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Modelling the Zero-Carbon Transition: International Approaches and Lessons for Ireland

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Chapter 1
Introduction

"All models are wrong, but some are useful" – George E. Box [1]

The zero-carbon transition is a form of socio-economic transition, involving major changes over decadal timescales in buildings, energy and transport systems that improve energy efficiency, reduce demand, or entail a shift from fossil fuels to renewable energy inputs [2]. Socio-economic transitions are enacted by a wide range of actors such as firms, consumers, policy-makers, local authorities, researchers, social movements and the wider public. These are complex, multidimensional problems [3].

Government policy is intended to lead the low-carbon transition by incentivising the innovation, diffusion and adoption of primarily energy-related low-carbon technologies. The principle of a just transition means no social groups (such as workers in the fossil-fuel industry) are abandoned in a process driven by government policies, including carbon taxes, feed-in tariffs, energy efficiency standards, industry subsidies and community support schemes. Quantitative models of the economy and energy system are often applied to determine appropriate responses to climate change in the energy sector, assess the impact of policy proposals on the economy and identify vulnerable groups during transitions. Such insights are crucial to a just transition.

Conceptualising a complex phenomenon like a socio-technical transition is incredibly challenging. All models of socio-economic transitions, therefore, require some simplification and assumptions in order to make them tractable. These simplifications and assumptions often lead models to investigate specific transition-related questions, such as the economic impacts of individual climate policies or the behaviour of economic actors in electricity markets. The results of these models are a useful input to the process of policy-making [4-8].

Integrated assessment models are the standard tool used to carry out climate and energy policy analysis at an international level. A subset of integrated assessment models, called energy-economy-environment models, are generally applied to assess the impact of policies on aggregate quantities such as gross domestic product, welfare and employment.

The structure and theoretical assumptions of a model determine its capability to answer particular research questions. A model's results are only as valid as its underlying assumptions. Stakeholders need to have sufficient confidence in the theoretical framework assumptions of the model. All studies should, therefore, clearly state their assumptions alongside their results, and policy-makers should have a sufficient understanding of the implications of the assumptions [7-9].

The problem of identifying the most vulnerable groups and sectors in the economy during a low-carbon or digital transition is complex. Several different theories and perspectives should be used to approach the problem [2, 4, 6]. A model that could provide insights into the dynamics of the transition with an emphasis on identifying vulnerable groups and sectors would require several distinct characteristics:

- Representation of the entire national economy, disaggregated into sectoral components.
    - Economic sectors are interdependent so a model must be able to account for the ripple effect of policies across the entire economy.
- Representation of exogenous variables such as foreign direct investment (FDI), technology costs and fuel costs.
- Representation of a suite of environmental, climate and energy policy instruments.
    - To investigate the effects of government policy, models must be able to carry out 'what if' experiments by applying different policy instruments.
- Representation of heterogeneous economic actors with bounded rationality.
    - Climate and energy policies often have distributional effects.
    - Economic actors with different incomes and attitudes are known to affect the rate of diffusion and adoption of technology.
    - Economic actors are known to act with bounded rationality, affecting their ability to make optimal decisions.
- Detailed representation of energy technologies, including alternative energy generation and transmission technologies, to allow for the growth of a renewable energy sector.
- Representation of innovation to model changes in technology and organisational or societal structures.
    - Government policy in the zero-carbon transition is intended to incentivise innovation and lead to more efficient technologies.
- Endogenous representation of the financial sector and the associated opportunity cost of sustainable development.

To effectively use modelling in Ireland, several important steps will need to be taken, including improving our current modelling capabilities and evaluating the results obtained from modelling in a sophisticated manner.

Chapter 2
Modelling Theory

The field of quantitative economic modelling is broad and complex. There are many competing approaches to projecting the effects of certain shocks or policies on our future economy. This section will lay out the fundamentals of modelling — with a focus on the impact of climate and energy policies on the economy — and provide a classification of the models generally used in climate and energy policy research.

2.1 What is a model?

Computer models are simplified representations of the real world in abstract, mathematical terms. They are useful in situations where it is impossible or unethical to carry out experiments, such as forecasting the weather or projecting the impacts of specific policies on the economy.

Algebraic equations or logical rules that describe the relationship between different variables generally constitute the inner workings of computer models. The variables describe real-world features that change over time, such as temperature, unemployment, or a carbon tax. In theory, if the relationship between certain variables is understood (either from an empirical or theoretical standpoint), a change in the values of one set of variables can be used to project changes in the values of another set of variables. For example, future average global temperatures can be inferred from the projected increased concentration of greenhouse gases in the atmosphere, or the future changes in employment across economic sectors could be projected from an increase in carbon tax.

All models require assumptions and simplifications in order to make the problems tractable and feasible to be calculated on limited computing power. These assumptions take many forms. They arise from economic theory, technological limitations, and climate science.

2.2 Model classification

Classifying the extensive variety of modelling approaches is a challenge unto itself. Models often have characteristics that merit their inclusion in more than one category, and researchers sometimes use different descriptions and definitions when referring to the same model structure or concept. Below is a discussion of the most common model types referred to in the literature. These model categories will form the framework for the rest of the report.

2.2.1 Top-Down/Bottom-Up Models

Before discussing the specific classifications, the concept of top-down and bottom-up models must be addressed. This broad categorisation indicates whether a model's focus is on aggregate variables such as GDP or employment, and forms a picture of the macro-economy (top-down), or if the focus is on disaggregated aspects of an economic system such as a technologically rich representation of the energy system (bottom-up).

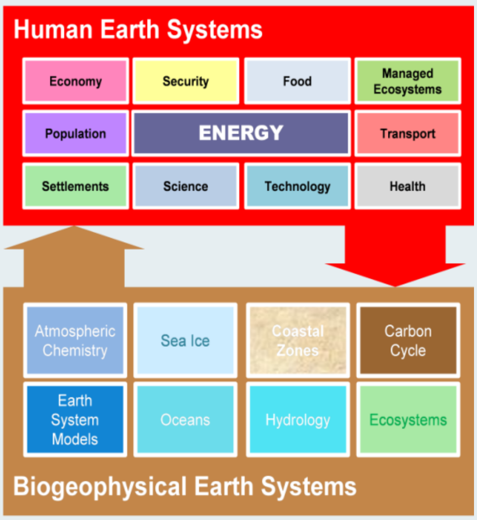
Top-down models represent the economy as a whole, distinguishing production sectors, consumer categories and often the government, each characterised by representative economic agents. The microeconomic behaviour of the economic agents is explicitly represented, generally either through a neoclassical framework or determined econometrically. Technological realism is usually lacking [4, 10].

Bottom-up models disaggregate various sectors and technologies, and focus on technological detail over realistic micro-economic behaviour and complete macro-economic representation. They generally focus on the energy system, representing the technical and economic information of a variety of technologies [10, 11].

2.2.2 Integrated Assessment Models (IAMs)

All models used to analyse the low-carbon transition fall into the category of integrated assessment models. This includes all of the model categories in the following sections. Any model which represents multiple domains of knowledge, examples of which are illustrated in Figure 1, can be considered an integrated assessment model. They are named thus because they integrate knowledge from two or more domains into a single framework; for example, combining climate science, energy engineering, and economic theory [12].

Figure 1 Schematic showing the integrated assessment of different knowledge domains



A subset of integrated assessment models that is of particular relevance to modelling the low-carbon transition is *energy-economy-environment* models. These models are the primary tool for investigating the implications of climate and energy policy on wider society [7]. When investigating vulnerable groups in a low-carbon transition, all models will require some representation of the three interacting arenas of energy, economics and the environment. They are also the reason for the commonly used fragment 'E3' in many model names.

