European Commission

# Policy-induced energy technological innovation and finance for low-carbon economic growth

*Deliverable D2*

*Study on the Macroeconomics of Energy and Climate Policies*

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# Executive summary

## Introduction and scope of the study

This report provides a review and synthesis of current knowledge regarding policy-induced energy innovation and technological change and its likely implications for the macro-economy and future low-carbon societies in the European Union.

Analysis carried out by and on behalf of the European Commission and other policy bodies to assess the potential cross-sectoral and economy-wide impacts of policies designed to promote a sustainable, secure and competitive energy future typically involves quantitative modelling using whole-economy macro-sectoral tools. A key lesson from these studies has been that conclusions about the scale and sometimes even the direction of the economic impacts of policies that incentivise the uptake of low-carbon energy technologies and practices differ considerably across different models. These differences are understood to reflect key differences in the models' theoretical underpinnings, but until now no comprehensive analysis has been prepared to explore these differences in depth.

This report has three goals:

(1) to *provide an exhaustive account of the theoretical origins of the differences in outcomes observed between models* with regard to innovation; an extensive literature review explores how energy innovation, technological change, and the finance of innovation are represented in existing theory and models, and what the implications are for the model outcomes.

(2) to *identify areas of knowledge that are missing in the models' treatment of innovation and technological change*, focusing on the drivers of and barriers to energy innovation: what constrains the pace of technological change and innovation?

(3) to identify the *key gaps in the existing models* with regard to how policy interventions affect energy innovation and what the subsequent consequences are, and to provide a list of developments that could realistically be carried out to address these gaps and so improve the quality of analysis to support policy assessment and design: how does policy interact with innovation processes and the macroeconomy?

In this report, the focus is on the treatment in empirical, particularly macro-sectoral models, since this study aims to improve their treatment. Energy innovation needs to be treated holistically and include all sectors producing, consuming, distributing, and regulating energy. Lessons have been learned in recent research on *Technology Innovation Systems* on the structure and determinant factors of the innovation process. These apply to the energy sector, on both the supply and end-use sides; these are brought into focus. While energy supply developments take the form of process innovation, end-use developments relates to product innovation.

## Review of the literature on modelling energy innovation

A thorough literature review was carried out of how innovation and technological change is explained in all existing major branches of contemporary economics and innovation research. We conclude that all the branches of macro-innovation theory can be grouped into two classes. 'Equilibrium – Optimisation' theories that treat innovators as rational perfectly informed agents who adopt rent maximising behaviours, driven by market price signals, consumer preferences and operate under specific institutional and policy frameworks. Market processes are equilibrating (i.e. reach a state where agents do not want to change their choices) via market price signals. The role of policy is to correct for particular 'market failures'. 'Non-equilibrium – simulation' theories emphasise that economic trajectories are in constant transformation shaped by institutions and history, but do not have a 'preferred' equilibrium state. This means that "free markets" do not exist in practice; markets have been and will be shaped by history and institutional forces. In these theories, there is no ideal equilibrium to target: the role of policy is to intervene in processes, given a historical context, to promote a better outcome or new economic trajectory.

We then review two whole-economy macro-sectoral empirical models used extensively for energy-environment-economy policy modelling that have their origins in each of the two classes of theories, namely GEM-E3-FIT pertaining to the equilibrium approach, and E3ME-FTT associated to non-equilibrium thinking.

In their simplest form, the two broad theoretical approaches yield different conclusions for the economic impact of policy interventions designed to decarbonise and transform the energy system. In the equilibrium approach the policy to reduce GHG emissions or pollution is always costly as long as the externality has not been internalised in agent's decisions. Once agents have assumed action based their preferences and technology constraints, any policy intervention that is misaligned with their optimising behaviour will have a welfare cost compared with the no policy action case (unless it simultaneously removes some other impediment to achieving the equilibrium outcome). The question, according to this theory is whether agents can actually have full access to the complete set of information and hence always select global optimal pathways.. In the non-equilibrium approach, the policy intervention influences the economic development trajectory, and may shift the economy onto a better or worse path. This divergence in modelling approaches being pursued has often been framed as a difference over the extent to which low-carbon investments, promoted by policy intervention, are understood to have or not the effect of '*crowding out*' other investments that would otherwise have taken place. Equilibrium theory *assumes* that resources are finite and fully employed, hence low-carbon investment displaces financial resources from other uses leading to an efficiency cost, while non-equilibrium theory does not (i.e. it assumes that financial resources are *created* by banks).

