapped GHGs (Weitzman, 2011).

The presence of heavy tailed uncertainty means analysis based on averages is no longer insightful because what happens at the extremes is both more likely and where the scale of the impacts at the extreme are large, this means consideration of variation in the expected outcomes. A clear example of this is in assessing the impacts of climate change, as in Coronese et al. (2019), where climate modelling highlights the heavy tail uncertainty of climate impacts from various emissions pathways and the nonlinear impact of temperature increase rather than leading to substantial changes in the average. The standard approach to take the average impact is misleading and obscures the much larger impacts that could occur in the more extreme ends of the tail. This is especially true for evaluating climate change and other complex system impacts where the impacts are expected to be non-linear, particularly where there may be tipping points.

Historically, economics has not done well at quantifying the implications of uncertainty, with modelling outcomes reported as discrete values. This contrasts with other fields such as climate and weather forecasting in which modelling results as a distribution of potential outcomes which build in some evaluation of the uncertainty.

In recent years, economists have tried to account for uncertainty in modelling methodology. The approaches vary across the literature and tackle different dimensions of uncertainty.



For measurable parameter uncertainty where you can reasonably attach a probabilistic distribution to, a common option is to carry out Monte Carlo simulations to evaluate the outcomes of models under different sets of inputs across a distribution. A key example of this is in Gillingham et al. (2015), where this approach was used to estimate the impact of parametric uncertainty in IAMs.

Where distribution of uncertainty is unknown, a common method used in economic modelling is scenario analysis/sensitivity analysis where various elements of the inputs are tested over a reasonable range. For example, you might test modelling outcomes sensitivity to change in fossil fuel prices over a range of different fossil fuel price projections. This does not require any evaluation of the distribution or likelihood of the projections but does allow for an assessment of the expected impact such parameter uncertainty may have on the model outcomes.

Where there is structural/model uncertainty arising from the key methodological framework of various macroeconomic models, this uncertainty can be accounted for by exploring scenarios/impact assessments through a multi-model approach. This has been carried out in numerous cases for impact assessment of policy outcomes such use of a macro-econometric model E3ME alongside a hybrid CGE model GEM-E3-FIT as in European Commission and Directorate-General for Energy (2022) or dynamic CGE model as in Bachner et al. (2020).

However, the use of a multi-model approach to account for the width of model uncertainty does require sufficient model validation. Such model validation helps to ensure there are no common biases in the models used which could skew the inference on uncertainty.

Suggested advancements

Per Appendix Part A, the large models used by the consortium do not quantify uncertainty systematically. Uncertainty can be accounted for exogenously instead through sensitivity analysis of scenario inputs to test the uncertainty of the shock that could be imposed on the economy. However, this sensitivity analysis does not consider parameter uncertainty.

There are a few key suggestions for the modelling in this regard:

1. Operationalise parametric uncertainty quantification; a standard way to quantify uncertainty is by varying uncertain input variables. This is now often done at hoc, depending on the project. Using climate science as an example, we can “operationalise this” and use a standard quantification for all model output
 - a. This would be an important input for the design of more robust inputs to decision-making frameworks, like the risk-opportunity framework.
2. Use model validation. While individual equations are validated in the modelling framework each update, a more robust model validation exercise – trying to



predict past trends with data up to that point – would increase trust in the modelling framework.

3. Incorporate important nonlinearities and feedbacks (for instance by using systems mapping). Heavy-tailed uncertainty originates from reinforcing feedbacks in the model, which may cause tipping behaviour. If these feedbacks are omitted, the model may overestimate stability and underestimate risk and opportunity.

System Dynamics and Systems Thinking

As calls for decarbonisation of the economy have increased, so too have the calls for integrated models that inform on the complex relationships between the social, economic and environmental realms (Bassi 2015). Whilst no model can capture all aspects of the green economy, System Dynamics (SD) has been advocated as potentially appropriate for investigating such relationships given its recognition of the importance of complex relationships between components of a system in determining overall system behaviour (Ghisolfi et al. (2022); Bassi (2015)).

This makes it particularly well suited for parts of the economy that interact heavily across environmental and social boundaries. Labanca et al. (2020) use a dynamical approach to look at how techno-centric views towards decarbonisation fail to account for their interplay with societal behaviours and norms. They argue that a research and policy agenda that incorporates understanding of social practice, complex and dynamic systems is urgently needed to better understand the role of innovation in decarbonisation of the energy sector from both a demand and supply perspective. Likewise, Ghisolfi et al. (2022) review the use of SD models applied to the freight transport sector. They hold that the SD approach is appropriate for analysing decarbonisation strategies as it can appropriately represent lagged responses, time dependence, feedbacks and other interaction effects of such strategies. However, they found that many of such models focusing on the freight transport sector evaluated only a restricted combination of strategies instead of a broad view of the system, limiting the understanding of policy impacts. This speaks to arguments put forward by Bassi (2015) which highlight that the majority of the tools available to investigate such issues, especially in policymaking, are specialised to certain sectors, leading to siloed thinking and a lack of understanding of side/spill-over effects and the threats and opportunities posed by them (2015). Bassi (2015) seeks to address these concerns by applying the Green Economy Model, a simulation model which accounts for the interconnections between the main types of capital that traverse societal, economic and environmental boundaries.

Papachristos (2019) looks in more depth into SD applied to the green transition and elaborates on further contributions of SD to transition research and how it traverses micro, meso and macro levels. SD work could benefit transition research in terms of methodology, case study research, and the behavioural aspects of transitions. The



authors draw a distinction between the traditional transition research, which has focused on historical case studies of sociotechnical transitions, and emerging sustainability transition research which focuses more on simulation in order to inform future policymaking.