2.2.3 Energy System (ES) Models

Energy system models are any model of an energy system, such as a machine, a building, a town or a region. National energy system models are commonly bottom-up techno-economic optimisation models. After exogenously inputting demand for energy services, such as heating, lighting and industrial processes, these models then optimise the energy system to provide a least-cost pathway under certain technological and resource constraints. In this way, they assess potential future energy systems and their interactions with different sectors [13]. There are several other approaches to these problems, including simulation models which attempt to provide a descriptive, quantitative illustration of energy demand and conversion, with the objective of modelling observed and expected decision-making that does not follow a cost-minimising pattern [14]. The Sustainable Energy Authority of Ireland (SEAI) makes use of simulation models regularly [15].

The models include representation of the entire energy system, including resources, energy production technologies, energy carriers, demand devices and sectoral demand for energy services. Sectors such as transport, electricity generation, industrial processes, heating and cooling, and lighting are usually included. Energy system models are best suited to identifying technical options such as the fuel and investment costs associated with particular climate and energy targets [16].

The most common modelling framework used in this context is the Integrated MARKAL-EFOM System (TIMES) family of models. The TIMES model generator is developed and maintained by the Energy Technology Systems Analysis Programme (ETSAP), established by the International Energy Agency in 1976.

TIMES is a technology-rich model generator for providing medium-to-long-term analysis and planning for national, regional and even city-level energy systems. The model assumes perfectly competitive markets and full foresight. The optimisation is based on welfare maximisation, by minimising the total system costs discounted to the reference year. The minimum total cost is achieved through decisions on equipment, operation, primary energy supply and energy trade. Inputs to the model are demand and supply curves, policies such as carbon taxes, and techno-economic parameters for each technology such as efficiency and investment costs. Outputs are the regional and time-specific optimal investments, operation and import/export levels, as well as costs, environmental indicators, marginal prices of commodities and energy flows [10, 13, 16-20].

Other examples include the PRIMES model instigated by the European Commission and operated at the E3MLAB National Technical University of Athens and the global MESSAGE model operated by the International Institute for Applied Systems Analysis (IIASA) in Austria [5].

2.2.4 Computable General Equilibrium (CGE) Models

Computable general equilibrium (CGE) models are top-down models that describe entire economies — national or global — and their sectoral interactions. They are the dominant tool in top-down energy-economy-environment modelling [4, 21-23].

CGE models follow the neoclassical theory assumptions of rational choice, utility and profit maximisation, and perfect information. The models make these assumptions to simplify the modelled system and reduce it to a tractable state. They seek to explain the behaviour of supply, demand and relative prices across an entire economy with many markets [7, 24-27].

The models consist of agents in an economy, with producers maximising profits and consumers maximising utility depending on commodity prices, until all resources are efficiently allocated and the economy is in general equilibrium. The behaviour of the agents in the model are represented by equations that determine the equilibrium conditions.

CGE models are widely used to simulate the direct and indirect economic effects of climate policies, most commonly carbon taxes. The analysis usually begins with the simulated economy in a general equilibrium condition, based on real-world data. A policy shock is then introduced, such as an increase in the price of carbon, which causes further changes in the prices of other commodities. Neoclassical economic theory asserts that the economic actors will then adjust their consumption and production to maximise their utility and profit in the new price regime, and that over time supply and demand will converge to another steady state, i.e. a new general equilibrium. CGE models attempt to model this convergence, across multiple interconnected markets, following the initial policy shock. Equilibrium can only be achieved when all markets are in equilibrium [24].

There are two main components in a CGE model: the structure and the database.

The standard structure is a relationship between all sectors and subsectors in terms of supply and demand of goods and services. Capital, labour and intermediate resources are inputs for producing a service or good. When the economy is at equilibrium, households, governments, investors and producers purchase these goods and services. The database consists of two parts: the flow of spending and income in an economy and the parameter values. The money flows are usually provided by national statistics departments in the form of input-output tables [24].

There are many categories of CGE models, but it is simplest to define static and dynamic CGE models. Static models look at ‘before and after’ equilibria of the economy after a policy shock. Dynamic models have time-variant capital stocks whose availability depends on investment in the previous year [24].

2.2.5 Macro-Econometric (ME) Models

Similar to computable general equilibrium models, macro-econometric models represent entire economies and often model the economic impacts of climate policies, but their treatment of economic behaviour is notably different from computable general equilibrium models.

In macro-econometric models, actor interactions are econometrically estimated from historical data. The statistical relationship between model variables such as price and quantities are used to determine the model dynamics. Therefore, the assumptions of neoclassical economic theory — perfect rationality, perfect markets, efficient use of resources and economic equilibria — are not enforced. This allows for disequilibria and inefficient allocation of resources, such as unemployed workers, unused equipment and financial capital. Macro-econometric modellers claim that their formulation provides a strong empirical grounding, and means the model is not reliant on many of the rigid assumptions common to other approaches [7, 26-28].

This econometric formulation allows many macro-econometric models to account for fundamental uncertainty. This post-Keynesian premise recognises that agents have limited knowledge and cannot know all the possible outcomes from a decision-making process. Fundamental uncertainty is often referred to as acknowledging the existence of 'unknown unknowns'. From a position of fundamental uncertainty, it is not possible to optimise the decision-making process, so either decision errors are made or actors plan ahead for uncertain outcomes.

2.2.6 Hybrid

Hybrid models link the previously defined modelling approaches (top-down and bottom-up) to examine the interdependencies across the energy system. They aim to capture both the representation of economic behaviour found in CGE or ME models and the technical detail of energy system models. From a national policy perspective, this has the advantage of addressing complex energy and climate policy issues by including detailed representation of the energy system and the economic interactions [25].

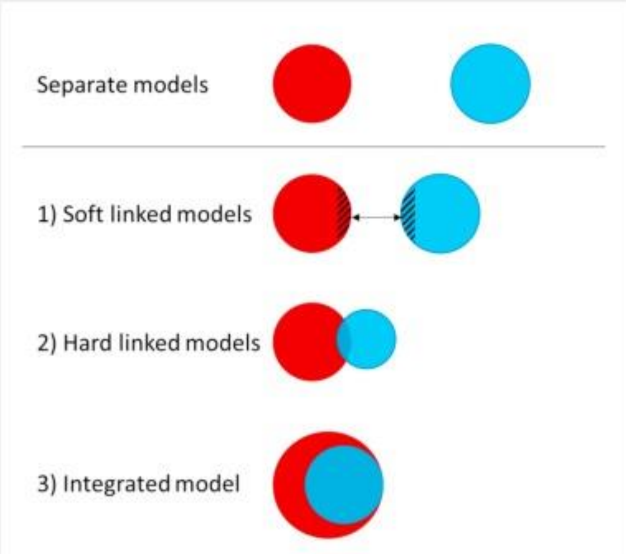
There are two main variants of hybrid energy-economy-environment models. *Soft-linking* involves exchanging data between top-down and bottom-up models or between separate models within the same domain. This method offers transparency in the chain of cause and effect, since both models are left intact. The running time to generate future scenarios is manageable. The transfer of information is controlled by the user [20, 25].

In *hard-linking*, information is exchanged without user judgement, directly within the computer program. The optimisation process occurs without any manual checks and the model process can be opaque. *Integrated* models, such as IMAGE [29], include representations of both bottom-up and top-down aspects within the same model.

The concepts of full-link and full-form approaches are also important in classifying hybrid models. 'Full-link' means that the model represents more than one economic sector, whereas 'full-form' combines detailed technology data with a disaggregated economic structure [10].

Ireland [30], Norway [20], Portugal [10], Sweden [16], Denmark [25], and Austria [31] have all developed hybrid models.

