Modelling Innovation and the Macroeconomics of Low-Carbon Transitions: Theory, Perspectives and Practical Use.

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Abstract

Analysis carried out by various institutions to assess the potential economy-wide impacts of energy and climate policies typically involves quantitative modelling using whole-economy macro-sectoral tools. When projecting economic impacts of policies for driving the uptake of low-carbon energy technologies, model based studies often conclude on different scales and even directions. These differences are attributed to the modelling methodologies used. This paper aims to provide a comprehensive account of the theoretical origins of the differences in outcomes observed between models, which are traced down to treatments of innovation and finance. We argue that all branches of macro-innovation theory can be grouped into two classes: 'Equilibrium – Optimisation' and 'Non-equilibrium – Simulation'. While both approaches are theoretically rigorous and self-consistent, they yield different conclusions for the economic impact of low-carbon policy. In equilibrium models, technology support policies tend to reallocate a fixed quantity of capital resources, which may lead to sub-optimal equilibria from an economic perspective. Meanwhile, non-equilibrium models emphasise entrepreneurial activity, the creation of purchasing power by banks, and a policy's impact on increasing economic activity. In case of scenarios that address capital intensive transformations of the economy and energy system, we find that the main determinants of model outcomes are current types of representations of the monetary and financial sectors, and of the barriers to innovation finance. Improving the representation of finance and innovation in all modelling approaches is crucial for gaining a more consistent picture of the macroeconomic impacts of energy system transformations and greenhouse gas emissions reductions. Better capturing finance and innovation may also help bring convergence in projected macroeconomic model outcomes.

***Keywords**: economics of innovation; innovation policy; finance of innovation; energy-economy modelling; energy and climate policy; policy impact assessment*

***JEL codes**: Q430; Q550; Q480; C630; O440; B220.*

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1. INTRODUCTION

After the Paris Conference of the Parties on Climate Change (COP21), during which the Paris Agreement (UNFCCC 2015) was drafted, consensus and agreement emerged globally over the need to reduce global anthropogenic greenhouse gas (GHG) emissions to avoid global mean temperatures warming of well below 2°C. As part of the process, countries have submitted Intended Nationally Determined Contributions (INDCs), committing themselves to certain reductions of their domestic GHG emissions. For instance, the European Union has committed to 40% reductions below its 1990 level by 2030.

Such climate and energy targets could be met via different pathways and different combinations of supply-side and demand-side technological and socioeconomic options. Significant debate exists on strategies for achieving an efficient and cost-effective sustainable energy transition (e.g. IPCC 2014; Edenhofer et al. 2010; Stern 2007; Nordhaus 2010; Nordhaus 2015). Macro-models are used extensively in this context to inform policy-making, in particular through the IPCC process (IPCC 2014), and at the European level.[1]

In the current context of economic stagnation in many countries across the globe, it is of primary importance to determine whether a policy aiming at reducing emissions will hinder or help economic recovery, whether it will lead to unsustainable debt levels, and whether it will produce economic opportunity or be an economic burden (Mercure et al. 2016). Nevertheless, innovation, in general, as a driver of economic activity is a recurrent theme in current discourses on economic development (BIS 2011; OECD 2015), and this specifically includes low-carbon and energy innovation, which could fuel future prosperity.

It is clear that a certain quantity of decarbonisation will come about through technological changes that reduce the need for combustion of fossil fuels, for example replacing existing large coal electricity plants by renewable energy systems, petrol cars by electric cars, as well as household gas boilers by electric heat pumps (e.g. see IEA 2012). It is however also clear that a large amount will stem from curbing the growth in energy demand, in particular if one considers contexts of increasing energy prices, which could be part of some scenarios of decarbonisation (e.g. Mercure et al. 2014). Structural change in the economy towards a pattern of consumption with less embodied energy could also contribute significant savings. Reductions in consumption of fuels themselves will come from two distinct contributions: changes in lifestyles and consumption patterns that require energy, and changes in efficiency of fuel use through replacement for more efficient equipment.

However, while energy-economy-environment (E3) models are typically designed to assess technology or economic scenarios, they do not always explicitly address in the required detail some of the key features of the policy frameworks that would be needed to bring about particular scenarios, leaving unanswered questions for actual policy application (Mercure et al. 2014; Mercure et al. 2016). Indeed, which policy frameworks are likely to reach cost-effectively multiple energy and climate objectives? Is the carbon price a sufficient signalling mechanism to drive the decarbonisation of the energy system or should it be combined with policies and measures (i.e. technology subsidies, feed-in tariffs, regulations, standards)? Should access to finance be improved and more versatile financial products become available? Which policy instruments are complements, compatible or cancel each other? These are questions that the modelling community continues to grapple with.

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[1] E.g. see http://ec.europa.eu/clima/policies/strategies/2020/studies_en.htm and http://ec.europa.eu/clima/policies/strategies/2030/documentation_en.htm

To be useful to the policy-maker, analysis tools built for providing insight for the design of energy and climate policies must accurately represent the key mechanisms of the economic-energy-environment system, and the behaviour of consumers and firms. Such representations are far from complete in current analysis tools. Furthermore, few of the current models used to analyse and assess energy and climate policies (GEA 2012; IPCC 2014) have representations of the financial sector, and its relevance for a large scale decarbonisation transition. This is a major shortcoming because such a transition will require large-scale investment (Pollitt & Mercure 2017).

This absence reflects partly the underestimation of the role of finance and money on real economy, and partly the difficulty in modelling energy-related innovation, technological change and the effectiveness of policy instruments, individually or as portfolios, as it requires a much better understanding of the complex behaviour and response of agents to policy incentives than currently exists in the community. It also reflects the difficulties in capturing sufficiently detailed bottom-up information on the energy sector within the top-down generalised macroeconomic framework of such models. Improving that understanding will require a diffusion of behavioural knowledge and evidence into the modelling community from more specialised fields of economics (e.g. investment behaviour under fundamental uncertainty, prospect theory, information asymmetry, social influence, information cascades, innovation systems). It will also require simply more behavioural empirical evidence to be included in empirical macro-energy models (Knobloch & Mercure 2016).

In this paper, we review current analysis methods and tools for assessing energy and climate policies, and in particular, the analysis of policy-induced energy innovation and technological change. That is to say: how can policy and governance accelerate rates of low-carbon technology substitution, innovation and energy efficiency changes? Will this help or hinder economic development? And, do models accurately capture the impacts of chosen policy instruments?

For this purpose, we first carry out an extensive literature review, covering energy innovation in economic theory, historically and currently, in order to explain and assess how innovation is presently understood and represented in models used to carry out analysis (e.g. for the European Commission, IEA, IPCC). We identify features and factors in theory and models that result in particular modelling outcomes. This requires looking at their underlying theoretical basis and methodological assumptions: how do we currently understand innovation?

Several reviews on how energy-related innovation is handled in macroeconomic and technology models have been written (Löschel 2002; Köhler et al. 2006;

Gillingham et al. 2008; Popp 2006). While these are exhaustive with lists of existing models, they do not cover the theoretical underpinnings of the various existing implementations. In particular they do not touch upon how innovation is financed, adopted and diffused. Here, we give particular focus to these aspects, which we consider key to the ability to inform effective energy-related policy-making.

In Section two, we review how innovation has been addressed in recent economic theory (both with respect to energy technologies and other forms of innovation, with further details on the history of development in the supplementary information) and its treatment in contemporary computational economic models. Section three shows how different theories imply different perspectives on the macro-economic effects of policies, and how this can be considered in policy-making. As most of the models used for climate and energy policy analysis have limited representation of innovation and finance, in Section four we identify the gaps that macro-sectoral models would need to tackle for better informing energy and climate policy. Section five concludes by proposing a research agenda for linking technology and innovation research to quantitative modelling applied to policy questions.

2. INNOVATION IN THE HISTORY OF ECONOMIC THEORY AND MODELS

An important debate has been going on for many years about the potential macroeconomic impacts of an energy-related sustainability transition (Grubb et al. 2014; Stern 2007; Edenhofer et al. 2010; IPCC 2014). Since innovation and technological change accounts for the largest component of economic growth (Solow 1957) and development (Schumpeter 1934; Schumpeter 1939) in all schools of economic thought, this debate points to the importance of the way in which innovation is included in models in order to better determine how productivity growth can be influenced by technology policy. With climate policy looming, this applies particularly to energy-economy systems (supply, demand, infrastructure), and remains an unsolved question.