Dall-Orsoletta et al. (2022) also cite SD as a suitable modelling technique to engage and investigate the interdisciplinary nature of energy transitions and review how energy system models use SD to incorporate social aspects in their modelling research. Whilst such social aspects were not uniform across modelling approaches, they included behaviour and lifestyle changes, social acceptance, willingness to participate and socio-economic measures. The last of which were mostly seen in energy-economy-environment and supply-demand models.

Mutingi et al. (2017) explores how the characteristics inherent in energy systems, non-linear relationships, time lags and feedbacks, make the incorporation of SD into modelling of such systems essential for development and evaluation of energy policy. The authors provide a review of SD approaches to energy policy modelling and simulation, in particular they review the variety of system dynamics archetypes relevant for energy policy both in the evaluation and projection of such policies. They put energy policy formulation problems into several categories each with a different archetype for modelling: energy-economy-environment (3E) problem, energy demand-supply management problem, new product innovation problem, capacity management problem, energy pricing problem, and hybrid energy management problem. These archetypes can be used to inform policy makers deeper insight into the underlying interactions and structures that give rise to system behaviour as well as possible future unintended consequences.

Leopold (2016) highlights the extensive use of SD as a method for decision support in the energy sector. They present the key research in the area and group them into four key energy topics. Fossil fuels, primarily to assist with understanding limits to fossil fuel resources and the economic impacts. Renewables, where the shift towards such energy sources is investigated. Electricity, where there is a focus on optimisation in planning, production and use of power plants. Finally, further energy related resources, such as nuclear energy or hydrogen, use SD to investigate future policies that may seek to phase down or up such resources. Krumm et al. (2022) highlights that many models focusing on the decarbonisation of the energy system focus heavily on the techno-economic aspects whilst inadequately representing social factors. They list a variety of types of models which they categorise into optimisation energy system models, simulation ESMs, integrated assessment models, agent-based models, and computable general equilibrium models. They synthesise how social aspects are integrated into each model type, with ABMs being particularly successful and representing social aspects.

Another route into systems thinking is making input-output tables dynamic. Input-output models provide a “recipe of production”, and IO tables capture the inputs of



one sector to the other. Under structural change, this recipe is expected to change, as we move from fossil fuel sectors to electricity and construction. Key ingredients for making input-output tables dynamic are using highly disaggregated models of the economy, or of subsectors. There are multiple examples of dynamic input-output modelling applied to the energy transition (Wimmer et al, 2023, and references therein), but it has not yet been applied to a global model of the energy transition as far as the authors are aware.

Suggested advancements

E3ME is a dynamic model (annual results) with path dependency and two-way linkages between the economic system and the energy system. E3ME captures system dynamics in response to the energy transition as the energy system changes feedback into the economic system. In addition, through the bottom-up FTT models, E3ME captures other dynamics including endogenous learning by doing across regions and technologies within a sector which allow tipping points and achieving s-curve technology diffusion. However, learning across sectors is not captured. The GEM-E3 model dynamics are mostly driven by R&D, learning by doing, investment and shift in sectoral multipliers.

There are two advancement we suggest making use of systems thinking and from the insights of Systems Dynamics modelling:

1. Acknowledge that large macro-economic models of the energy transition cannot capture social interactions for which data is lacking, and that Systems Dynamics models or ABMs play a complementary role. These models may also help identify aspects of large models that are missing
2. Increase the granularity and technology choices in CGE models adding larger substitution possibilities using tailored functional forms. M This will improve the dynamics, capturing structural change induced by the energy transition and other large socio-economic trends such as robotisation and AI.



Conclusion

In this report, we highlight the main limitations of the existing theory, methods and models. To accelerate the energy transition, knowledge from a wide set of disciplines is necessary. We described a set of recent branches of economics, including ecological economics (which uses biophysical insights), complexity economics (with a strong focus on the mathematics of complexity) and evolutionary economics (explaining innovation and diffusion).

Using insights from these recent branches of economics, we describe model limitations and recent methodological advancements in 6 key themes that can be applied to the energy transition literature. We focus on relevant strands of this literature, namely the role of climate finance, labour markets, and their interaction with the green transition, as well as the behavioural changes induced by environmental policies. We also examine the role of endogenous innovation through the decarbonization of the economy, and finally, we discuss the uncertainty and dynamical systems and their relevance to the ongoing energy transition.

Finally, we suggest several areas of improvements to the set of models used in policy appraisal. Large macroeconomic models would benefit from having a better representation of potential limitations to mobility on the labour market, across sectors (i.e. skills) and regions. These limitations and opportunities can be mapped with a network analysis from complexity economics. This is crucial to quantify the speed of the green transition. Furthermore, models often put more emphasis on the supply-side of the transition, and refocusing on demand-side policies and behavioural change will allow for a broader picture of the transformational change needed. A good example could be Agent-Based Models (ABMs) that to some extent represent social dynamics, including key insights from behavioural economics. In terms of finance, the integration of technology and country-dependent risk into macroeconomic models, along with the inclusion of endogenous financial learning, are also discussed as important features to improve the model. From a more methodological point of view, transparent model validation and operationalised uncertainty quantification would be beneficial, using empirical methods.

In some cases, alternatives to large macro-economic integrated models may be helpful. System dynamics models may be better in the interplay between social change, policy change and economics, whereas stock-flow consistent modelling allows for a better representation of financial risk and instability.