Figure 2 Hybrid Model Variants



2.2.7 Agent-Based Models (ABMs)

ABMs describe the behaviour and interaction of heterogeneous actors in a complex evolving system of objects and environment across different spatial and temporal scales. The models have the unique capability to capture emergent system-level behaviour out of the individual behaviour of its actors, defined by aggregate properties that cannot be derived from the simple aggregation of individual agents [21, 22, 32].

Unlike in a CGE or ME model, there are no equations governing the system as a whole. Instead, actors in an economy are represented by computer-coded agents given a simple set of rules or properties that constitute their individual identity and determine their interactions. These agents are the individual unit of analysis.

Through their interaction rules, the agents observe a surrounding set of data (their 'environment'), exercise decisions based on that data and then update the dataset. The new data becomes part of the environment seen by the other agents in the system and is incorporated for future rounds of decisions. In this manner, the emergent collective behaviour is then investigated to determine if there are any patterns in the system. In contrast to CGE models, with ABMs it is possible to design irrational agents with incomplete information in relatively uncertain situations – arguably a more realistic representation of reality [33-35].

Examples of ABMs include the famous Sugarscape model [36], the Dystopian Schumpeter meeting Keynes (DSK) model (used to investigate the economic impacts of different types of climate shocks) [21] and the Dutch-led EMLab-Generation, which is looking at a range of projects, including price stability in the EU-ETS market and the representation of intermittency in national energy system analysis [22].

2.3 Modelling Shortcomings

2.3.1 Integrated Assessment Models (IAMs)

Integrated assessment models in general have been criticised on theoretical and empirical grounds. According to Nicholas Stern [37], author of the famous Stern Review, current climate models tend to underestimate the impact of climate change and the benefits of a low-carbon transition. In particular, IAM estimates of the social cost of carbon (SCC), the incremental change or damage to global economic output resulting from one tonne of anthropogenic carbon dioxide emissions or equivalent, are generally far too low because the major risks such as climate tipping points are not accounted for. SCC estimates depend on questionable discount rates that translate future costs to present values, and assume that benefits to people in the future are less important than benefits to people today.

Most IAMs also omit the huge costs due to air pollution by fossil fuels and often fail to describe the developments in alternative energy due to learning processes and economies of scale, leading the models to overestimate the costs of decarbonisation by not fully capturing the low-cost opportunities for emission reduction [38].

Many IAMs also rely on mainstream economic theories that make restrictive assumptions about the behaviour of social and economic actors, and on the idea of a 'fully informed benevolent social planner' that can shape the system from the outside. They also privilege price-based instruments and restrict considerations of a wider range of policy instruments [2].

2.3.2 Energy System Models (ESMs)

Energy system models depend on demand inputs, usually determined by macroeconomic models. The assumptions of these macroeconomic models are inherently uncertain and therefore introduce uncertainty into the energy system model.

ESMs also struggle to account for feedback between the energy system and the wider economy, although researchers at University College Cork (UCC) have done so by hard-linking a macroeconomic model to the energy system model [39]. Most importantly, energy system models do not simulate consumer behaviour in highly realistic ways, relying on standard economic assumptions about the rationality and foresight of model actors [10, 19].

2.3.3 Computable General Equilibrium Models (CGEMs)

All CGE models are based on a general framework of *neoclassical economic theory*. Following exogenous policy shocks, the economy is assumed to return to a stable equilibrium, driven by the utility or profit optimisation of economic actors. The economic actors are assumed to have complete information, perfect foresight, rational decision-making, and competitive price-taking behaviours (with no monopolies). The term *homo economicus* is used for this portrayal of human economic behaviour. This type of perspective is in a sense a *normative* approach, indicating how economic actors ideally should behave, rather than how they are observed to behave [8].

Contrary to the neoclassical economics of CGE models is post-Keynesian theory, which sees the economy as being in perpetual dynamical change and assumes that economic decisions take place under *fundamental uncertainty*. This means that certain outcomes and implications of economic decisions are impossible to quantify [8].

Moreover, behavioural economics demonstrates that many other behavioural factors influence the decisions of consumers, firms and policy-makers, such as routines, norms, belief systems and interpretations. Such a range of influences on behaviour leads to heterogeneous actors, whose aggregate behaviour may not be captured by a single representative agent. Utility maximisation is also known to exclude attitudes towards risks, gains, losses and uncertainty [2, 40, 41].

The economic equilibria of neoclassical theory are defined as optimal states at which supply meets demand and all markets clear. Following exogenous disturbances such as policy shocks, the economy will tend to a new equilibrium, which involves the efficient use of all economic resources, including employment and capita, under a new price regime. It is this assumption that leads CGE models to consistently signal the negative impacts of proposed policies.

If the economy is assumed to be in an initially optimal state that, following the introduction of a policy shock, will move to a different equilibrium state with a less efficient use of resources, then by definition the introduction of a policy has a negative impact on the economy. It is important to clarify that this does not mean the models predict that the introduction of policy shocks will result in recession, but only that there will be less economic growth than would occur if the climate policy had not been introduced. The negative impacts of policies manifest in the models as reduced GDP growth *relative to the baseline scenario*. The baseline scenario is initially calculated and involves the efficient use of all resources given certain constraints. Following a policy shock, such as a carbon tax, a new scenario is modelled, which inevitably has less GDP growth than the baseline [41].

The equilibrium approach can be countered with the observation that the economy is currently in a suboptimal state. Factors such as unemployment occur frequently in economic history [41]. This leads researchers in the field of complexity economics to believe that equilibrium is the wrong paradigm through which to view the economy [42, 43].

Taking into account fundamental uncertainty, behavioural economics and the criticisms of equilibrium theories, the suitability of neoclassical economics in CGE models as a representation of realistic economic behaviour can be reasonably questioned [2, 41].

There is also the contentious issue of money. The treatment of finance in CGE models follows a Walrasian concept of money as simply an exchange value, with the total money supply generally fixed over time. This explains the fact that CGE models consistently show the negative impacts of policies; they assume that investments driven by climate and energy policies can only be financed by taking investment from elsewhere in the economy (crowding-out) or by reducing consumption (and therefore welfare). Essentially, money is treated as a metric for presenting model results. This assumption does not necessarily mirror the real world [8].

Post-Keynesian economic theory suggests that, in reality, commercial banks have the ability to generate new money in the system through debt, allowing for investment in new infrastructure, bringing in unused resources and potentially reducing unemployment, ultimately driving economic activity. In the context of climate and energy policy, which often seek to reduce investment in carbon-intensive activities and increase investment in the renewable energy industry, realistic representation of finance is critical. Otherwise, CGE models will fail to capture some of the economic opportunities associated with climate and energy policies [7, 26].

2.3.4 Macro-Econometric Models

Since the behaviour of actors in macro-econometric models is dictated empirically from historical data, they do not suffer from the same criticisms regarding the assumptions of neoclassical economic theory. Furthermore, in contrast to the *normative* representation of economic activity in equilibrium models, macro-econometric models take a *positive* view of behaviour, attempting to describe how economic actors do behave, rather than how they should behave.

However, it can be debated whether equations describing the behaviour of economic actors in the past are necessarily accurate in describing their behaviour in the future. The implicit assumption in macro-econometric models is that behaviour that characterised economic interactions in the past will continue into the future, despite factors that are expected to change behaviour, such as the impending digital and low-carbon transitions. This a form of the Lucas critique [44, 45].

Another important consideration is that macro-econometric models are dependent on the availability of high-quality, fine-grain historical time series data to determine the empirical relationships between sectors. Many models require data going back 40 or more years, with several indicators for each sector across several countries.

2.3.5 Hybrid Models

Hybrid models seek to overcome the respective shortcomings of bottom-up and top-down approaches by combining insights from both types of model. Nevertheless, the assumptions about the behaviour of actors are still present in the combined models, depending on the assumptions of the macro-economic component of the hybrid model [4]. Also, the issues that occur in CGE models regarding the representation of finance are also present in hybrid models.