2.1. TECHNOLOGY AND INNOVATION IN THE HISTORY OF ECONOMIC THEORY

We start by describing the general treatment of innovation in economic theory, because the lessons apply equally to innovation in energy systems. In particular, R&D investments for end-use technologies do not typically focus solely on improvements in energy-related characteristics, but instead target several simultaneous performance changes or cost advantages (e.g. new car models embody many performance changes, and investments cannot easily be attributed to energy goals specifically). Thus, energy innovation can also arise as a spillover of other activities. At the same time, R&D in energy supply technologies targets process innovation for the production of improved machines and devices. We provide further details in the Supplementary Information.

Schumpeter (2014; 1934; 1939) focused on the role of the entrepreneur and of the enabling financial institutions. His simple but telling representation has resurfaced in various forms throughout modern economics, and is of particular interest in the area of low-carbon and energy technological change, for example in Endogenous Growth Theory (Aghion et al. 1998), Evolutionary Economics, (Freeman & Louça 2001), Sustainability Transitions Theory (Geels 2002), Energy Technology Innovation Systems (Grübler & Wilson 2013; Hekkert et al. 2007), directed clean innovation, (Acemoglu et al. 2012) and 'planetary economics' (Grubb 2014).

The analysis provided by Keynes of the mechanisms that operate in the macro-economy is crucial in order to understand the relationship between investment and macroeconomic dynamics (Keynes 1936), which has been extended by the 'Post-Keynesians' into a complete theory of economics (e.g. Lavoie 2014). In fact, the Post-Schumpeterian and Post-Keynesian theories could be seen as two different perspectives over the same theory (e.g. see in Perez 2001). With behavioural economics (e.g. Kahneman & Tversky 1979; Simon 1955), these form together the non-equilibrium economics school.

In contrast, the development of the equilibrium school of Post-Walrasian neoclassical theory has taken a radically different direction, explaining finance, innovation and productivity change in a completely different way (Solow 1986; Arrow 1962; Romer 1986; Acemoglu 2002; Aghion et al. 1998). This includes how clean energy technological and productivity change is understood to take place.

The treatment of innovation throughout the history of economic thought requires an extensive review, which is provided as supplementary material to this paper. We summarise it here by stating how economic development is understood to come about for each of two schools.

The basic view of the equilibrium school is one of optimal allocation of scarce economic resources under given technological choices and of optimal capital accumulation (Figure 1 left):

1. Given a finite set of production factors, technology options and households' preferences for consumption, firms produce by fully using resources (full employment)[2] to meet the intermediate and final demand of their products.

2. Firms seek financing for their investment from the capital markets, which the interest rate clears.

3. Households receive payments for providing labour, from firms' profits (according to their shares), from property rents and subsidies they receive. Based on an intertemporal utility maximisation, they choose how to allocate their income between consumption (of various goods) and saving.

4. Savings[3] are used to finance firms' investments. Investment accumulation defines the capital stock available for production, which includes: physical production facilities (e.g. new factories, replacement of retired machinery etc.), and investments into knowledge stock (e.g. technical progress, R&D).

5. The increased amount of capital, labour (population) and their improved factor productivity expand the production frontier and allows higher volumes of production.

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[2] This reflects a standard assumption in textbook models. Contemporary equilibrium theory can allow for partial employment, market imperfections, oligopolisitic competition, (Dixon & Jorgenson 2013).

[3] We note the distinction between *saving* (the action of not spending a fraction of income) and *savings* (a certain amount of accumulated wealth). Here we use the verb saving, which implies a yearly *flow of income not spent on consumption.*

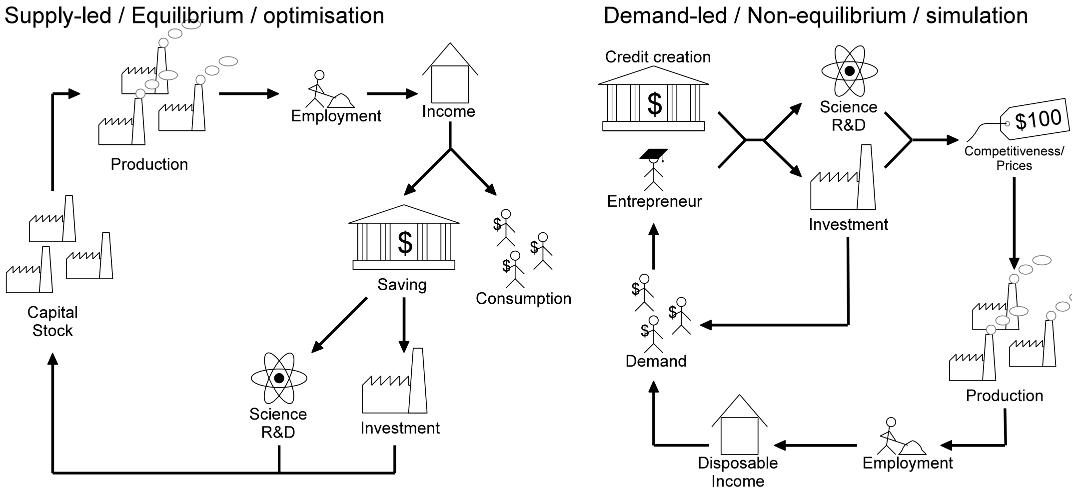

Figure 1: Contrasting representations of economic growth in the Post-Keynesian/Post-Schumpeterian (non-equilibrium) schools to the neoclassical (equilibrium) school.

Meanwhile, the non-equilibrium school contends that economic development takes place through entrepreneurial activity and the creation of purchasing power by banks (Figure 1 right):

1. Entrepreneurs sense where potential demand is not satisfied or new consumer preferences could be shaped, and see potential applications for their ideas. They apply to financial institutions to finance their innovative improvements to the existing capital stock. Banks offer loans and create deposits based on entrepreneurs' credit-worthiness and the expected profitability of the investment project.

2. Bank-funded investment in new capital involves R&D expenditure in various connected technologies and sectors, which increases their productivity.

3. Productivity improvements reduce production costs. This can involve a mixture of (1) profits for the entrepreneurs and (2) price reductions in consumer markets, depending on the degree of monopolistic power that firms have with respect to the new products. Both cases result in higher income for households, higher demand for the new products, and/or (3) reduced imports, and/or (4) increased exports.

4. Higher income leads to higher effective demand (for all products) and higher saving.

5. Higher demand and profits incentivise firms to re-invest in R&D and to expand their capital stock, leading to further expansions of the stock of knowledge.

These two representations are radically different in their key principles and lead to contrasting approaches when implemented quantitatively. These are depicted in Figure 1, in which one can see that the direction of causation is different between all variables across the two groups of schools. This difference has far-reaching consequences for the macroeconomic effects suggested by each school.

The theoretical difference between the schools has at its heart a difference in the treatment of uncertainty and, in particular, the distinction made in early writings by Keynes with respect to fundamental uncertainty (Keynes 1921; for a recent account, see Fontana 2009). Keynes describes risk as quantifiable probabilities of outcomes of an action (e.g. investment), while uncertainty is unquantifiable. When, in Post-Keynesian theory, it is assumed that investment takes place under fundamental uncertainty, it is then not possible for agents to estimate the likelihood of different outcomes and therefore, by definition, not possible for them to define an 'optimal' strategy (in the sense of some function of probability-weighted possible outcomes). For example, in the non-equilibrium school, under uncertainty over variations of demand, the investor plans for spare production capacity, intentionally placing the firm in a sub-optimal mode of operation, in order to be able to respond if the regime of demand suddenly changed (Lavoie 2014). Under this context, investment, depending on investor and bank confidence in markets, drives income and employment (or unemployment) of resources. Meanwhile in pure equilibrium theory in its most basic form, income determines investment (through the propensity to save), and the theory functions the other way around.[4] Thus, the different direction of economic causality in equilibrium and non-equilibrium theory is a consequence of their respective treatments of risk and uncertainty.

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[4] In equilibrium theory, there are different options for macro closure (S=I). i) Households decide on S and I adjusts, ii) firms decide I and S adjusts, iii) different supply and demand functions for investment savings are formulated cleared by the interest rate. The direction of causation from income to investment, however, remains the same.