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Appendix A:

Model descriptions

E3ME-FTT

E3ME-FTT is a global dynamic econometric simulation model of the economy–energy–environment systems, developed by Cambridge Econometrics over several decades, with contributions from academics at various institutions. E3ME is designed primarily as an empirical tool and draws on the Cambridge (UK) tradition of macroeconomics, supplemented by more recent applications of complexity theory to economics. The key properties of the model include recognition of fundamental uncertainty, possible non-rational behaviour and market structures determined by the available data.

E3ME-FTT is an E3 model, meaning that it has a representation of economy, energy and environment interactions. The economy module provides measures of economic activity and general price levels to the energy module; the energy module provides measures of emissions of the main air pollutants to the environment module, which in turn can give measures of damage to health and buildings. The energy module provides detailed price levels for energy carriers distinguished in the economy module and the overall price of energy as well as energy use in the economy.

Although E3ME can be used for forecasting, the model is more commonly used for evaluating the impacts of an input shock through a scenario-based analysis. The shock may be either a change in policy, a change in economic assumptions or another change to a model variable. The analysis can be either forward looking (ex-ante) or evaluating previous developments in an ex-post manner. Scenarios may be used either to assess policy, or to assess sensitivities to key inputs (e.g. international energy prices).

For ex-ante analysis a baseline forecast up to 2050 is required; E3ME is usually calibrated to match a set of projections that are published by the European Commission and the International Energy Agency but alternative projections may be used. The scenarios represent alternative versions of the future based on a different set of inputs. By comparing the outcomes to the baseline (usually in percentage terms), the effects of the change in inputs can be determined.

The structure of E3ME is based on the system of national accounts, with further linkages to energy demand and environmental emissions. The labour market is also covered in detail, including both voluntary and involuntary unemployment. The other econometrically estimated equations cover the components of GDP (consumption, investment, international trade), prices, energy demand and materials demand. Each



equation set is disaggregated by region and by sector, and the whole system is solved simultaneously. All EU MSs, the UK and other major global economies are represented individually, other world regions are represented in regional aggregates. Key economic indicators are solved through 28 econometric relationships across all domains (e.g., employment, industry prices, consumer expenditure, industrial investment, etc.).

As a general model of the economy, based on the full structure of the national accounts, E3ME is capable of producing a broad range of economic indicators. In addition, there is a range of energy and environment indicators. The following list provides a summary of the most common model outputs:

- GDP and the aggregate components of GDP (household expenditure, investment, government expenditure and international trade)
- sectoral output and GVA, prices, trade and competitiveness effects
- international trade by sector, origin and destination
- consumer prices and expenditures
- sectoral employment, unemployment, sectoral wage rates and labour supply
- energy demand, by sector and by fuel, energy prices
- CO₂ emissions by sector and by fuel
- other air-borne emissions
- material demands

This list is by no means exhaustive, and the delivered outputs often depend on the requirements of the specific application. In addition to the sectoral dimension mentioned in the list, all indicators are produced at the national and regional level and annually over the period up to 2050.

The main dimensions of E3ME are:

- 71 regions – all major world economies, the EU27 and candidate countries plus other countries' economies grouped
- 44 industry sectors, based on standard international classifications
- 28 categories of household expenditure
- 25 different users of 12 different fuel types
- 14 types of air-borne emission (where data are available) including the 6 GHGs monitored under the Kyoto Protocol

The technology disaggregation for the FTT sector models follows:

- 22 power generation technologies
- 28 personal transport vehicle options
- 13 options for household heating
- 26 technology pathways for steel production



E3ME's historical database covers the period 1970–2019 (with estimates for Covid-19 impacts and recovery for 2021) and the model projects forward annually to 2050 (2100 is also possible). The main data sources for European countries are Eurostat and the IEA, supplemented by the OECD's STAN database and other sources where appropriate. For regions outside Europe, additional sources for data include the UN, OECD, World Bank, IMF, ILO, and national statistics. Gaps in the data are estimated using customised software algorithms. Chapter 6 describes in further detail E3ME's data inputs.

E3ME is often compared to Computable General Equilibrium (CGE) models. In many ways the modelling approaches are similar; they are used to answer similar questions and use similar inputs and outputs. However, there are important underlying differences between the modelling approaches. In a typical CGE framework, optimising behaviour is assumed, output is determined by supply-side constraints and prices adjust fully so that all the available capacity is used. In E3ME the determination of output is demand-led with supply constraints, and it is possible to have spare economic capacity. Capacity variables have price feedbacks, but with the impacts estimated using econometric equations rather than assuming movement towards an equilibrium value, nor do prices always adjust to market clearing levels.

Labour markets

E3ME includes econometric equation sets for employment (as a headcount), average working hours, wage rates, and participation rates. The first three of these equations are disaggregated by economic sector while participation rates are disaggregated by gender and five-year age band. The labour force is determined by multiplying labour market participation rates by population. Unemployment (both voluntary and involuntary) is determined by taking the difference between the labour force and employment. For the EU, E3ME includes measures of skills demand which are derived from the model results for sectoral employment, an off-model estimation of occupational shares within sectors and qualification shares within occupations.

Finance

The most important characteristic of the model's treatment of finance is its 'endogenous' money supply, suggesting that the money supply is related to investment demand. Investment demand (measured as Gross Fixed Capital Formation) in E3ME is determined through econometric equations estimated on time-series data. The only limit on the supply of money is not available savings but the willingness of banks to lend and businesses to borrow. This willingness may be influenced by expected rates of consumer price inflation, future growth in the economy and the rate of interest. Due to data limitations, investment is not disaggregated by asset in E3ME. While the identity that savings and investment are equal (at global level) is respected, investment is not constrained by the available savings.