2.3.6 Agent-Based Models (ABMs)

A significant drawback of agent-based models is that the interactions between agents are typically not calibrated to data and instead determined by behavioural rules instigated at the discretion of the modeller. It can be unclear what is learned from the model outcomes, as the emergent complex patterns can obscure the nature of the underlying phenomena and depend on the definition of the interaction rules [7, 22, 24].

ABMs are typically one-off modelling exercises tailored to very specific problems. Often, they focus on specific sectors such as energy markets where uncertainty and heterogeneity are known to be important. This can lead to a lack of robustness in the modelling approach, with models often having strikingly different theoretical content and investigating unrelated phenomena. In general, there is a lack of standard techniques for constructing and analysing ABMs [46].

Chapter 3
International Approaches

Figure 3 Notable international modelling approaches

Region	Model	Class
Ireland	I3E [47]	CGE
	Irish TIMES [19]	ES
Global	TIAM-MACRO [48]	IAM
EU	GEM-E3 [49]	CGE
	PRIMES [50]	Hybrid (CGE)
	NEMESIS [50]	Hybrid (ME)
OECD	ENV-Linkages [51]	CGE
UK	E3ME [28]	ME
Denmark	IntERACT [25]	Hybrid (CGE)
Portugal	HYBTEP [10]	Hybrid (CGE)
Netherlands	AgentSpring [22]	ABM
	IMAGE [29]	IA
Norway	REMES [20]	CGE
Germany	PANTA RHEI [52]	ME
	REMIND-D [53]	Hybrid (CGE)
France	3ME [54]	Hybrid (ME)
Sweden	EMEC / TIMES [16]	Hybrid (CGE)
Austria	e3.at [31]	Hybrid (M-)

Many governments and international organisations apply energy-economy-environment models to support decision-making, especially related to climate and energy policies. These models are intended to aid the design of optimum policies. The above table is intended to provide an overview of the approaches by organisations relevant to Ireland, and frame Ireland's efforts in the context of the general international approach. Case studies of notable models are outlined in the following sections.

3.1 OECD

3.1.1 ENV-Linkages

The OECD deploys a global recursive dynamic general equilibrium model called ENV-Linkages to assist governments with decision-making and investigate the medium-to-long-term impacts on macroeconomic variables such as GDP and labour-market statistics from a range of climate-change mitigation and environmental policies. Like all computable general equilibrium models, the model is based on neoclassical microeconomic foundations [51].

Economic activity is aggregated into 22 sectors, while seven distinct electricity production technologies are specified, each with its own carbon emission parameter, determined from the International Energy Agency. Households are included as a representative consumer that allocate their disposable income according to preferences on commodities. A representative electricity producer maximises profit by using five available energy technologies – fossil fuels, hydro and geothermal, solar and wind, and renewable combustibles and waste. Carbon capture and storage technology is also represented. The governments collect taxes and can also provide subsidies.

The ENV-Linkages model has been applied to research competitiveness and carbon leakage in the face of climate policies [55], the impact on emissions of reducing fossil-fuel subsidies [56], and – particularly relevant to identifying vulnerable sectors of the economy during a transition – the labour-market implications of mitigation policies [57]. The results of this final piece of research suggested that the impact of climate and energy policies is generally small and overall positive, given that the emission reduction targets are not too ambitious and carbon-tax revenues are recycled to lower income taxes. Low-skilled workers were found to be more affected by the policies than other categories of workers.

3.2 European Union

3.2.1 GEM-E3

The General Equilibrium Model for Economy-Energy-Environment (GEM-E3) is a multinational collaboration project partly funded by the European Commission, regularly used to provide support to European Commission services, especially on the economics of climate change [49]. GEM-E3 is a highly detailed and sophisticated CGE model.The world version of GEM-E3 represents 38 regions and 31 sectors linked through endogenous bilateral trade flows. The economic agents in the model individually optimise their objective (maximising profit or utility) while the prices, derived from supply and demand interactions, guarantee global equilibrium. The model has bottom-up representation of different power-producing technologies, semi-endogenous learning-by-doing effects, equilibrium unemployment, and options to introduce energy efficiency standards and emission permits for GHG and atmospheric pollutants.

There is also a variety of emission abatement policy instruments in the environmental module, including different allocation schemes (grandfathering, auctioning, etc), user-defined bubbles for traders, and various exemptions and revenue-recycling systems.

GEM-E3 focuses on sustainable economic growth and supports the study of related policy issues. The model is designed to support the analysis of the distributional effects, both among countries and among social and economic groups in each country. It emphasises the analysis of market instruments for energy-related environmental policy, the assessment of the distributional impacts of those policies, and the need for the European Commission to produce energy and environment policy scenarios.

Examples of analyses that GEM-E3 has undertaken include contributing to the EU's 2030 Climate and Energy Framework and the EU's preparation of the international climate negotiations at COP21 in Paris in December 2015.

3.2.2 E3ME-FTT-GENIE

E3ME is a global model covering the world's economic and energy systems and the environment. Initially instigated through the European Commission's research framework, since 2015 Cambridge Econometrics has maintained and developed the model further.

The model's theoretical approach is post-Keynesian, meaning that actors in the model are assumed to base their decisions on limited knowledge and not expected to optimise their behaviour [28]. E3ME also rejects perfect competition and fully flexible prices. The formulation allows for the possibility of unused resources such as labour and capital. Instead of using textbook optimisation and maximisation functions to model behaviour, the relationships between actors and goods are determined through econometric estimates based on historical data. The econometric relationships are regressed on 45 years of data and projected 35 years into the future. There is a high level of detail in the model, with significant disaggregation across sectors, regions and socio-economic groups.

The question of whether historical behaviour will continue into the future generates greater uncertainty about model results as the time horizon increases (the Lucas critique), but the researchers believe their estimations provide the best, non-biased guess of economic behaviour and 'do not rely on assumptions about optimisation that behavioural economists have repeatedly disproven'.

E3ME has been applied to generate an assessment of the economic and labour-market effects of the EU's long-term climate policies [58], including a novel integration with the technology diffusion model (FTT) and atmospheric circulation model (GENIE). This hybrid model, dubbed E3ME-FTT-GENIE [27], was also used to assist the New Climate Economy report [59].

The FTT model determines the changes in environmental intensity of economic processes, while the GENIE models the climate-carbon cycle and the associated emissions from economic activity. The E3ME model also incorporates endogenous money, addressing a major shortcoming of standard modelling approaches. Endogenous money means that investment is not a function of total output but is instead determined by increases in economic growth rates. The money supply is therefore determined endogenously. This allows the model to yield positive economic and social benefits from technological change following the introduction of climate policies. The researchers claim that this model is the first of its kind, combining economics, technology and the climate system with the highest available definition of policy instruments [27].

3.2.3 NEMESIS

The New Econometric Model of Evaluation by Sectoral Interdependency and Supply (NEMESIS) is a system of economic models for every European country (EU27 apart from Bulgaria and Cyprus and including Norway), USA and Japan. The model studies issues that link economic development, competitiveness, employment and public accounts to economic policies. It is used to develop business-as-usual scenarios, up to 30 years into the future, as well as alternative scenarios for the EU to reveal future economic, environmental and societal challenges (projections of employment, for example) [50, 60].

The mechanisms of the model are based on the behaviour of representative agents: enterprises, households, governments and the rest of the world. The behaviour of these agents is econometrically determined. NEMESIS can be viewed as a macro-econometric hybrid of bottom-up forces from sectoral dynamics and top-down macroeconomic factors.