Table 1: Schools of economic thought

	School Name		Micro-foundations		Money	Estimation method	Innovation Technology	Economic change
			Rational	Agent				
Equilibrium	Neoclassical	Solow[1]	RE	RA	Commodity	Optimisation	Exogenous	Capital accumulation
		Endo Growth[2]	RE	RA	Commodity	Optimisation	Knowledge in production functions	Capital & knowledge accumulation
		GE[3]	RE	RA	Commodity	Optimisation	Knowledge in production functions, learning curves	Capital & knowledge accumulation
Non-equilibrium	P-S	EE[4]	Behavioural[8] Heterogeneous		Asset (Credit creation)	Dynamical systems (EE), Historical approach[9]	Knowledge networks, Diffusion, learning	Entrepreneur, Innovation clustering, creative destruction
		TT[5]					Historical	
		TIS[6]					Case studies	
	P-K[7]	Horiz	Behavioural[8] Heterogeneous		Asset (Credit creation)	Time series Econometrics	Sectoral tech. progress functions	Investment (Innovation)
		Struct						
	Behavioural[8]		Numerous agents		--	Empirical	--	--
	Marxian		Classes		--	Econometrics	--	--

Notes P-S: Post-Schumpeterian. P-K: Post-Keynesian. GE: General Equilibrium. EE: Evolutionary Economic. TT: Transitions Theory. TIS: Technology Innovation Systems. Horiz: Horizontalists. Struct: Structuralists. RE: Rational Expectations. RA: Representative Agent. TFP: Total Factor Productivity.

Models [1]Nordhaus (Nordhaus 2010), [2]REMIND (PIK 2016), [3]IMACLIM (CIRED 2006), AIM (NIES 2012), GEM-E3 (E3MLab 2013), [4]Safarzynska & van den Bergh (2010), [5]Geels (Geels 2002), [6]Hekkert et al (2007), [7]E3ME-FTT (Cambridge Econometrics 2014a), GINFORS (Lutz et al. 2009),[8] Kahneman & Tversky (1979), Domencich & McFadden (1975), [9]Freeman & Louça (2001), Geels (2002)

2.2. CONTRASTING ASSUMPTIONS ON THE DRIVERS OF INNOVATION

Innovation (including energy innovation) drives most of economic development and growth. However, there is disagreement over the mechanism by which it takes place. Table 1 summarises the representations of money, innovation, technology, methodology and the source of economic change in ten schools and research areas in economics. These schools or fields are not necessarily mutually exclusive, although clearly some approaches are. In particular, the Post-Keynesian and Post-Schumpeterian schools use significant amounts of common concepts, including from the behavioural school, while equilibrium schools tend to differ from non-equilibrium schools over fundamental methodological and theoretical issues.

Planetary Economics (Grubb et al. 2014) attempts to reconcile schools of thought for the climate change mitigation context by structuring the analysis in three different areas that address different obstacles to mitigation: the adoption of sustainability innovations, altering markets to support low-carbon innovation, and transforming infrastructure and institutions. For this, Grubb et al. invoke methods from, respectively, behavioural, neoclassical and evolutionary economics. The problem of climate and energy policy-making is described along the lines of three policy pillars for sustainable development (respectively): standards and engagement, markets and prices and strategic investment.

The rate of technology uptake by agents is determined in large parts by behavioural aspects, such as barriers to innovation and/or technology adoption, the local regulatory and policy structure, and cultural dimensions, all typically described by a behavioural approach to economics. Economic trade-offs, externalities and market design are typically well described by neoclassical economics, in perhaps a normative (optimising) perspective (e.g. electricity markets). However according to Grubb et al., innovation and the transformation of firms and institutions are typically best described by Technology Innovation Systems, Evolutionary Economics, and Transitions Theory (see the supplementary material). The contemporary equilibrium school views this through knowledge spillovers and market imperfections.

2.3. CURRENT MACRO-MODELS: A TAXONOMY OF ASSUMPTIONS

Current macroeconomic and macro-sectoral economic models are typically classified along the categories of general equilibrium, partial equilibrium, macro-econometric, systems dynamics and agent-based. Within each of these, sub-categories exist. We provide a taxonomy of approaches according to the types of assumptions adopted for the structure of technological change, its representation at the micro and macro levels, and their representation of the entrepreneur at both levels.

Table 2 lists the main macroeconomic and macro-sectoral economic modelling methodologies currently used to inform policy-making. We have classified these in terms of their representation of energy-related innovation, and representation of agents, at the micro and macro levels. Here 'micro' and 'macro' are used to refer to the level of aggregation: 'micro' means for example distinguishing individual technologies (e.g. solar PV), while macro means modelling aggregates at sectoral or economy-wide level (e.g. the electricity or automotive sectors as whole). Innovation indicates representations of cost-reducing or productivity-enhancing activity, while agents refer to representations of decision-making and behaviour (e.g. investment decisions).

Representations of endogenous innovation and induced/endogenous technological change (ITC/ETC) were explored extensively in the project 'Innovation Modelling Comparison Project' (IMCP, Edenhofer et al. 2006), in which endogenous representations of innovation were introduced to a number of economic and technology models applied to energy and climate policy.[5] The unsurprising result was that the investment costs required to implement technological change become less over time if learning-by-doing and technological progress is allowed to take place endogenously in the models. This led to the general conclusion that (1) ETC is important, and (2) ETC reduces the 'costs' of an energy sustainability transition. However, there was no consensus on the meaning of economic costs, which is still the case now (Grubb et al. 2014, ch. 11). Indeed, in some studies, costs are identified with total energy system costs, in others cases with additional investment costs, and yet in other cases, with changes in GDP or changes in (conceptualised) utility or welfare.

However, a subtle interaction was at play, which is not extensively described in the project: endogenous technological change was replacing older assumptions, in which technological change was exogenous. In earlier neoclassical models where

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[5] For a more recent but similar project, see also http://simpatic.eu/.

inter-temporal optimisation is assumed, the representative agent was optimising utility (discounted consumption now and in the future, with full knowledge of the future) over a trend of productivity predetermined with certainty. This had generally the perverse effect that the representative agent could anticipate with complete certainty future gains in productivity and so refrain from investing in low-carbon energy, delaying action in the present. The presence of so-called back-stop technologies[6] also had the same effect, promising future solutions that would appear with certainty once made economical. This in general meant that pre-ETC model results were to a great extent determined by assumptions about exogenous total factor productivity over time and the existence of back-stop technologies. Thus anyone wanting to extract information on economic impacts of energy and climate policy faced the problem of outcomes pre-determined by assumptions.

Semi-endogenous technological change solved this problem: in neoclassical models, the representative agent invests in R&D in the present in order to maximise future utility by increasing current and future productivity. Circular reasoning is avoided by removing exogenous productivity growth from optimisation approaches. Indeed, exogenous productivity ties model results to a pre-written future where entrepreneurship does not need to exist in order for productivity to increase.

Exogenous productivity has been equally problematic in Post-Keynesian / Post-Schumpeterian simulation models. There too, any such assumptions guided the whole model scenario towards part-pre-defined outcomes. For example, if the efficiency of new energy-using technology did not endogenously respond to a change in prices, models would predict continuous slowdowns of energy-based service demand (e.g. transport, energy intensive goods, and perhaps economic growth) in scenarios of increasing energy prices, something not observed in reality (Grubb 2014, p. 209). In reality, an asymmetry exists between price rises and price falls for energy use as the economy adjusts over time to new contexts. Price rises incentivise investment in higher efficiency and faster technological turnover, while price falls do not incentivise the reverse effect (though they may slow down investment in greater efficiency, and encourage behaviour that uses more energy, Grubb et al. 2014). It may perhaps be argued that investment behaviour is always driven by 'something', and cannot be brought into models as explained by 'nothing'.

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[6] A backstop technology is a hypothetical future technology that, given that the consumer is willing to pay a high enough price, could provide infinite amounts of clean energy (e.g. solar photovoltaic or nuclear fusion).