Innovation

E3ME incorporates bottom-up technology models of four major energy-using sectors (power, personal transportation, steel and household heating).⁷ FTT models are based on the concepts of technology diffusion, bounded rationality in decision making, path dependency and learning-by-doing as technologies progress. These models follow the 'S-shaped' diffusion paths of new technologies as they gain market acceptance and incorporate cost reductions through learning rates. This learning is global and endogenous. It follows Wright's law, so that cost declines come from learning-by-doing as a function of cumulative investment in a technology.

The FTT models simulate investor decisions with limited information using not just levelized costs of technologies, but a distribution of technology costs. As a result, the model can show rapid transitions as technologies gain market penetration, reinforced by cost reductions that result from learning rates. Under higher uncertainty, technology uptake can accelerate or slow down. For new expensive technologies, a higher uncertainty in cost estimates means that a subset of investors will find the technology attractive, accelerating uptake. For (newly) cost-competitive technologies, higher uncertainties slow down diffusion, as not all investors are convinced of the cost-effectiveness of a new technology.

Within sectors, there is cross-learning. As such, investments in onshore wind drive down costs for offshore wind and vice versa. This cross-learning is not yet implemented across sectors.

For other sectors not represented with an FTT model, a top-down index-based approach for process and product innovation is applied at sectoral level. The model's endogenous technical progress indicators (TPIs), a function of R&D and gross investment, appear in nine of E3ME's econometric equation sets including trade, the labour market and prices. Investment and R&D in new technologies also appears in the E3ME's energy and material demand equations to capture energy/resource savings technologies as well as pollution abatement equipment. R&D spillovers are included in the model, based on patent data.

Energy

Energy demand data in E3ME cover the use of 12 different fuels by 23 fuel users. The representation of energy demand in E3ME incorporates both top-down and bottom-up modelling approaches. Part of energy use is handled within the econometric framework (top-down), while some parts with high innovation potential and major bearings on the green transition are modelled through the FTT models (bottom-up). Energy use is captured through equations within the E3ME framework and are linked to economic activity and to cumulated investments (capital – energy substitution).

⁷ Called the FTT (Future Technology Transformation) models. See e.g. Mercure et al (2014) for details.



For key energy-using sectors covered by the FTT models that simulate technological decision making. Resulting investments, end-use prices, and energy consumption are fed back to the economy module and the rest of the energy module in the E3ME framework.

Trade

E3ME solves for detailed bilateral trade between regions (similar to a two-tier Armington model). Trade is modelled in three stages:

- econometric estimation of regions' sectoral import demand
- econometric estimation of regions' bilateral imports from each partner
- forming exports from other regions' import demands

Trade volumes are determined by a combination of economic activity indicators, relative prices and technology.

Regional disaggregation

With certain assumptions, regional E3ME results may be disaggregated to more granular spatial resolution in various applications. For example, results for the ASEAN region can be disaggregated to country level. For European regions, further disaggregation to sub-national levels is possible. Within Europe, sub-national extrapolation of results is also possible, to both the NUTS-2 and NUTS-3 level. Results for employment and GVA can be derived, subject to available data. The method, based on the one presented in Mayor et al (2007), combines historical data to determine regional competitiveness. Auto-Regressive Integrated Moving Average (ARIMA) modelling is used to project competitiveness factors forwards and E3ME scenario results for national level impacts.

GEM-E3

GEM-E3⁸ is a large-scale multi-sectoral CGE model that since the 1990s is extensively used by governments and public institutions to assess the socio-economic implications of policies, mostly in the domains of energy and the environment. The development of GEM-E3 involved a series of modelling innovations that enabled its departure from the constraining framework of standard / textbook CGE models (where all resources are assumed to be fully used) to a modelling system that features a more realistic representation of the complex economic system. The key innovations of the model relate to the explicit representation of the financial sector, semi-endogenous dynamics based on R&D induced technical progress and knowledge spillovers, the representation of multiple households (the model represents 460 households distinguished by income group), unemployment in the labour market and endogenous formation of labour skills. The model has detailed

⁸ A detailed technical presentation is available in the manual at: <http://e3modelling.gr/modelling-tools/gem-e3/>



sectoral and geographical coverage, a default of 51 products and 46 countries/regions (global coverage) and it is calibrated to a wide range of datasets comprising of IO tables, financial accounting matrices, institutional transactions, energy balances, GHG inventories, bilateral trade matrices, investment matrices and household budget surveys.

All countries in the model are linked through endogenous bilateral trade transactions identifying origin and destination. Particular focus is placed on the representation of the energy system where specialised bottom-up modules of the power generation, buildings and transport sectors have been developed. The model is recursive dynamic coupled with a forward-looking expectations mechanism and produces projections of the economic and energy systems until 2100. The substitution elasticities of the model are not derived from the general literature but are estimated according to its dimensions and functional forms using the latest available datasets.

The model is founded on rigorous and sound micro-economic theory allowing it to study in a consistent framework the inter-linkages of the economic sectors and to decompose the impacts of policies to their key driving factors. It is acknowledged that the model simulations are sensitive to a number of input parameters and modelling assumptions including capital costs of power producing technologies and associated learning rates, cost of capital and financing availability, easiness to substitute production factors, preferences over domestic and imported goods etc. To address the uncertainty within, the model provides the option to make all its parameters stochastic according to user defined probability distributions and perform extensive sensitivity analysis.