The model distinguishes 32 production sectors on the supply side, each modelled with a representative firm that takes production decisions based on capacity expansion and input prices. Their behaviour is based on innovative features grounded in new growth theory, including endogenous R&D decisions that allow firms to improve their process productivity. On the demand side, household consumption is dependent on current income, adjusted for regional interest rates and inflation. The energy/environment model computes primary and final energy demand of 10 different energy products and the resulting CO_2 emissions.

The NEMESIS inputs are interest rates, exchange rates, prices of commodities, demographic assumptions by country, and assumptions on national policies (fiscal, energy and environment). The model then outputs detailed projections on GDP, prices, competitiveness, employment, revenues, energy demand by product and sector, electricity mix and GHG emissions. NEMESIS has been used to study the economic impacts for alternative EU climate policies and policy assessment regarding research and innovation [50].

3.3 Germany

3.3.1 PANTA RHEI

In 2011, research was carried out at the GWS (Gesellschaft für Wirtschaftliche Strukturforschung) by Lehr *et al*. [61] to investigate the economic impacts of renewable energy expansion in Germany, in particular on employment. An econometric simulation and forecasting model called INFORGE was environmentally extended to create a hybrid economy-energy-environment model called PANTA RHEI.

The behavioural equations in the model do not assume optimising behaviour by economic agents and instead reflect bounded rationality. All parameters that determine the behaviour of agents were estimated econometrically from time-series data, from 1991-2008. The agents therefore have myopic expectations following routines developed in the past, and can make suboptimal decisions. Markets in PANTA RHEI will not necessarily be in an optimum equilibrium; thus energy policy interventions can have positive impacts.

The core of PANTA RHEI is the economic module that calculates final demand (consumption, investment and exports) and intermediate demand (domestic and imported) for goods, capital stocks, employment, wages, unit costs and producer and consumer prices in deep disaggregation of 59 industries. The energy module captures the dependence between economic development, energy input and CO_2 emissions.

A key element of this model is the integration into the modelling framework of input-output structures for the renewable energy sectors. Since the research set out to investigate the impacts of renewable energy on the economy, it was considered necessary to adequately model the sector. 'Production of systems for the use of RES' was included as a sector and divided into subsectors, each representing a defined RES technology.

Using their model, the researchers carried out a scenario analysis, including various possible futures depending on international energy prices, domestic investment in RE, additional costs of RE systems, and international developments and exports. They found that, in their model, an expansion of renewable energy in Germany leads to positive net employment in most scenarios. The best-case scenario was a high-export, large PV expansion, providing 200,000 more jobs in 2030 than would be created without the expansion of RE [61].

This research demonstrates the importance of representing the renewable energy sector when modelling the impacts of climate and energy policies on the economy.

3.4 Portugal

3.4.1 HYBTEP

In 2014, Fortes *et al*. [10] soft-linked a bottom-up energy system model of Portugal based on the TIMES framework (TIMES_PT) with a top-down CGE model (GEM-E3_PT) to create a hybrid modelling platform, named HYBTEP (Hybrid Technological-Economic Platform). Their motivation was to overcome the primary shortcoming of CGE models in their view (the representation of a range of technology options) and assessing the benefits of developing a hybrid model.

The simulation process of the soft-linked full-form hybrid is typical of the iterative hybrid approach. In summary, the TIMES model determines the configuration and evolution of the energy system and costs, and the GEM-E3 model defines the national economic structure that drives the energy service demands, which are fed to TIMES. Challenges in the soft-linking included defining a coherent structure across models and developing a new energy module for GEM-E3 to match the TIMES energy system profile.

To determine the advantages of the HYBTEP platform, the researchers constructed three policy scenarios, alongside a baseline calibration scenario:

1) Current policy regulation (CPR): a scenario matching the current Portuguese energy-climate policy within the EU climate energy package extended beyond 2020.

2) CO_2 price scenario (TAX): in addition to the CPR assumptions, there is a domestic carbon tax on GHG emissions from energy consumption, set at the highest carbon price indicated in the EU roadmap to a low-carbon economy.

3) RES support scenario (RES): in addition to the CRP assumptions, a monetary incentive to renewable energy is included.

These scenarios were run on both HYBTEP and on the standard TIMES_PT, and the results were compared. The important differences identified between the modelling tools relate to the impact of policy scenarios on energy system costs and thus on demand for energy services.

The researchers claim that the results illustrate that HYBTEP, and other hybrid models, have advantages compared to the independent use of bottom-up energy system models and top-down equilibrium models. These advantages are due to the integration of both their strengths – detailed representation of technology options and the impact of policies on economic drivers, respectively – and the improved transparency of modelling outcomes. The representation of feed-in tariffs as a policy instrument is also notable [10].

3.5 Sweden

3.5.1 EMEC / TIMES-Sweden

Work undertaken in 2017 by Krook-Riekkola *et al*. [16] detailed the procedure of soft-linking a CGE model of the Swedish economy, the Environmental Medium-term Economic model (EMEC), with an energy system model, TIMES-Sweden, based on the generic TIMES model structure that is shared with many other national European energy system models.

EMEC is a typical CGE model in that it investigates the changes in sectoral supply and demand and the relative prices due to policy changes. However, it differs from many other models through its description of energy use and different environmental policy instruments, and its detailed representation of emissions resulting from a range of sources. TIMES-Sweden is rich in technological detail, including a large number of current and future energy technologies as well as their possible energy conversion efficiencies.

The researchers detailed the challenges they met while soft-linking the models. The procedure involves identifying the similarities and differences between the models, from there picking connection points to exchange information during iterations, and finally the technical aspects of developing a translation model to harmonise variables.

A particular challenge is harmonising data across the linked models. The data for the top-down economic models and the bottom-up technology models are collected from different sources and are rarely consistent. By keeping the models independent and intact (soft-linked), the consistency of each database is maintained without having to directly reconcile across the models. An intermediate module translates output from one model into a format that is suitable for the other model.

The hybrid model was tested on a straightforward climate policy scenario in which a higher price on CO_2 was implemented. A comparison was made between the scenario analyses both with and without the soft-linking approach. The study found that the soft-linked model found significantly lower CO_2 emissions following the increased carbon price, mainly due to lower demand for energy-intensive goods fed into the TIMES-Sweden model from EMEC.

Krook-Riekkola *et al*. [16] claim that the 'soft-linking methodology led to a new picture of the economy's energy use' and that the 'scenario analyses become more transparent and consistent'. They also note that a mutual understanding of the respective scientific approaches arose following the collaboration between modellers.

3.6 Denmark

3.6.1 IntERACT

Andersen *et al*. [25] undertook the hybrid approach in 2019, by soft-linking a CGE model and a national energy system model based on the TIMES framework, called TIMES-DK. The top-down and bottom-up models were created from scratch for the project, creating highly consistent parallel structure between the models.

The model was used to investigate the impacts of a mandatory adoption of coal carbon capture and storage in the Danish concrete sector. The model projected that this would lead to a large contraction in the Danish concrete sector and carbon leakage effects of up to 88 per cent, demonstrating the necessity of adequately capturing the macro-economic effects of investment flows when modelling climate mitigation policies.

The most notable feature of this project is the explicit modelling of energy service demands in the top-down model, which allowed easy model harmonisation during the soft-linking. Furthermore, the consistency of the parallel structure avoids the need for a translation module, improving the soft-linking method. Finally, the approach captures the investment flows related to the sectoral demand for particular energy services, demonstrating the utility of accounting for the macro-economic impacts of certain climate and energy policies.