Table 2: Types of macro-models and summary of their assumptions regarding energy-related innovation and investment behaviour

	Assumption type		Micro innovation	Macro innovation	Micro agent	Macro agent
Optimisation	Optimal growth[1]		Does not have detailed disaggregated sectors	Knowledge accumulation in economy production function	Normative social planner optimising utility inter-temporally	
	GE*	CGE*[2]	Can be linked to detailed technology models	Endogenous productivity in sectoral production functions	Representative agent with rational expectations (deterministic) optimising utility, prices adjust to clear all markets	
		DSGE*	Can be linked to detailed technology models	Exogenous technological change	Heterogeneous stochastic representative agent	
	Partial equilibrium Cost-optimisation[3]		Learning curves, exogenous diffusion rates, vintage capital	Productivity not defined, can be linked to a CGE model	Can be heterogeneous, market segments	The normative social planner
Simulation	Macro-econometric[4]		Can be linked to detailed technology models	Technology progress indicators (fn. of cumulative investment)	Can be linked to detailed technology models	Investment behaviour derived econometrically
	SD*	Discrete choice[5]	Vintage capital (fleets), learning curves	Productivity not defined, but can be linked to any macro-model	Multinomial logit regressions, heterogeneous agents	Can be linked to macro-model
		Diffusion[6]	Selection-diffusion evolutionary model, learning curves	Can be linked to a path-dependent economic model	Decision-making under bounded rationality, social influence	Can be linked to macro-model
	AB*	Sectoral[7]	Vintage capital (fleets), learning curves	Can be linked to a path-dependent economic model	Decision-making under bounded rationality, social influence	Can be linked to macro-model

*Notes GE: General Equilibrium. CGE: Computable General Equilibrium. DSGE: Dynamic Stochastic General Equilibrium. SD: Systems Dynamics. AB: Agent-Based. PE: Partial Equilibrium

Model examples: [1] RICE/DICE (Nordhaus 2013), FUND (Anthoff & Tol 2014), QUEST (ECFIN 2015)[2] GEM-E3 (E3MLab 2013), IMACLIM (CIRED 2006) [3] MESSAGE (IIASA 2013), TIMES (IEA/ETSAP 2016b), PRIMES (E3MLab 2015), [4] E3ME (Cambridge Econometrics 2014b), GINFORS (Lutz et al. 2009) [5] IMAGE-TIMER (Bouwman et al. 2006) [6] FTT (Mercure et al. 2014) [7] MATISSE (Köhler et al. 2009).

Thus, nearly all contemporary models now feature representations of some degree of ETC/ITC. These representations can be radically different however, and these conceptualisations trace back again to basic economic theory, namely the neoclassical, Post-Keynesian and Post-Schumpeterian schools of thought.

2.3.1. Innovation and technological change in macro-economic models

The two theoretical paradigms discussed in section 2.1, embody the following, opposite, directions of causation with respect to the treatment of innovation and technological change:

(1) In the equilibrium/optimisation paradigm, the representative agent chooses the proportion of consumption of income now and in the future. The resources made available by saving (i.e. not consuming) in the present are employed to undertake investment that increases (with certainty) production capacity for supplying consumption in the future, through the accumulation of physical capital and knowledge (Keynes' C-M-C economy, see supplementary material).[7] Central for innovation and technological change, some of this investment takes the form of R&D in various sectors, increasing their productivity. Capital resources in a year are finite and they are employed to the uses that provide the highest rates of returns. Because in deterministic equilibrium models investment outcomes are known with certainty, only the efficient portfolios are selected (technology risk-returns relationships and their evolution are exogenously introduced).

(2) In the non-equilibrium/simulation paradigm, the entrepreneur faces fundamental uncertainty, and decides whether to apply to borrow funds in order to invest into production capital, R&D and technology. When banks agree to offer loans, money is created in the form of deposits (the finance for investment), and saving and investment both increase equally. This leads to increased debt and income (unless the economy is operating at full employment; Keynes' so-called M-C-M economy, see supplementary material).[8] In the theory, when banks refuse to offer loans, saving and

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[7] Models of this type include GEM-E3-FIT (E3MLab 2013), IMACLIM (CIRED 2006), GEMINI (EPFL 2008).

[8] Models if this type include E3ME-FTT (Cambridge Econometrics 2014a) and GINFORS (Lutz et al. 2009).

> investment do not increase. Collective effects can lead to economic cycles. Central for innovation and technological change, individual investments may or may not lead to their intended productivity improvements and profit; however at the aggregate level, they all contribute to an increasing body of knowledge, the key process represented. Economic growth can arise as a result of increasing debt. Eventually, the increased level of debt has to be repaid. In the case of energy technologies, finance is typically recovered from energy consumers in the form of higher energy prices.

In the first instance, since the representative agent maximises utility by allocating fixed resources between possible uses, the methodology is tied to constrained optimisation (every point in time is optimal within its context). In the second instance, since at every time step the state of the economy primarily depends on its states in previous time steps and some form of expectations of the future, the methodology is tied to dynamical systems simulations. These are independent traditions of mathematics research often pursued independently from one another.

In practice, the current model zoology is not so clear-cut, and many models are hybrid (e.g. IMACLIM, see CIRED 2006; for GEM-E3-FIT, see E3MLab 2013 and the Appendix) . In particular, when equilibrium models feature elements that cannot be changed even when it would be optimal to change them (e.g. physical capital with long lifetimes, sticky prices), solutions are ‘sub-optimal’ and models deviate from ‘aspirational’ efficient markets towards descriptions that more closely reflect real-world ‘imperfections’. Furthermore, the representative agent can be given limited foresight (often called the ‘myopic mode’, relaxing the constraints of rational expectations). Finally, if a financial sector is introduced, saving can be borrowed from abroad and repaid in the future (e.g. in GEM-E3-FIT).

In the general equilibrium approach, models are based on agents’ behaviour optimisation, in which every configuration is a steady state or converges to a long term steady state. Productivity change takes place either exogenously or by knowledge capital accumulation, learning by doing, and from spillovers. Models are based upon production functions, which are representations of firms’ technical choices and trade-offs in resource allocations, substituting between labour, physical capital and knowledge capital (R&D). The choice and substitution of goods for one another is typically based on substitution functions (e.g. Constant Elasticity of Substitution (CES) models). Input-output tables determine the base year supply, use and trade for intermediate products in the economy and internationally. Using goods and labour supply functions, the economy is solved by finding the set of commodity and factor prices that clears all markets simultaneously.

Some CGE models are termed 'recursive dynamic' (e.g. IMACLIM, see Crassous et al. 2006, GEM-E3-FIT), which refers to their process of updating core variables between equilibrium calculations at each time point, including elements such as demography, stocks of physical capital, and other dynamics, and not carrying out inter-temporal optimisation.

A note should be given concerning increasing returns. Optimisation calculations apply to problems described by 'convex' functions, i.e. multidimensional functions that have a single unique optimum. As famously described by Arthur (1989), any process that results in increasing returns (e.g. choice events that result in the increased likelihood of the same choice events, or investments that result in more likely investments) bring models to fall into one of several optimal points. Taking for example learning-by-doing, if investing in solar PV panels makes the price of PV panels decline, that investment might result in a self-reinforcing cycle, and lead the model to solutions with high amounts of PV, in large part determined by early decisions. However, the model can equally fall into an onshore wind power future for relatively small differences in parameters. Once the model solution has adopted one direction, the other direction will no longer be selected (lock-in effects): it is trapped in a lock-in. For optimisation models, it may imply that at each time point, several optimal exist (several price vectors solve the general equilibrium). In the presence of increasing returns, indeterminacy exists between possible alternate futures at every point in time (e.g. Köhler et al. 2006). Sorting out the variety of model solutions at all time points in order to clearly identify scenario outcomes can become a serious challenge for modellers. This problem arises both when increasing returns are included at the micro (technology) or macro (sectoral) levels.

In the Post-Keynesian world, models are simulations, and productivity change takes place through knowledge accumulation, using Kaldor's technological progress function (Kaldor 1957; Lee et al. 1990), as model time goes by. Investment is endogenous to the economic context; sectors of higher growth see higher investment and thus faster change overall, and knowledge accumulation takes place whenever entrepreneurs invest (the process of cumulative causation discussed in the supplementary information). Since models do not minimise or maximise functions of several variables, the curvature of functions does not matter in this case. The multiplicity of solutions produced by knowledge accumulation does not generate solution identification problems for the modeller. Every model run evolves towards slightly different path-dependent directions for small differences in starting parameters, in the same way that complex climate or earth system models do. This demands special attention to statistical (sensitivity) analysis of model outcomes with respect to input parameters (Mercure et al. 2016).