Focus is placed on the representation of the energy system where specialised bottom-up modules of the power generation, buildings and transport sectors have been developed. GEM-E3 features a soft-link approach in integrating a bottom-up representation of power generation (explicit representation of load curve, RES potential, utilisation rates etc.). The model further represents explicitly the manufacturing of clean energy technology equipment, such as wind turbines, PV modules, batteries but also of advanced energy carriers such as hydrogen and clean fuels. The production functions and global market structure of these sectors have been introduced to the model from bottom-up engineering information and other databases. The model covers all GHG emission sources, including energy and process related emissions, excluding those related to the LULUCF sector, and can provide projections for Scope 1, 2 and 3 emissions.

The most important results, provided by GEM-E3 are: Full Input-Output tables for each country/region identified in the model, dynamic projections in constant values and deflators of national accounts by country, employment by economic activity and by skill and unemployment rates, capital, interest rates and investment by country and sector, private and public consumption, bilateral trade flows, consumption matrices by product and investment matrix by ownership branch, GHG emissions by country,



sector and fuel and detailed energy system projections (energy demand by sector and fuel, power generation mix, deployment of transport technologies, energy efficiency improvements).

The Financial Sector

The representation of financial transactions and instruments in the general equilibrium modelling framework is not new (Capros & Karadeloglou (1993), Capros et al (1991), Bourguignon Branson and de Melo (1989), Tobin (1969)) whereas the 2008 financial crisis and its impact on the real economy revived the efforts in developing and applying CGE models that explicitly treat financial flows (Dixon et al (2014), Martin Cicowiez, C. G. M. (2010))⁹. The latest version of the GEM-E3 model features the financial sector in detail and can assess the interlinkages between the financial sector and the real economy.

The representation of the financial sector in the GEM-E3 model starts from the complete accounting of the financial flows – transactions among economic sectors¹⁰. This accounting allows to determine the flow of funds, the debt profiles and the composition of agents' disposable income. The base year financial position of each agent is calculated using the institutional transactions statistics¹¹ (full sequence of National Accounts that include all secondary transactions like property income, income from deposits etc.). The net lending position of each agent is built from bottom up data (all sources of income including dividend payments, interest rates, debt payments, bond interest rates etc.). Data regarding the structure of the bilateral debt by agent are constructed according to current account statistics and proxies using cumulative bilateral trade transactions. All

⁹Capros P. and P. Karadeloglou (1993) "Structural Adjustment and Public Deficit: A Computable General Equilibrium Modelling Analysis for Greece", in P. Capros and D. Meulders (editors) "Budgetary Policy Modelling: Public Expenditure", Routledge Publ. Co., Chapman and Hall, London, book published in 1996

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¹⁰ The model identifies: Firms, Banks, Households, Public and the external sector.

¹¹ Main data sources used are EUROSTAT and IMF-IFS



the financial transactions are arranged in a financial SAM framework for each country that is represented in the model.

All agents' decision to lend or borrow is driven by the market clearing interest rate. Through the use of alternative macroeconomic closures different options are available for global clearing endogenous interest rates, national interest rates and interest rates that are differentiated according to agent specific risk premium and associated financial position. Money supply can be fixed with endogenously determined interest rates, can fluctuate across time depending on capital capacity utilisation or adjusted at a given interest rate following endogenous money supply (bank reserves adjust as needed to accommodate loan demand at prevailing interest rates).

The inclusion of the financial sector improves the simulation capabilities of the model in the following aspects: i) It moderates the short-term stress on capital markets by allocating capital requirements over a longer period (long-term financing schemes/loans). This effect is particularly visible in scenarios where the economy transits to a more capital intensive structure and any limited availability of financing capital implies that capital costs will always rise, ii) it allows to simulate the role of carbon – funds in the implementation of ambitious energy and climate policies, iii) it allows the assessment of socioeconomic impacts of investment projects characterised by different risk profiles performed by agents with different risk/debt profiles, iv) it allows for a detailed budgeting of debt by agent while it takes into account the impact of debt accumulation and debt sustainability in the ability of agents to borrow, v) it provides an endogenous computation of interest rates for different financial assets (deposits, bonds, household and business financing, etc.) and direct link of nominal variables to the real economy, vi) Versatile financing options that correct market gaps (i.e. financing to low income households through energy saving programs) and inclusion of financial repayment plans that allow to trace the interest payments in the future. Recent studies using the GEM-E3 model illustrate the importance of the financial mechanism in simulating policies that lead to capital intensive economic structures. In EC (2016), Paroussos et al (2019^a) and Paroussos et al (2019^b) it is shown that timely availability and access to low cost financing can be a game changer in the implementation of ambitious energy and climate policies.

Human capital and endogenous skills formation, unemployment and multiple households

A key issue for assessing the economic impact of decarbonisation or other structural policies is whether the attempt to drive up investment will run up against capacity constraints, including both capital and labour constraints. In



particular, the accurate representation of policy implications on the labour market requires a distinction among labour skills and their availability, as policy instruments would have differentiated impacts across skills and can potentially cause a mismatch between labour demand and supply for specific skills (i.e. a policy strongly promoting R&I should be complemented with increased human capital, as R&I activities require a high-skilled workforce). Conventional macro-economic models do not differentiate between skills or they exogenously project the number of skills and the size of the labour force, and capture only the potential constraint of broad labour demand and supply imbalances.