3.7 Norway

3.7.1 REMES / TIMES

In 2018, Helgesen *et al*. [20] developed a hard-linked hybrid model of the Norwegian energy system and economy. This was the first hard-linking of a large-scale stand-alone model employing full-link with regional resolution and full-form bottom-up and top-down approaches. In the standard hybrid approach, they combined a TIMES model with CGE (REMES), with the CGE model determining energy service demand and the ripple effects of policies through the economy, and the TIMES model providing technological detail and granular data of the energy sector. The ultimate research question was to investigate the feasibility and welfare effects of reducing GHG emissions from transport by 50 per cent.

The particular challenges of such an endeavour are detailed in their paper, but the researchers note that hard-linking the models (as opposed to soft-linking) allowed them to achieve stable convergence, meaning for each run the model reached the same equilibrium. Their work exposed many challenges in achieving convergence in hybrid models.

Convergence issues were noted by other researchers undertaking similar research projects, including Fortes *et al*. [10] in Portugal and Krook-Riekkola *et al*. [16] in Sweden.

The model results showed that the transport emissions reduction targets were achieved by investments in hydrogen vehicles, but would involve reductions in income and utility. The researchers stated that their hybrid approach gave new insights in terms of the possible technology mix to achieve emission reduction targets, as well as providing surprising results regarding ripple effects through the economy and regional welfare effects. They noted that it would be interesting to extend their analysis to include additional policy options that affect demand, since the energy system costs depend heavily on demand differences in various scenarios.

3.8 The Netherlands

3.8.1 EMLab-Generation

Researchers at TU Delft in the Netherlands have developed an open-source agent-based modelling framework called AgentSpring. Under this framework, Chappin *et al*. [22] created EMLab-Generation, an agent-based model of two interconnected electricity markets. The purpose of the model is to investigate the long-term effects of interacting energy and climate policies. The two markets can represent two countries, such as the Netherlands and a neighbouring country, or two groups of countries, such as the UK and the EU.

Power companies are modelled as the main agents. Each agent makes autonomous investment decisions, based on their individual imperfect forecasts, to bid into a power market and invest in new power-plant technologies based on the net present value of the investments. The agents interact through markets such that over time their decisions have an influence on each other. All decisions over time determine the system-wide developments.

Energy and climate policies, like the EU Emissions Trading Scheme and CO_2 taxes, can then be implemented to observe the effect on agent investment behaviour. The goal is to explain the effects of policy on sector goals such as increasing renewable energy generation penetration.

The results of the initial research at TU Delft, into questions such as improving EU-ETS price stability, security of supply, investment models and improved representation of intermittency, suggest that policy questions related to the ongoing energy transition in Europe increasingly interrelate with other sectors and are surrounded by fundamental uncertainties.

The researchers claim that only a modelling approach that makes explicit the side-effects of *imperfect* investment behaviour, combined with other approaches, can adequately provide policy advice in this complex context. They state that the agent-based modelling approach is different from mainstream approaches in that it explicitly takes into account differences in actor behaviour, imperfect foresight, path dependence, cross-policy effects, and cross-border effects, and that these effects cannot be effectively represented through standard CGE model approaches.

Chapter 4
The Irish Approach

There are two prominent, active models in Ireland for investigating the low-carbon transition in an integrated framework that includes economic factors: I3E, developed by the Economic and Social Research Institute (ESRI), and Irish TIMES, developed by the MaREI centre at University College Cork (UCC). UCC is also currently improving the LEAP 2050 model and the PLEXOS model.

4.1 I3E

4.1.1 Features

I3E is a dynamic computable general equilibrium (CGE) model developed by the ESRI, based on a framework of neoclassical micro-economic behaviour. It is similar in structure to other notable international CGE models, such as the ENV-Linkages model developed by the OECD, the GEM-E3 model employed by the European Commission, and the EMEC model used in Sweden.

The entire Irish economy is represented, including many productive sectors, 10 representative households, and the government. Consumers maximise utility and producers maximise profits in line with their budget constraints. The model provides insight into how inputs/outputs flow from various sectors, shows how goods are finally consumed by households, and allows researchers to investigate the direct and indirect economic impacts of policy changes.

In addition to monetary flows between producers, households and the government, energy flows and carbon emissions are modelled. This allows the emission reduction due to a particular policy to be assessed. A set of carbon commodities is explicitly included, such as peat, coal and natural gas. The various sectors of the Irish economy are represented by production activities that choose the cheapest way possible to produce, from their options for capital, labour, energy and other inputs. The EU Emissions Trading Scheme is also represented. The model runs from 2014 to 2050.

Production is comprised of 32 representative firms that produce multiple products. The 10 representative household groups, five rural and five urban, are distinguished by their income level. This makes it possible to analyse the distributional impacts of policies on households. Additionally, there are three labour types in I3E, based on skill level, allowing investigation of distributional effects across labour types. However, the labour supply is an exogenous variable and there is no representation of unemployment. In the case that labour demand is reduced in a certain sector, the affected employees find employment in another sector with higher demand.

Economic growth comes from the growth of employment driven by population growth and the growth of technology. These variables are obtained from a separate ESRI model, named COSMO.

The government sector collects taxes and allocates the revenues to consumption of commodities, transfers to households and enterprises, recycling of carbon tax to households and interest payments on foreign debt. All other countries except Ireland are assumed to be a fixed unit called the Rest of the World.

4.1.2 Research

There are two studies by the ESRI applying the I3E model to investigate the economic effects of increasing the Irish carbon tax. The studies [62, 63], published in March 2019 and October 2019, investigate the effects of increasing the Irish carbon tax towards 2030. The first study analyses two carbon tax scenarios while the second study is concerned with the distributional impacts of an increased carbon tax depending on different revenue recycling schemes.

The results of both studies suggest:

- The electricity generation, transport and mining sectors will be hardest hit by the increases in carbon tax.
- Less energy-intensive sectors, such as education and health, will benefit.
- Households will face higher energy prices, although overall prices will only moderately increase.
- Household nominal income will increase due to carbon tax revenue recycling, but, due to inflation, real disposable income impacts vary by scenario.
- The impact on households of increasing the carbon tax depends on how carbon tax revenues are used:
    - Recycling revenue to households through transfers benefits poorer households.
    - Recycling revenue to reduce wage tax results in the highest average increase in real income, but the impacts are regressive.
- Rural households are more affected by price increases than urban households. Among rural households, the impacts are regressive in that poorer households face the highest price increases. Among urban households, the highest price impacts are for middle-income households.
- Carbon emissions would be significantly reduced by increasing the carbon tax, but not enough to bring Ireland close to reaching its EU emissions targets.

Additional research by the ESRI applying the I3E model involved investigating the regional labour impacts of the transition to a low-carbon economy [64] and the effects of eliminating Irish government fossil-fuel subsidies on the Irish economy [65].

The modelled scenarios in the simulations on regional labour impacts are the already announced annual increases of the carbon tax by €6 until it reaches €80 in 2029 and the gradual phase-out of peat and coal as power-generation fuels. The results of the simulation indicate that the mining and transportation sectors could be the most negatively affected due to their higher levels of carbon consumption, while the government-based sectors could increase labour demand.

Westmeath and Dublin are likely to face the most substantial negative labour demand impacts, due, respectively, to comparatively smaller shares of employees in the positively affected sectors and comparatively larger shares of employees in the most negatively affected sectors. Still, the impacts at county level appear modest for all counties.

However, the calculations of the regional impacts required some approximations that may distort the final interpretations. For example, the total of employees for each region is determined by the location at which the respective sectoral businesses are registered, rather than the locations where employees actually work.

The results of the study simulating the economic impacts of eliminating fossil-fuel subsidies indicate that this policy shock would have a negligible overall impact on economic activity and household welfare, with the exception of removing household energy allowances, whereby the disposable income and welfare of the two poorest household groups in urban and rural areas are negatively affected. The study also suggests that the removal of such subsidies will not be enough to meet Ireland's EU emissions reduction targets for 2030, and shows that policies must be supported by a suite of other environmental policies such as electrification of transport, increasing renewables in power generation, and energy efficiency measures.