2.3.2. Innovation and technological change in bottom-up technology models

At the micro or bottom-up technology scale (e.g. energy models, transport fleet models), a similar division of paradigms exists, also linked to an optimisation versus simulation methodological divide (Hall & Buckley 2016). A large number of partial equilibrium cost-optimisation models of technology are in use, and form the most common model type.[9] They originate from an energy sector central planning tradition. Their normative purpose is simple: how to develop and operate a national energy system at minimal cost to the operator (and ultimately, to the consumer). In the field of climate policy, these models, dating from the 1970s-1990s, have taken the centre stage (e.g. IPCC). Their use has become increasingly tied to descriptive purposes, not what they were originally designed for. With typically vast amounts of data on energy technology, they have been productively used to explore complex scenario spaces.

Cost-optimisation models operate using similar linear programming methods and software as applied in CGE models. Thus, partial equilibrium models are described as operating under the 'social planner' paradigm: the social planner organises the actions of otherwise uncoordinated technology investors such that the total cost is minimised in comparison to other configurations that could have resulted from uncoordinated cost-minimising action. To obtain optimal configurations that reach certain objectives other than pure whole-system cost-minimisation, the modelling tradition follows a Pigouvian approach by internalising externalities: valuations are given to externalities such as CO2 emissions and energy security (see McCollum et al. 2013; Jewell et al. 2016).

Due to their optimisation foundation, partial equilibrium (cost-optimisation) models also suffer from convergence difficulties if increasing returns are introduced. This is notably the case with energy technology learning curves. Studying this problem has yielded useful insights, in which clustering of solutions have been found with either 'green' or 'brown' optimal futures (Gritsevskyi & Nakićenovi 2000), an

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[9] In particular, the IEA's Energy Technology Systems Analysis Program (IEA/ETSAP 2016a) has been created in order to support the creation and development of cost-optimisation models based on the MARKAL/TIMES framework operated using the optimisation software GAMS. This networks has members globally. Other well-known models include MESSAGE (IIASA 2013), GET (Grahn et al. 2013), AIM-End-use (NIES 2012) and PRIMES (E3MLab 2015). IPCC models are primarily partial-economics-based.

illustration of how decisions now may lock us into particular futures (Grubb 2014, p.385).

Innovation, however, is not only a question of falling costs with cumulative investments, but includes the process of technological adoption itself, and the generation of new products. Adoption and diffusion is a process that is not modelled very well in the community: energy models are found to produce typically pessimistic outcomes in comparison to observed diffusion trends (Wilson et al. 2013). This points to a clear need to improve this representation, which is currently addressed in existing programs (e.g. the ADVANCE project, Wilson et al. 2015). The difficulty in modelling energy technology diffusion is linked to the lack of representation of decision-making by consumers and firms themselves (behavioural economics), and their heterogeneity (Rogers 2010).

The problem of energy technology diffusion is a complex one, for several reasons (e.g. see Mercure 2015). (1) Adoption decisions do not follow cost-minimisation at the system level, since the actions of agents (who are heterogeneous) are uncoordinated. (2) Projecting the diffusion of technology cannot reliably be done based on historical data since it is highly non-linear. (3) Adoption decisions are typically not made solely on cost considerations, but rather, can include biases, interaction and recursive effects such as social influence, i.e. what others have adopted (e.g. with cars, see McShane et al. 2012). (4) The diffusion process also includes the ability and pace of industry to expand production, i.e. it includes industrial inertia (see Grubb 2014, ch. 10).

Models of energy-related technology diffusion exist, and they are typically built with emphasis on decision-making by interacting agents, whether firms or consumers. The method of agent-based modelling lends itself well for this purpose (Köhler et al. 2009; Holtz 2011). Other model types are emerging in the field of TT (Holtz et al. 2015; Holtz 2011). Agent-based models however raise scalability challenges for modelling at national and, particularly, international or global scales, and remain tied to micro-level analysis, although they can provide results at a macroeconomic (city or national) level. Equivalent but simpler statistical models at higher aggregation scales have been designed, that offer essentially the same benefits without scalability challenges, using concepts from evolutionary economics (Mercure et al. 2014).

3. IMPLICATIONS FOR POLICY-MAKING AND MACRO-ECONOMIC EFFECTS

3.1. CLARIFYING THE PURPOSE OF MODELS: NORMATIVE OR POSITIVE?

The use of the representative agent or the social planner in modelling raises questions on the nature and purpose of models: are they normative or positive? Positive refers to models that attempt describe an observed reality and project future events, while normative refers to models that attempt to identify best courses of action or optimal system configurations for reaching certain objectives within a specific context. It is also useful to distinguish models used to make forecasts and models used for comparative analysis.

Scenarios calculated using normative models are by definition 'possible/plausible'; however, they are not necessarily 'likely'. To be precise, it is not possible to determine the likelihood of optimal scenarios occurring in reality, simply because, even if agents were inclined to take decisions that contribute to creating an optimal technology system configuration, they would have no way of finding out which decisions would make the correct contribution. This is a coordination problem (Kirman 1992).

As discussed above, normative model (e.g. cost-optimisation) results are often interpreted in a descriptive paradigm (for instance assuming that whole-system cost-optimal scenarios should happen in reality, e.g. the pathway RCP8.5 in IPCC 2014, calculated using optimisation model MESSAGE, but generally interpreted as a current policies baseline; see also Geels et al. 2016), resulting in a problematic scientific inconsistency. Normative models do not typically model or reproduce diffusion trends as reported in the empirical literature (e.g. as in Marchetti & Nakicenovic 1978; Grübler et al. 1999). While obtaining a system that operates at minimal society-wide cost may be socially desirable, nothing ensures that it should happen, and thus it is not a valid premise to adopt when attempting to describe reality. One clear drawback of using normative models for descriptive purposes is that normative scenarios are difficult to interpret for policy-making, since such pathways are not normally created based on particular policy instruments or frameworks; they are generated by integrating to optimisation algorithms normative valuations of externalities.

One clear danger exists in the interpretation of normative models for descriptive purposes in policy-making, which lies in their Pigouvian approach. In a normative frame, internalising externalised costs (e.g. GHG emissions) using pricing policies is desirable, since it corrects market failures. However, in a descriptive frame, while internalising externalities using pricing policies does create incentives to agents towards fixing market failures, to determine their likelihood of achieving normative objectives requires studying how agents take decisions, including how they take account of such taxes. Cost-optimisation and pure representative agent equilibrium models offer the attractive but potentially misleading suggestion that only pricing policies are necessary to correct market failures (such as climate change). Indeed, suggesting so relies critically on assumptions of how agents make decisions and how much knowledge they have, but there is no reason for their collective behaviour to match in reality the outcomes of a normative theory. Positive models of technological change must involve evidence from behavioural sciences in order to parameterise how agent decisions are made; otherwise they remain normative.[10]

3.2. POLICY INCENTIVES AND THEIR IMPACTS IN MODELS AND THEORY: A CLEAR SCHISM

The theory and modelling paradigm schism has important implications for policy interpretations. On the one hand, the equilibrium Pigouvian approach suggests that pricing an externality generates the correct incentive for agents to correct the targeted market failure (e.g. curtail their GHG emissions). Meanwhile, in a non-equilibrium perspective, pricing an externality provides an incentive for change, but the outcome is not necessarily the normative outcome.

This is reflected in model behaviour. In optimisation-based models, given that points in time are in equilibrium steady states, configurations (e.g. energy carrier flows, output and trade by sector) only change when exogenous variables change, as for example, regulations, trade agreements, the price of carbon, technology costs or taxation. The converse is that configurations do not change unless an exogenous parameter is altered. This has the result that, for climate change mitigation,

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[10] In contrast to the claim of Geels et al (2016), models of technology currently widely used for climate policy analysis (IPCC) are not positive, but indeed use cost-optimisation or based on multi-nominal logits (both representative agent-based) and, in almost all cases, only feature the carbon price as a policy option. Thus they embody this problem by construction.

emissions reductions occurring with the diffusion of low-carbon energy technology only take place when the price of carbon increases.[11] Technology diffusion stops if the (real) price of carbon or other incentives become constant, and reverses if they decrease.[12]

In a non-equilibrium perspective, model states typically evolve even if the policy context does not change, in parts pre-conditioned by their history, momentum and inertia. Thus, technology diffusion does not solely take place when relative prices change, but instead, continuously takes place. In this paradigm, taxes create incentives to re-orient an ever-changing system towards a new course.[13] For example, the higher the value of the carbon price, the faster changes take place, but changes keep taking place (since there is no steady state) irrespective of whether incentives changes. For the same reasoning, other types of unchanging policies can also create incentives.