In GEM-E3, labour demand by firms depends on cost minimisation of their production function while labour supply is distinguished by skill and is modelled through an empirically estimated wage function (linking wages and labour supply) that allows for the existence of unemployment. A more likely source of labour constraint in a scenario involving substantial structural change is at skill level. The shift of labour demand to sectors requiring highly-skilled labour (i.e. a shift from agriculture to industrial manufacturing or financial services) can potentially cause a mismatch between demand and supply for specific skills and a potential skill shortage. An important caveat in model-based employment projections is that they commonly assume that labour markets are fully flexible, meaning workers can easily migrate to new jobs (i.e. costless and instant skills transformation).

The human capital module in the GEM-E3 model allows households and firms to endogenously decide upon the optimal schooling-education years and on the optimal workforce training respectively. Household's decision to enter the labour market or acquire a skill (through additional education) depends on expected income (based on expectations on wages and unemployment rate by skill). The schooling decision of households concerns only certain age cohorts and allows to endogenously determine the participation rate and the supply of skills¹²¹³ in the economy. The decision of firms to train their workers allows representing endogenous labour productivity growth through training. In this modelling approach, there is no mobility among skills but workers of the same skill are mobile across sectors.

¹² The household choice for education has the following implications: i) Reduction of the available working hours in the short term, ii) Increased demand for education services, iii) Increased labour productivity, due to highly-educated workforce

¹³ Five skills: unskilled workers (level 1), service and shop workers (level 2), technicians / engineers (level 3), clerks (level 4) and managers (level 5)



Implications of policies are not evenly distributed across industries and households. For example in the case of energy system decarbonisation the suppliers of new clean energy technologies and skills will benefit (wind turbine manufacturers or PV installers) whereas some industries will decline (coal mines) and social groups may experience “technology gaps” and “energy poverty”. In order to capture the “inequalities” within households that certain policies may imply the GEM – E3 model features for each country ten households that are distinguished by income class with different consumption patterns, different saving rates and different sources of income according to the allocation of labour skills by type of household.

The inclusion of multiple households and human capital improves the simulation capabilities of the model in a number of aspects: i) Identification of potential bottlenecks due to skills scarcity, ii) the availability of Human Capital and skills is essential to enable productivity growth induced by R&I and knowledge spillovers. Without sufficient human capital and provision of highly-skilled labour (researchers, engineers, STEM), R&I expenditures perform poorly whereas the capacity of the economy to absorb knowledge produced elsewhere is low (limited knowledge spillover effects), iii) reflection of the social dimension of climate policies enabling the assessment of income inequality within and across countries and the identification of vulnerable regions or agents.

R&I and Knowledge spillovers

The modelling of technological progress in GEM-E3 draws on the endogenous growth theory developed in Romer (1990), and Acemoglu (2001). Technological change in the model is endogenous deriving from spending in R&I. The potential of productivity improvement driven by R&I expenditures is based on learning curves (with learning rates derived from a comprehensive literature review). The model simulates innovation which leads to reduction in production costs in terms of each factor of production. GEM-E3 has been updated to the latest data on R&I obtained from the IEA, the OECD and the European Commission.

The R&I capacity of countries is linked to the respective human capital availability. The productivity improvements and associated cost reductions occur once the investment decision is made and thus the gains from the learning effect occur with a one period lag (usually five years). Knowledge spillovers are represented¹⁴ in the model as positive externalities leading to higher productivity of R&D expenditure. Some of the key factors affecting spillovers include: the geographical proximity, distance to the technological frontier, absorptive capacity, human capital, property rights policy. The conventional modelling of knowledge spillovers

¹⁴ Currently knowledge diffusion relates to R&I activities of clean energy products only



in CGE models is based on the exchange of efficient products/services through the bilateral trade transaction of countries. In GEM-E3 knowledge diffusion is based on a novel approach that includes technology transfer matrices based on patent citation data and is linked to the absorptive capacity of a sector/country, with data from the EU and national Patent offices.

Total factor productivity of each firm depends on R&I expenditures, learning by doing and knowledge spillover effects. All parameters related to the specification of endogenous productivity growth (learning by doing, learning by research, knowledge spillovers, human capital) are estimated¹⁵ using panel data analysis with cross country data for the EU member states, China, USA, Korea, Japan and Russia for the period 2005–2016.

The inclusion of endogenous R&I decisions, knowledge diffusion and learning effects improves the simulation capabilities of the model in the following aspects: i) ability to capture impacts on production costs through economies of scale and R&I specialization. Positive effects due to increase in productivity may create comparative advantages in domestic and international markets for firms, ii) induced R&D spending on technologies mitigates the cost impacts of a capital-intensive transition (i.e. energy system restructuring) and magnifies economic growth potential, iii) allows the model to consistently evaluate the impacts of innovation policies and targets for specific sectors and countries and assess alternative R&D portfolios in clean energy technologies.

Regional module GEM-E3-R

GEM-E3 features a link with a regional module that is explicitly developed to allow for an assessment of regional implications on the NUTS2 levels. The regional economy model down-scales national economic trends captured by an Attractiveness Index and considers country-wide results as boundary conditions; hence the national model subordinates the regional. Activity by sector, hence employment, depends on the location of primary production factors (i.e., capital and labour) which draws from new economic geography theory. Regional distributional differences are attributed to local specificities which include resource endowments, human, environmental and infrastructure features of regions. The modelling of location choice aims at quantifying agglomeration and dispersion force that influence regional performance. The regional features that determine the regional performance are often cited in the literature as amenities (positive effect) and dis-amenities (negative effect).