Throughout their studies, the authors noted several areas of further research to improve the model. These include:

- addition of international energy price projections;
- ability to simulate investment in certain sectors from funding raised by the introduction of certain climate policies;
- modelling of particulate matter to analyse air pollution;
- a climate-change model to simulate climate-change impacts on areas such as agricultural production and health;
- a complex representation of the exemption from carbon tax for EU-ETS firms;
- endogenous labour-market supply and the introduction of involuntary unemployment; and
- representation of the renewable energy sector and associated renewable energy commodities.

The final two improvements appear the most important in the context of identifying vulnerable sectors and groups during a low-carbon transition. Simulating involuntary unemployment is critical to developing lines of sight on those potentially left behind during the transition. Since a primary goal of increasing carbon taxes is to stimulate the growth of green technologies and a renewable energy sector to replace carbon-intensive economic activities, it is imperative that this be represented in Ireland's modelling studies. Any modelling of a future economy without representation of unemployment and the key renewable energy sector is certain to be distorted and will likely underestimate aggregate variables such as employment and GDP.

4.2 Irish TIMES

4.2.1 Features

Irish TIMES is a medium-to-long-term energy systems model for Ireland, based on the TIMES modelling framework used in 200 institutions in over 70 countries. The TIMES modelling tool has its roots in the International Energy Agency. The Irish TIMES was originally extracted from a pan-European model and developed further at the MaREI centre in UCC from 2009 to 2011. It capacity was extended in Phase 2 (2012-2014) and Phase 3 (2013-2017) [66], focused on evaluating the role of energy technology in climate mitigation in Ireland.

The analysis focuses on building a range of medium-to-long-term energy and emissions policy scenarios in order to inform policy decisions. Irish TIMES outputs a technology-rich, least-cost future energy system pathway. This pathway is determined by minimising the total discounted energy system cost — including investment, operation and maintenance, cost of imported fuels minus exported fuels, and the residual value of technologies at the end of the horizon — while respecting environmental and technical restraints. Irish TIMES can be considered a 'techno-economic optimisation model'. The time horizon extends to 2050, with a time resolution that includes four seasons and day-night cycles.

The Irish energy system is modelled in terms of its supply sectors (fuel mining, primary and secondary production, and import/export), power sectors (heat and power generation with different voltage levels), and demand sectors (60 different energy service demands across a range of sectors). The core model contains a large database of supply-side and demand-side processes (approx. 1,700) in which commodities are converted to energy service demands.

Exogenous macro-economic forecasts are used to drive demand, while International Energy Agency assessments are used for fuel prices. These inputs determine the energy supply resources and costs, and demand for energy services. The model is capable of generating a wide variety of outputs, assessing the policy implications for the economy (fuel and energy prices, investments in the energy system, marginal abatement costs), the future energy mix and energy dependence and greenhouse-gas emissions [17-19].

The Phase 3 report included the representation of negative emission technologies in the model, allowing MaREI to build emissions scenarios that are consistent with the Paris Agreement goals.

4.2.2 Research

Following Phase 3 of its development, the Irish TIMES model was applied to the following research topics:

- soft-linking to a power systems model to gain further insights into the power system using a multi-model approach [67, 68];
- the impact of the economic recession on the future evolution of the energy system [69];
- long-term (2050) energy security issues [70, 71];
- extending the energy systems modelling approach to agriculture with the development of the Agri-TIMES model to explore mitigation scenarios that focus on both energy and agriculture [72]; and
- contributing to the White Paper on Energy in 2015 [73], Ireland's first National Mitigation Plan in 2017 [74], and the Government Climate Action Plan 2019 [75].

Chapter 5
Lessons for Ireland

As demonstrated, the field of transition modelling is broad and complex. Despite well-founded criticism regarding the theoretical assumptions of modelling approaches, there is no doubt that quantitative modelling is a critical and necessary aspect of a just transition. Modelling can help to identify the sectors and groups most vulnerable as the Government implements climate and energy policies.

Transition modelling is growing rapidly and many innovative approaches are being developed. Ireland should take heed of the work being done internationally and incorporate this body of knowledge into our modelling capabilities, while acknowledging the inherent limitations in computer simulations.

The important lessons we can take are categorised below into possibilities for improving the technical structure of models and frameworks through which to evaluate the output of modelling. A list of key recommended actions is then provided.

5.1 Improving Modelling Capabilities

Ireland's modelling approach is generally consistent with the international models investigating the economic impacts of climate policies, yet it is clear that we are missing some important novel approaches. Our capabilities should be enhanced by improving current models and adding other approaches, while a range of important transition elements should be included in future model development.

5.1.1 Improving I3E

The further developments of I3E suggested by the ESRI appear sensible and informed [62-65]. Representation of the renewable energy sector and involuntary unemployment are especially vital forward steps for identifying vulnerable sectors and groups in the economy during a low-carbon transition. Consumers and households are likely to switch to renewable energy commodities in the face of increasing prices for carbon-intensive energy sources, while one of the primary concerns with climate policy is its impact on jobs.

5.1.2 Further Developing Hybrid Models

The reports from the hybrid modelling work done in UCC [39], Portugal [10], Norway [20], Sweden [16], and Denmark [25] detailed the benefits of such an approach. These include better insights into transition dynamics, the improved transparency of the modelling outcomes, and the increased understanding between the respective researchers using both modelling approaches following the collaboration.

Developing a suite of hybrid models for Ireland would improve our capabilities. Taking an approach separate from the energy system/macro-economic hybrid developed at University College Cork (UCC) would supplement this analysis and allow Ireland to ask modelling questions with a variety of tools.

The approach taken in Denmark involved developing both the CGE and energy system models simultaneously, while the Swedish researchers linked the models after their initial development. At present, MaREI in UCC are collaborating with the ESRI via the Climate Action Modelling Group to soft-link Irish TIMES and I3E. This joint effort should improve the macro-economic realism of the Irish TIMES and the technological detail of the I3E.

5.1.3 Developing a Macro-Econometric E3 Model

Developing a macro-econometric model with energy and environment modules to investigate climate and energy policy impacts would contribute substantially to Ireland's modelling capabilities. This would counterbalance the country's current dependence on the equilibrium-based I3E model, and much expand the potential modelling experiments that could be carried out to assist Irish climate and energy policy-makers. The ESRI has previously used similar models, such as the HERMES model which looked at the potential for a double dividend from carbon tax [76]. The E3ME model (see Section 3.1.2) is the cutting edge of such models and could serve as a blueprint for the development of an Irish version.

5.1.4 Including Important Transition Elements

While the current state of energy-economy-environment models is sophisticated, generally they are missing some key elements that will influence the dynamics of the low-carbon transition.

As addressed in the Modelling Shortcomings section (from 2.1.8), a realistic representation of finance during the low-carbon transition is important. Mercure and Pollitt [7, 8, 41] argue that the most common modelling approach, CGE models, do not accurately represent how money influences the economy. Investment is taken as a fixed portion of saving in the standard CGE framework, whereas modern macro-economics understands that money is created in the economy by commercial banks [77]. Nevertheless, the alternative approaches to finance also have their limitations. Socio-economic transitions require large-scale investment, and therefore improper representation of this sector will distort model results.

Another important aspect of a low-carbon transition, which can significantly affect economic activity, is the adoption and diffusion of technology. The heterogeneity of agents is an important factor to understand these dynamics and therefore should be properly represented. Diversity of incomes and attitudes are known to determine the rates of diffusions of innovations. Furthermore, the interactions between agents are known to influence the rates of technology adoption. Equilibrium and optimisation approaches disregard heterogeneity and agent interactions. Remedying such neglect in Irish modelling would considerably improve our capabilities to gain insight into the dynamics of transitions [41].