Thus model representations of policy are consistent with respective theoretical underpinnings. This links further to a divide within the policy sphere as well. The world of climate policy is divided along two lines of thought. On the one hand, in the Pigouvian paradigm, policy-makers see carbon pricing following an ethics and social justice motivation for re-allocating significant amounts of scarce funds to fix a critically important market failure, climate change (Anthoff & Tol 2013; IPCC 2014; Stern 2007; Nordhaus 2010). In this approach, the challenge lies in the two difficult tasks of evaluating the social cost of carbon, and the marginal cost of abatement, and equating both, determining the carbon price that decarbonises the economy most efficiently (or, perhaps, justly), in terms of how much society values the future in comparison to the present (the social discount rate). As a result of this paradigm, it is often argued that a ton of carbon dioxide, wherever emitted, contributes equally to climate change, and thus the price of carbon should be the same worldwide, and all carbon markets should be linked into a single one for highest market efficiency.

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[11] With the exception of policy instruments involving setting standards which optimisation models reflect by reducing the menu of technological choices, eliminating those polluting technologies that do not meet the standards imposed. In this case emission reductions can still occur as a response to setting standards.

[12] And more or less proportionally: e.g. if the carbon price doubles, it is likely optimal to halve the number of carbon emissions, unless constraints prevent it. Diffusion is a unique function of the carbon price.

[13] Diffusion is not a simple function of the carbon price or other incentives: increasing the carbon price does not always incentivise the same number of agents deciding to purchase a particular durable good; it depends on history. But also, due to inertia in diffusion, an unchanging (real) carbon price/tax signal can sustain low-carbon technology diffusion.

In the innovation-diffusion perspective, energy and climate policy-makers involved in technology and systems of innovation see the carbon price as a price signal instrument to incentivise faster innovation and support the creation and development of low-carbon systems of innovation (Neuhoff 2011; Grubb et al. 2014), which can lead to first-mover advantages. In this perspective, the price of carbon must be sufficiently high (and reliably so) to provide a clear signal that communicates the current and future value of low-carbon R&D investment to firms. In practice, the price of carbon constitutes a market-pull policy, as it creates space in the market in which low-carbon technologies can grow. However, the carbon price is not the only market-pull policy available, and regulation can play an important role. The key point generally argued is that market-pull and technology-push policies must be co-designed coherently in order to bridge the technology valley of death (Grubb 2014, sect. 4.5). In the case of carbon markets, it may be argued that different national innovation systems, facing different contexts, are likely to require different magnitudes of incentives (e.g. what creates incentive for R&D investment in China is not the same as in Germany), and thus should not always be linked internationally for accelerating decarbonisation.

3.3. THE ROLE OF MONEY AND FINANCE IN CURRENT MACRO-MODELS

A transition to a decarbonised energy system will require significant amounts of investment in energy R&D, supply chains, infrastructure and physical capital, which could exceed what might have been invested in this sector in an otherwise business as usual scenario. Even in contexts favourable for entrepreneurs to invest in low-carbon technology, they require access to funds in order for the transition to take place. Such investments could, in principle, displace other (arguably more productive) investments that would have been made, a so-called ‘crowding out’ effect that could be detrimental to the economy.

In the context of this work, we use the general meaning of ‘crowding out’, which consists in the debated process by which when an agent or group of agents (government, firms, individuals) borrow(s) significant amounts of funds in order to invest into productive capital, this demand diverts funds that would otherwise have been used elsewhere in the economy, by bidding upwards the price of finance (the interest rate), i.e. pricing out competing projects. Where the investment is carried out by firms using internally generated funds, the interest rate is implicit and crowding out concerns the use of funds to invest externally. The crowding out term can also be applied to physical capital or labour, in which cases prices or wages clear the respective markets.

It is clear, from the above, that the degree to which crowding-out takes place in the model is quite determinant for model results. The potential extent of ‘crowding out’ processes depend on the amounts of funds available in the economy for investment.

This subject is once more fundamental to economic theory, where we again have the same two paradigms, (1) equilibrium and (2) non-equilibrium. Summarising this time with a focus on money, for policy contexts favourable for entrepreneurs to invest significant amounts of funds into low-carbon ventures (e.g. due to carbon pricing), outcomes will be either:

(1) Investment is determined by saving, which is a proportion of income. Entrepreneurs compete for this restricted amount made available through financial institutions or directly by households. Demand for money by different sectors at the same time is cleared by the rate of interest, i.e. some entrepreneurs are outbid by the willingness to pay of others, and are thus crowded-out. Money is a commodity in a finite quantity chosen by the central bank; if the central bank prints more money, its value decreases proportionally (the ‘neutrality of money’). Thus equilibrium models have no representation of money or inflation, only relative prices (Wing 2004). In the climate policy context, low-carbon investments promoted by policy crowds out other investments key to the economy. This leads to underinvestment in key sectors for growth, leading to less productive use of money and high costs to the economy.[14]

(2) Investment is determined only by the willingness of entrepreneurs to invest and the willingness of banks to lend (unless funds are re-invested profits). The willingness to lend is determined by the perception by banks of the credit-worthiness of entrepreneurs. Banks are not solely intermediaries, but have a balance sheet and strategy. Banks borrow from each other, to diversify risk, and to the central bank, to gain reserves necessary to underwrite their lending activities (they minimise the risk of their balance

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[14] This is different in GEM-E3-FIT, which does include a fully detailed financial sector treatment in an equilibrium modelling context. Effectively, moving money through time changes this outcome even in a CGE model, suggesting a degree of convergence between such types of equilibrium CGE models and non-equilibrium Post-Keynesian models.

sheet). Money, whether in paper form, or in commercial bank accounts, is a form of asset-liability pair, between two entities, the bank (debtor) and the owner (creditor). Thus all forms of money are financial instruments that can be created or destroyed (see Fontana 2009; Lavoie 1992; Schumpeter 2014, Barker 2010, McLeay et al. 2014).

Money creation is limited by the supply of credible lucrative ventures (in the prevailing context). If loans are allocated on the basis of speculation on the value of existing assets (in a way similar to Ponzi schemes, see Keen 2011), the financial sector becomes fragile and susceptible to domino effects (financial crashes). In times of economic optimism with high returns on investment, banks expand lending, leading to growth and prosperity; in times of high perceived risk of default, financial institutions restrict lending, leading to economic recession (Schumpeter 1939; Perez 2001; Freeman & Louça 2001).

In the perspective of climate change mitigation, the outcome is context-dependent. Climate policy could create employment due to enhanced investment, but can also lead to higher energy prices used to service debt. At the global level, employment and GDP can be enhanced or decreased (Barker et al. 2015; Mercure et al. 2016).

In practice, without explicit representations of the financial sector, current non-equilibrium models assume the allocation of finance (bank behaviour) exogenously,[15] while equilibrium models take the premise that banks do not play sufficiently important role to be represented. With the notable exception of GEM-E3-FIT (see the appendix), none of the existing large-scale models applied to energy-environment issues yet have a complete or at least satisfactory representation of finance and its interactions with the real economy.

3.4. MODEL OUTCOMES AND POLICY IMPLICATIONS BY MODEL TYPE

We conclude by summarising typical outcomes that may be produced by models depending on their theoretical underpinning, grouped following the equilibrium and

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[15] Godley & Lavoie (2007) provide methods with which detailed combined stock-flow models of finance and of the real economy could be designed. This has yet to be brought to climate policy analysis.

non-equilibrium classes discussed above (Figure 3). We also illustrate the behaviour of uncertainty in economic projections, which also reflect the underlying theory.

In the case of equilibrium models, with crowding out of investment, an investment-intensive energy transition displaces resources that would have been used more productively elsewhere in the economy, leading to a sub-optimal equilibrium at lower GDP in the short run.[16] As the transition completes itself and high carbon equipment becomes replaced by low carbon technology, this displacement ceases and investment returns to other purposes. In the long run, with learning-by-doing, productivity increases, while lower expenses on fossil fuels may be incurred, and GDP recovers, or may even be improved due to improved productivity and trade balance.