¹⁵ A detailed representation of the methodology and econometric techniques used to estimate the absorption rates of the learning by research and spillovers can be found in the D3.4.2 of the MONROE EC funded project



The regional specificities currently used by the GEM-E3-R model are as follows: i) Natural resources – energy: oil fields, gas fields, coal mines, ii) Energy: refineries, power generation facilities by fuel type, RES capacities and potentials, iii) Industries: cement plants, vehicle equipment plants, iv) Transport: airports, stock of vehicles and trucks, v) Tourism: accommodation facilities, vi) Population: population density, vii) Other socioeconomic indices including human capital (i.e. the share of people with higher education in total active population), vertical integration (presence in the region of activities that are used as input for the sector under consideration), capital intensity.

The starting point for the regionalization of GEM-E3 outputs is the Eurostat's regional database (regional account, SBS and LFS). The goal is to populate the sub-indices of the Attractiveness Index and to construct regional Input-Output tables taking into account all the available information and by combining in a consistent way alternative data sources. This is done by applying iterative methods for filling the missing values and disaggregating the regional datasets to increase sectorial coverage and match the national accounts.

Appendix B: Known limitations of existing models

As a second part of the deliverable, we made an inventory of questions asked to consortium members that often go unanswered. We have split these questions along the same themes as the literature review of new economic modelling techniques in part A. In part B, we collected themes based on a limited-size expert elicitation of modellers from Cambridge Econometrics and E3-Modelling, where we asked what modelling questions go unanswered.

Part A: what economic theory is not well integrated in the model or missing that you believe may have significant impacts on decarbonisation policies?

Innovation science (for instance the impact of R&D funding or regional learning)

- The E3ME model accounts for learning by doing and interregional learning as technologies are deployed in the sectors covered by FTT bottom-up models. However, cross-sectoral learning is not fully captured. For example, batteries used in EVs can help to bring down costs for batteries in grid storage, but innovation in transport and the power sector is modelled separately.
- GEM-E3 captures well the R&D funding and activities, including learning by doing and by research, interregional and intersectoral knowledge spillovers, including also endogenous human capital.

Behavioural economics (f.i. social contagion during a transition, demand reductions)

- In E3ME, changes in consumer preferences (e.g. diets, recycling etc., modal shift) are not simulated endogenously. As a macroeconomic model, E3ME assumes behaviour going forward will match the behaviour observed historically. It currently cannot endogenously consider how behaviour might change over time.
- GEM-E3 includes some elements of behavioural economics for the adoption of new technologies in the transport sector (electric vehicles, shared mobility etc.). Apart from that, any other behaviour changes are only cost-driven. Agents' behaviour is largely the same as the historical observed, while changes in consumption expenditure are driven mainly by price and income elasticities – which are rarely estimated for the particular country/sector/economic agents.



Uncertainty quantification (Are current methods able to capture heavy-tailed uncertainty?)

- FTT does make some consideration of uncertainty in investors preferences for technologies, while uncertainty is not captured endogenously in E3ME. Uncertainty can be accounted for exogenously instead through sensitivity analysis of scenario inputs to test the uncertainty of the shock that could be imposed on the economy. However, this sensitivity analysis does not consider parameter uncertainty.
- Uncertainty in GEM-E3 is captured through extensive sensitivity analysis around its core parameters (substitution-trade-price-income elasticities). This sensitivity is sufficient to capture the uncertainty within “normal” deviations but not the impact of fat tails / extreme events.

Restrictions on finance (for instance due to institutional factors, or currency uncertainty)

- E3ME: While savings equal investment at global level, the money supply is determined by investment demand instead of available savings. Investment demand is assumed to be driven by expected rates of consumer price inflation, future growth in the economy and the rate of interest. Currently, the model does not endogenously account for the difference in financial risk premiums either between regions, technologies or asset classes.
- GEM-E3 is a global economy model, where savings of agents form the basis on which financial supply is determined. The model is “closed” in financial resources / income accounting in the sense that expenditures/investments must match income/savings. As a result, any additional to the reference investment (such as low carbon investments) need to be financed either by domestic or by external capital which is available by crowding out investments or by reducing consumption / increase savings. This “replacement” of investments or consumption can take place in the same time period or in a future one (through loans).

Restrictions on labour (for instance a skills shortage, loss of labour due to health effects from COVID)

- E3ME projects labour demand by sector and accounts for labour supply restrictions in aggregate. It assumes that labour is mobile between sectors and subnational regions. It does have ways to estimate the general skills requirements and supply that may change over time, but this is an off-model extension and there is no feedback imposed from potential mismatches to employment outcomes.
- GEM-E3 features involuntary unemployment also at a skill level (5 or 8 skills). Labour mobility is allowed across sectors, but not across skills unless there is the investment in education (activation of the human capital module).



Dynamical systems science/complexity science (irreversibility, path dependency, feedbacks)

- Within E3ME-FTT, a lot of the dynamics and path-dependencies in the transition to low carbon technologies are captured. However, cross sectoral learning-by-doing is largely missing.
- GEM-E3 is recursive dynamic in the sense that the major path-dependency can be observed for capital accumulation via the investment function. There is semi-endogenous learning, which may create further path-dependency.

Part B: What unanswered questions do policymakers ask most?

What modelling input or output is either missing in the model, or you believe should be incorporated better to answer recent questions from policymakers?