Future economies are envisioned to involve a new type of economic actor, a ‘prosumer’. This provides a good example of a heterogeneous actor (with regard to the typically represented economic actors) which will significantly influence the transition dynamics. In the case of the energy system, prosumers are actors that both consume and generate power [78]. It would be prescient to model such actors and investigate their economic impacts.

The low-carbon transition will also include many benefits from reducing fossil fuels that are rarely quantified in economic models, such as improving air quality and other avoided damages. Efforts to include quantified benefits of these elements, such as reduced healthcare costs, would lead to a more balanced perspective on the transition [61].

A prominent transition researcher at University College London, Francis Li, listed the requirements for models capable of exploring the dynamics of ‘socio-technical energy transitions’ [4]. The paper suggests three requirements.

First is *techno-economic detail*, so that the model is capable of exploring the economic trade-offs between different technological options. This means that the model should include a disaggregated selection of technology options with different price and performance characteristics.

Second is *explicit actor heterogeneity*, in order to conceptualise the behaviour of individual actors and their emergent behaviour. These actors are not limited to producers and consumers but could also include policy-makers, regulators, and civil-society organisations. The model should therefore be able to represent multiple actors, with different selection criteria or behavioural parameters, that have the agency to shape transitions.

Third, to adequately model the variety of possible transition pathways and their associated dynamics, models should include an *assessment of normative goals* to understand if transitions are feasible, *time horizons* sufficient for exploring long-term socio-technical change, and the possibility of *radical alternatives* to the status quo technology or behavioural options.

5.2 Evaluating Results

The suitability of models for investigating certain questions depends on their assumptions. Policy- and decision-makers should be aware that modelling is a tool for debate rather than an ultimate answer to complex and multi-faceted questions. Models can generate *projections* about what *might* happen based on certain assumptions, not *predictions* about what *will* happen. To properly evaluate the results from models, policymakers must understand models, models should be validated, and uncertainty in models should be addressed.

5.2.1 Model Validation

While uncommon in the computable general equilibrium literature since the 1980s [79], empirical validation of models was initially put forth by Johansen in a 1960 paper discussing a CGE model of Norway's economy [80]. Johansen analysed the ability of his multisectoral model to reproduce the changes in industrial composition during the 1950s, but similar efforts in recent times appear sparse.

Attempts at empirical validation in contemporary models could increase confidence in model results and also highlight any deficiencies in the model that can be better understood and improved upon [81]. Empirical validation involves comparing simulated quantities — in the case of E3 models, examples are GDP, employment or emissions — to the corresponding empirically observed values, to determine if the model is a suitable representation of what is being modelled. This is regularly done with climate models [82].

For example, I3E could be calibrated using data available up to 2010, and then run from 2010 to 2019 following the introduction of a carbon tax set at €10 per ton of CO_2. The output of the model in 2019 could then be compared to the observed outcomes. Such an approach was applied to the USAGE model of the USA [79].

Other researchers have argued for increased transparency in model development and application, particularly in the case of analysis informing public policy. By making model source codes available to the public, third parties can attempt to reproduce model results. This would allow for experiment repeatability, an essential quality in science. Without repeat model analysis, the researchers argue, it is impossible to fully understand model formulation, expose hidden assumptions, or identify key model sensitivities [83].

5.2.2 Uncertainty Analysis

Representing uncertainty is a critical aspect of any modelling, both to increase confidence in model results and properly delineate any limitations. Some argue that economic analyses could benefit from harmonising their methodology with the climate sciences [41]. Briefly outlined below are some approaches to quantify and address uncertainty that are taken in climate modelling. These approaches could also be followed in economic modelling of climate and energy policies.

A modelling ensemble involves running model versions that are related but different thousands of times and then assessing the range of results generated, either by combining them into a single result or comparing them. In climate modelling, the ensemble approach is used to explore the uncertainty in model simulations that arise from internal variability and other factors. There are two types of ensembles: multimodel ensembles and perturbed parameter ensembles [6, 82].

Multimodel ensembles involve running different models – for example, a CGE model, a macro-econometric model and a hybrid model – over the same period. In the case of transition modelling, they could all investigate the impacts of a climate or energy policy. The results of the models are then compared and contrasted so as to investigate the structural uncertainty of the models in question. In climate modelling, to characterise the results from multimodel ensembles, the arithmetic mean of the results is often presented. Similar approaches could be taken in energy-economy-environment models, with variables such as GDP and employment.

By applying different models to the same question, researchers can identify where the models converge and diverge, gaining further insight into the dynamics of the low-carbon transition. If models disagree, modellers can attempt to establish whether the uncertainty is due to the model or the system [6].

Perturbed parameter ensembles assess uncertainty from a single model, but the model is run several times, with small variations in its internal parameters, to investigate which parameters drive the uncertainty in the model results. In the case of energy-economy-environment models, perturbations could be implemented for the elasticities of substitution between various fuels, for example.

Pollitt and Mercure [7] have advocated using both the CGE and macro-econometric modelling approach to test climate or energy policy. They claim that this will provide benefits by obtaining a range of results, and by assisting discussions about model results, which can help policy-makers to understand the key assumptions.

5.2.3 Understanding Models

For modelling to be most effective, particularly in the case of identifying vulnerable sectors and groups during socio-economic transitions, the users of the model, primarily policy-makers, should have an appropriate understanding of the model. This understanding applies to the model's purpose, strengths and shortcomings, and theoretical underpinnings. Without such an understanding, model results are likely to be misinterpreted and could lead to unwise policy proposals [7].

A collaborative review by researchers across the UK, published in the Royal Society *Open Science* journal, discussed the important considerations when using computer modelling to aid decision-making [6]. Four key points are made in the paper.

First, the modeller and user (policy-maker) should understand that different models have different uses. For example, a CGE model is designed to provide insight on the intersectoral impacts of policies on the economy, whereas an agent-based model is intended to illuminate the emergent behavioural properties of systems of heterogeneous actors. These are two very different uses, and such purposes should be clear to all stakeholders. Furthermore, the distinction between the *normative* (what agents ought to do) and *positive* (what agents are observed to do) approaches to modelling is critically important for policy-makers to understand [8].

Second, models should be constructed in close collaboration between the model commissions, developers, users and reviewers. This provides a framework that ensures all stakeholders have sufficient confidence in the model. In the case of models to aid the just transition, this would involve policy-makers collaborating with the modellers in MaREI and the ESRI as our present modelling capabilities are improved.

Third, it is useful for stakeholders to have knowledge of the technical basis on which various models are built. The contrasting theoretical assumptions and empirical calibration of CGE models and macro-econometric models provide a typical example of the variety of modelling techniques that are used. Model assumptions should always be considered when evaluating results.

Fourth, awareness among modellers and model users of the future opportunities that could transform policy-making, such as advanced agent-based models, would allow Ireland to take advantage of the future modelling landscape.

5.3 Key Recommendations

Further capabilities should be developed to:

- include representation of unemployment and the renewable energy industry in our current models;
- continue efforts to soft-link *Irish TIMES* with *I3E*;
- explore novel modelling approaches such as macro-econometric models that include energy and environment modules and agent-based models; and
- endeavour to represent important transition elements such as finance.

To better evaluate the results from modelling in Ireland, we should:

- encourage modellers and policy-makers to work in close collaboration during modelling programmes to increase understanding of modelling across stakeholders;
- carry out modelling in collaboration with qualitative research, including dialogue with relevant stakeholders;
- attempt to validate models to increase confidence in results; and
- address uncertainty within models by emulating approaches taken in the climate sciences, such as ensemble modelling.

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