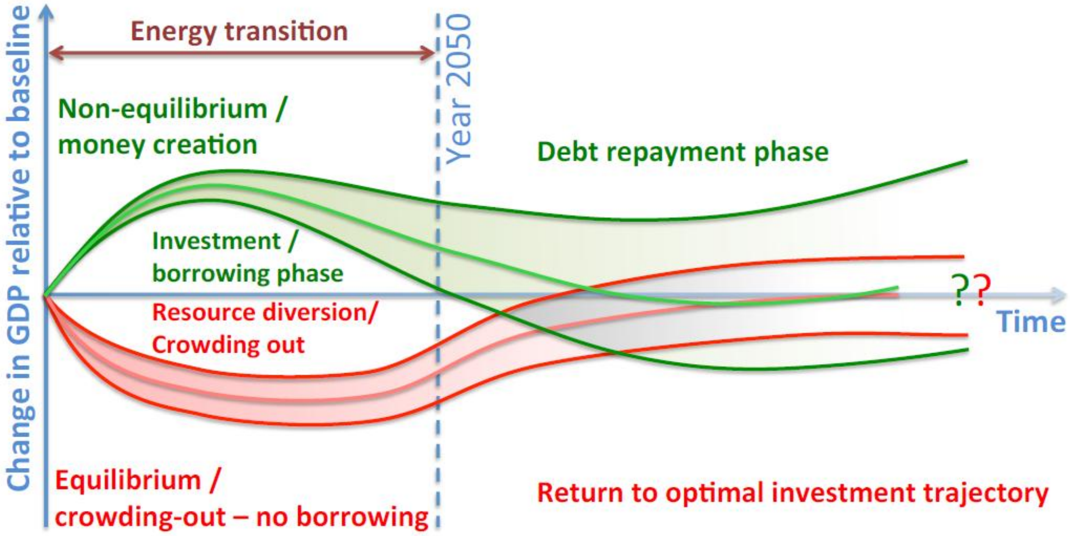

Figure 2: Illustration of GDP changes, relative to a baseline, of a policy-driven sustainability transition for the two groups of modelling schools of thought, equilibrium and non-equilibrium. In this image, a sustainability transition is financed (self-financed or via borrowing) from time zero until the vertical dashed line, after which low-carbon finance stops (figure co-designed by the authors).

In the case of non-equilibrium models (green curves), an investment-intensive energy transition program is predicted to create additional employment and to boost GDP in the short to medium run, due to a boost in employment stemming from

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[16] Unless, for instance, if the baseline initially included distortions that were then removed in a mitigation scenario.

higher investment (which is not offset by the impact of higher interest rates), but followed by a possible reduction in macro-economic gains or even decline in the long run depending on debt servicing conditions.[17] This is due to money being created by banks for investment in the early phase, which funds construction and results in activity across the economy, but also increases the debt burden, which remains in the longer term. Once the transition ends, spending declines but debt repayments remain, reducing income again, unless a new impetus is given to the economy and debts are refinanced. Long-lasting productivity increases typically remain in the long run, however, following cumulative investments in new technology and equipment. In the short run, if decarbonisation is carried out faster than capital turnover rates allows, an additional cost is incurred related to scrapping capital earlier than its payback time, a cost that can be higher than the income generated by job creation.

This explains how models exhibit essentially opposite outcomes for the economics of a sustainability transition, where the different model types exhibit exact opposite behaviour. Uncertainty also behaves differently: in equilibrium, due to the use of optimisation, uncertainty with solutions is linearly related to the uncertainty in parameters. It primarily represents the gradient of the optimisation function near the optimal point. In contrast, non-equilibrium models are strongly path-dependent, which means that uncertainty on parameters generates alternate scenarios that diverge from each other, differing minimally in the short run but becoming significantly different in the long run, such that model outcomes in the far future are more uncertain than those in the near future.[18] This property is standard in complex systems, and emerges for example strongly in climate models.

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[17] For example, debt repayments for capital intensive renewable electricity generators passed-on to consumers through an increased price of electricity affects the economy in the long run as a legacy of the transition (see Mercure et al. 2016).

[18] Lower apparent uncertainty bounds in equilibrium models should not be understood as better treatment of real-world uncertainty, but rather, as the uncertainty that *can* be represented in optimisation algorithms, which are not strongly path-dependent. I.e. increasing uncertainty bounds stem from path-dependence.

4. SUMMARISING THE GAPS FOR BETTER POLICY IMPACT ASSESSMENT

Following the discussion in the previous sections, we summarise here the identified gaps in modelling techniques commonly used to assess the macroeconomic and inter-sectoral impacts of policies for sustainable energy transitions and emissions reductions. These apply to macro-sectoral models generally. We classify these in terms of gaps for modelling energy-related innovation itself, gaps for modelling the finance of innovation, and gaps for modelling economy-wide impacts of innovation, in the context of energy and climate change policy. Understanding these gaps is directly relevant for institutions commissioning policy impact studies (e.g. impact assessment for the European Commission). Meanwhile, since model results disagree by model type, addressing these gaps in models is crucial in order to reliably inform policy-making.

Undoubtedly, some of the issues raised here cannot be easily solved in models. In part, this is due to data availability or reliability, partly it is simply that modelling methods simply do not yet exist (e.g. modelling investor risk perceptions of low-carbon projects). Moreover, scale issues arise between the bottom-up and top-down scales, where some data exists aggregated at sectoral level (e.g. production, productivity) while particular policy instruments apply at the level of individual technologies or equipment (market-pull, e.g. eco-design standards or feed-in tariffs). We included Figure 3 to help the reader grasp the modelling implication of model choices for policy assessments. Recent model developments show outcomes that are converging, however. Here, we summarise knowledge gaps to better address the economic impacts of a sustainability transition. We note that they mostly relate to either or both representations of innovation and finance processes, and their respective possible barriers.

4.1. CURRENT GAPS IN THE MACRO-MODELLING OF FINANCING LOW-CARBON INNOVATION

a. Access to finance by entrepreneurs (bank deposits, equity, debt and money-creation) is not fully represented in any energy-economy model.

b. It is not determined or agreed across the field whether crowding out takes place or not and to which degree. While the emphasis tends to be the crowding out of investment through competition for finance for investment, it could include crowding out due to scarce production capacity or labour.

c. Models do not adequately capture the role of private and public R&D financing in promoting innovation. Poor representation of different financial/fiscal instruments (i.e. tax credits vs subsidies) in providing effective incentives for innovation.

d. In a perspective without crowding-out, it is also not determined whether there are, and if so, what are, upper limits to the availability of finance for low-carbon innovation, driven by the perception of risk by investors and banks in low-carbon innovation, and therefore whether large-scale finance of climate mitigation measures affects future economic stability and well-being in Europe.

4.2. CURRENT GAPS FOR MODELLING THE ECONOMIC IMPACTS OF ENERGY INNOVATION

a. There is no consensus on the existence and degree of crowding out of productive capital, (correctly) skilled labour, and investment. Empirical determination is highly desirable.

b. The link between R&D expenditures and productivity and/or competitiveness needs to be empirically estimated. Only very few studies provide results on this matter.

c. Intra- and inter-industry spillover effects are poorly validated empirically.

d. No limit to finance is fully determined in either types of models, and the mounting of debt is not typically fully kept track of, nor of debt servicing. Stock-flow models of finance are needed, requiring further research and model development.

4.3. MODELLING FINANCE, DEBT CREATION AND CREDIT-WORTHINESS

It emerges from our findings that models currently only offer an insufficiently detailed representation of how low-carbon technology ventures are financed, and how resources are allocated to entrepreneurs. This limitation impedes improved understanding and insightful impact assessment of policies for climate change mitigation. Since different modelling approaches provide different outcomes of such policies, and since their empirical validation is far from complete, the best approach for policy impact assessment currently lies with the use of both modelling approaches in studies (see e.g. Cambridge Econometrics 2013; Cambridge Econometrics 2015), ensuring transparency and providing clear mappings of results and drivers. Moving beyond lies in improving the representation of the economics of innovation and finance in both modelling approaches.

The process of allocating finance to entrepreneurs is not represented in nearly all models[19] currently used to study climate change mitigation. It is, however, one of the key drivers of the magnitude and direction of the macroeconomic impacts of policies promoting low-carbon technological change (GDP, employment, exports, sectoral structural change). Building such a representation is challenging, as the finance of low-carbon ventures involves many types of financial instruments, thus requiring building detailed financial sector modules using significant amounts of data. Standard equilibrium models without any representation of finance implicitly assume that firms can only finance investment out of accumulated profits, and cannot borrow funds.