- Value Chains
 - Example questions: what bottlenecks can be identified in the transition? If you trace the ownership of companies, which countries benefit from the policies such as CBAM?
 - Bottom up representation of companies and their ownership is essential for tracking the impact of policies across countries and economic agents. Introducing origin and destination of capital in models, and allowing for a separate estimation of GDP and GNI. The distinction between national and international capacity (technical, financial etc.) to meet energy and climate targets is essential to understand the reallocation of resources (both capital and employment remuneration), and further assessment of income inequality etc. Both models do not cover the above.
- The full cost of climate policies accounting for physical damages
 - Example questions: How does climate damage impact clean industries? What are the economic benefits from mitigating climate change – from a physical impacts perspective.
 - Models either capture only the physical impacts or the monetary impacts – very few are the cases where a holistic, comprehensive and consistent modelling approach is used to provide the full cost of climate change. Both models do not cover the above.
- Plausibility / Success of policies
 - Example question: what are the risks of policies failing and the policy mix not meeting the set targets?
 - Evaluation of the success rate of different policy implementations design is missing, in the sense that models assume full implementation/complete success of introducing policies. Both



models do not cover the above. This sometimes includes an unrealistically fast initial implementation of policies.

- Environmental outcomes of policies
 - Example question: what are the environmental impacts of the installation in clean technologies?
 - From an environmental perspective, both models do not (yet) account for (both as impacts and with economic feedbacks): Land use Water Loss of natural resources/biodiversity
 - E3ME does not account for the spatial distribution of environmental outcomes within a region.
- Specific sectors (for instance hydrogen, shipping, the informal economy)
 - Example question: What policies are needed to accelerate the transition in demand and supply of hydrogen?
 - E3ME does not have a good representation of hydrogen technologies and the economic supply chain to support it, and a model on agriculture and land use is still in progress.
 - The two models cannot capture endogenously the creation of new low-carbon industries/technologies that are not widely deployed yet. In E3ME, the simulation of CCS and BECCS is almost entirely based on assumption (through kick-start policies) whereas others (e.g. batteries, green steel, hydrogen, biofuels, recycling) are not typically included or can be modelled only through exogenous assumptions and simplified treatments.
 - GEM-E3 captures the hydrogen, clean fuels, batteries, BECCS etc. and also the manufacturing sectors of low carbon technologies but does not capture yet other negative emission technologies (e.g. Direct Air capture).
- Downscaled inputs/outputs
 - Example question: which subnational regions have the largest opportunities in the transition?
 - E3ME cannot easily evaluate inputs that target specific elements of a distribution i.e household energy efficiency savings targeting low-income households has potentially different consumption/savings implications to energy efficiency savings in high income households
 - E3ME does not produce outcomes at a subnational/subregional level. This is sometimes covered through off model analysis using simple disaggregation techniques such as shift share analysis
 - GEM-E3 has a regional module that uses sophisticated techniques to downscale national results to sub-national (NUTS2) levels, but the module needs further refinement in terms of data revisions. Also, currently the module has not been used for the assessment of region-specific policies. This is not possible at the moment.
- The type of systemic or financial risks



- Example questions: how to resolve barriers to finance for green investment in the Global South? How does decarbonisation policy impact the stability of currencies and financial markets?
- Financial sector representation – The representation of the financial sector in E3ME is rather limited. This makes the modelling of debt-funded investments and climate finance (often through loans/debts) so far incomplete.
- Consequences of financial (and, in turn, macroeconomic) stability are thus not considered.
- GEM-E3 does not feature a climate damage function and thus depends on biophysical models to assess climate physical risks. On the financial risks, GEM-E3 features a financial module with detail in the national and international capital composition. Nevertheless, the module requires further developments and data to be effectively used in standard assessments.
- Opportunities from the transition (for instance from being an industry leader)
 - Example questions: how large are the first-mover advantages of the transition? To what extent do other countries catch up?
 - E3ME does not have a way to model first mover advantage in securing more of the global value chain in new markets.
 - On the other hand, GEM-E3 models first mover advantages through semi-endogenous technical change. In the low-carbon sectors there is learning by doing and by research, with associated spillovers across sectors and regions.
 - GEM-E3 represents explicitly some low-carbon manufacturing sectors (PV modules, wind turbines, batteries, hydrogen etc), allowing for job creation when the respective demand is increasing
 - Neither model captures very new technologies well.
- The interaction between climate risk and decarbonisation policies
 - Example question: how does climate change and extreme weather pose risk to the energy transition and clean technologies?
 - Climate-related impacts – gradual physical risks, biodiversity tipping points, extreme weather events. These types of effects are not captured endogenously in E3ME nor GEM-E3. This means that:
 - The negative economic impact of these climate damages is not well-represented in the baseline scenarios
 - Policies to address them can only be modelled indirectly through exogenous assumptions for the initial policy impacts on economic variables.
 - The positive economic impact from decarbonisation to avoid those damages is not fully captured
 - Adaptation modelling: neither of the models currently has a treatment for this, and we also cannot track well international aid for adaptation/mitigation



- The physical resource constraints to deliver the economic transition.
 - Example question: are there sufficient minerals available to produce low-cost green technologies?
 - While FTT does consider some resource constraints for global energy resources (both for non-renewable resources (i.e. oil reserves) but also constraints on renewable energy potentials) beyond this, E3ME-FTT does not account for any short-term supply constraints or mineral shortages.
 - In a demand-led model such as E3ME, we do not capture the possibility of hard supply constraints that restrict output (leading to behavioural responses e.g. the balance between prices and rationing etc).
 - GEM-E3 is currently extended so as to account for the material balance Input Output framework and consider stock flow relationship of raw materials.