In equilibrium models, the factor limiting the total amount of borrowing is the interest rate, which clears the market. It is clear, however, that what is financed in reality depends on the credit-worthiness of investors in their own specific sectoral context, and using a single interest rate is likely not sufficient to capture details of what gets financed and what does not. In non-equilibrium theory, credit-worthiness is what ultimately determines the confidence of banks to invest (i.e. Keynes' 'animal spirits'). This is not represented in any form in applied non-equilibrium models either, but rather, is left to the modeller to take assumptions deemed reasonable (e.g. by assuming policies deemed credible by agents that ensure low-carbon ventures are profitable, itself a debatable premise). It would appear, however, based on comparison of results from the models E3ME and GEM-E3 (see the Appendix),

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[19] We note the exception of new developments with the model GEM-E3 regarding the financial sector.

that improving representations of finance in both model types, leads them to converge towards increasingly similar outcomes.

5. CONCLUSION AND OUTLOOK TO THE FUTURE

Policy assessment often requires the use of large multi-sectoral computational economic, technology and environmental models, to carry out quantitative analysis. The outcomes of these models are tied to their assumptions and theoretical underpinnings. Therefore, it is always crucial to lay out these assumptions and theoretical details in a way that makes understanding the results as straightforward as possible.

This paper presents the outcome of an important effort towards this very goal:

(1) to explain why particular results are obtained out of particular models for analysing the economic impacts of low-carbon energy policy, and the crucial roles that innovation and finance play in determining and adequately explaining model outcomes. We have presented how the historical development of economic theory underpins the various types of models that exist today: two major branches of theory led to the development of two main branches of models that typically produce very different results. We have attempted to explain this in the most balanced and limpid way possible, in order to clearly explain how to interpret results of models.

(2) to list what improvements to current models could lead to better informed analysis of the macroeconomic impacts of energy, climate and energy efficiency policies.

Our explanation of the theoretical origin of model differences can help policy-makers and policy-analysts understand what broad mechanisms the models have and have not taken into account when interpreting the results of empirical policy analyses. The differences between the models, including differences in their treatment of innovation, reflect the lack of scientific consensus among economists/social scientists. While both approaches are theoretically rigorous and self-consistent, it is important for policy-makers to have some insight into this state of often conflicting knowledge. It needs to be recognised by the modelling community that this schism exists, that representations are incomplete, and therefore that further research is critically needed in order to further our ability to effectively inform climate policy-making.

It emerges from our study that developing representations of the monetary and financial sectors is crucial in models used for studying the economic impacts of energy system transformations and emissions reductions. Furthermore, model differences completely hinge on whether crowding out of financial resources takes place or not, which thus needs empirical verification. In addition to this, improving representations of behavioural features in agent decision-making (e.g. technology adoption, bank lending) can improve the accuracy of models to assess the effectiveness of proposed policies.

These results will help, we hope, to shape the future direction of research and development in theory and models that are used for the analysis of energy and climate policies, including related impact assessments – for example, by the European Commission, at the state level or in the climate change research community (including the Sixth Assessment Report of the IPCC). We trust that the knowledge reviewed here can help build a new research agenda, but also, shape the direction of enquiry in policy assessment. We stress that these issues of finance, credit-worthiness and crowding out should not be seen as peripheral, but rather, should be considered at the very heart of what determines the far-reaching economic impacts of low-carbon and climate mitigation policy.

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A. APPENDIX: TWO FEATURED MODELS EXTENSIVELY USED IN POLICY-MAKING

Two models, E3ME-FTT and GEM-E3-FIT have been used extensively by the Commission for recent reports on the macro-economic impacts of energy policy and energy efficiency (e.g. for employment impacts, see European Commission 2013; 2015). In these studies, model outcome differences highlighted above were prominent and were explained primarily under the different assumptions over crowding-out of investments. In this section, we introduce briefly these models, and describe how this is observed in the model results. These models are representative of what is observed in the broader community, and therefore this analysis has relevance for better understanding the outcomes of all quantitative studies of the economic impacts of climate, energy and energy efficiency policy.

A.1. THE RECURSIVE DYNAMIC CGE MODEL GEM-E3-FIT

GEM-E3-FIT[20] is a global, multi-region, CGE model that covers the interactions between the economy, the energy system and the environment. GEM-E3-FIT is a new generation version of the GEM-E3 model that includes the financial sector, semi-endogenous technical progress, detailed transport representation and a detailed representation of the sectors producing clean energy technologies. The model is recursive dynamic in which, at each time step economies are found in equilibrium, but where technical progress, capital accumulation and expectations of agents (modelled as myopic) are manifested through stock and flow relationships. The model includes a bottom-up representation of power generation technologies and it calculates endogenously the energy-related emissions of CO2 per economic sector.

In the standard CGE setting all savings are exhausted in financing current investment projects: the realisation of any alternative investment plan requires that either consumption is reduced (savings increase) or other investment projects are cancelled (crowding out). Limited availability of financing capital implies that capital costs will always rise when the economy transits to a more capital intensive structure. Increasing capital costs raises production costs, having a direct negative impact on the competitiveness of economic sectors. A representation of the financial

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[20] GEM-E3-FIT stands for: **G**eneral **E**quilibrium **M**odel for **E**nergy, **E**conomy, **E**nvironment with **Fi**nancial & **T**echnical progress modules.

sector in a CGE context can thus moderate short-term stress on capital markets by allocating capital requirements over a longer period (i.e. money flows over time as well as space).

GEM-E3-FIT has been extended so as to include the explicit representation of the financial sector and its links with the real economy. Thus the model deviates from the standard CGE framework where agents can create unsustainable deficits and still borrow. A bank has been included that issues loans at interest rates that clear the market while taking into account the net credit position of each agent. Governments and firms issue bonds to cover their deficit while households receive loans. Agents' decisions to lend or borrow depend on the interest rate.

GEM-E3-FIT is of the optimisation model class, with results consistent with the conclusion of section 3. The economic impacts of policy-induced technological change in GEM-E3-FIT are significantly influenced by its treatment of the financial sector. Bank lending will enable to finance at time t large infrastructure energy projects that would otherwise displace significant finance from other productive uses in other sectors at that time in a standard CGE model without a financial sector. This therefore mitigates the classical GDP impacts of climate mitigation policy observed in standard models (e.g. Edenhofer et al. 2010). However, money must be paid back during the modelled time span after time t in order for model closure over time, and hence bank finance ends some time before the end of the scenario. The impacts of policy for a sustainability transition in GEM-E3-FIT follow the representation in red of Figure 3.

A.2. THE MACROECONOMETRIC-DIFFUSION MODEL E3ME-FTT

As with GEM-E3, the E3ME-FTT is a global model that features both top-down (E3ME) and bottom-up (FTT) representations. E3ME-FTT is a macroeconometric model that derives aggregate economic behaviour in many sectors, countries, fuel users and fuels, using regressions carried out on historical yearly data, and projects the global economy until the policy horizon of 2050. It is based on regressed equations governing various areas (the energy sector, prices, investment, output, employment, etc). It also features a bottom-up representation of technological change in the power and transport sectors. As opposed to GEM-E3-FIT, E3ME-FTT is based on a simulation framework. This implies that scenarios produced are not optimal under any criteria (i.e. no quantity is maximised or minimised), and that scenario development is path-dependent, each following different trajectories determined by cumulative causation of factors (e.g. exogenous factors, endogenous technical progress, technology diffusion trajectories), in other words, conditioned by history (past scenario events).

The direction of information flow is opposite to GEM-E3-FIT: while GEM-E3-FIT starts from the production function and goes towards consumption and capital accumulation, which then goes back to further production, E3ME-FTT starts from aggregate demand, which determines production and investment, the latter adding to the capital stock, and income, stemming from employment of households, leads to further aggregate demand for goods (see Figure 1).

E3ME-FTT does not have an explicit representation of the financial sector. Finance is implicit in E3ME-FTT, in that money is assumed created when demanded by entrepreneurs. Thus money is then used by entrepreneurs to add to the capital stock and increase productivity, which increases aggregate demand and creates employment. Thus in the short run, GDP and employment increases result from any incentives to invest. Finance is not crowded-out, in other words, banks deciding to finance particular projects does not affect the likelihood of banks financing other projects (and the amount of money is not fixed, the central bank creates money on demand for commercial banks). However, there is no explicit representation in the model of decision-making by financial institutions, of the risk of particular ventures or the criteria by which projects get funded: all projects modelled (e.g. investment in low-carbon electricity generators) get financed by assumption. GDP does not increase indefinitely with investment, however, as in the long term, money must be paid back, which cost is assumed passed on to consumers through prices (e.g. a higher price of electricity).

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