## Summary of drivers and barriers to energy innovation

In order to improve the representation of the process of policy-induced energy technological change and innovation in models, this report argues that the most useful approach is to distinguish different processes in the *Energy Technology Innovation System*. We find that each stage of the *energy innovation chain* typically requires different types of policies, and involves different types of investors.

We also find broad agreement in the literature that it is the alignment between market pull and technology push policies, at both ends of the energy innovation chain, that offers the best prospect of accelerating the pace of innovation and technological change to meet energy, economic, climate and environmental objectives. Without this alignment, many innovations may not survive the journey across the technology 'valley of death' between the lab and mainstream use.

For example, policies may be adopted to support R&D for electric vehicles, but new technologies developed might not find their way to the market without price or regulatory policies to reduce uncertainty on expected economic returns. Similarly, price policies may not yield effective change in externalities (e.g. pollution) on their own without an actual R&D and technology development strategy.

## Knowledge gaps in current models and recommendations

We review the gaps in existing models for representing policy-induced energy technological change and innovation. We do so by taking account of our findings on the drivers and barriers to innovation, and focusing on the models GEM-E3-FIT and E3ME-FTT. We find that it is not currently possible to model the alignment of technology pull and push policies because the representation of the innovation chain is incomplete in the models. We suggest ways to improve the representation of innovation processes in macro-sectoral models. These include a better treatment of *technology innovation systems*, financial markets and behaviour, and the modelling of more diverse and explicit energy and climate policy instruments impacting innovation.

We recommend that more evidence be gathered and included in models with regard to the conditions under which policies that promote low-carbon, capital-intensive investment in the place of conventional, less capital-intensive alternatives would divert financial resources and displace investment elsewhere in the economy. More analysis is needed to explore whether the pool of financial resources is finite, or whether its size could adjust in response to the intervention and profitability prospects.

## Conclusions

Regarding the three goals of this study, we conclude, respectively, the following:

(1) 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. *Equilibrium models offer a perspective of allocation of scarce resources and the cost and benefit of changing individual choices, while non-equilibrium models offer a dynamic perspective of decision-making by investors and financial institution under fundamental uncertainty and inherent constraints.*

Model analysis outcomes are consistent with these perspectives: in equilibrium models, technology support policies tend to reallocate financial resources that under certain price and technology dynamics assumptions may lead to *sub-optimal equilibria from a growth perspective*. Meanwhile, non-equilibrium models allow *new growth possibilities* associated to the development and deployment of *new technologies,* such as environmentally friendly goods and services.

*It emerges from our study that a representation of the monetary and financial sectors is crucial in models for the study of the economic impacts of energy system transformations and emissions reductions.* It is important to adequately capture the perception of risk by investors and financial institutions in different types of ventures. Furthermore, model differences *completely hinge on whether crowding out of financial resources takes place or not*, which thus needs more empirical verification.

(2) Our review of the innovation research literature has revealed key gaps in the models' existing treatment of the innovation process. *A better representation of the energy innovation chain in models and theory would significantly improve policy analysis. In particular, the ability to model the alignment of technology market-pull to technology-push policies would significantly advance knowledge and analytical capacity on the macro-innovation modelling front.* It would allow to explore the 'lead markets' hypothesis in which technological leadership provides competitive advantage and exploit new markets globally, and transitions of socio-technical regimes.

(3) Our recommendations for model improvements give priority to (a) representing the financial sector in models, including perceptions of risk and uncertainty by financial institutions, (b) representing more policy instruments that act at different stages of the energy system innovation chain to overcome non price barriers as well as price barriers for new technologies, and (c) carrying out empirical work to establish an evidence base for assessing whether crowding out of financial and real resources takes place or not.

# Part I. Introduction

## 1 Framing of the problem and scope of this report

Environmental protection and human development objectives in Europe are very clear. 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 to reduce global anthropogenic emissions in order maintain global average temperatures warming well below 2$^{o}$C. As part of the process of submission of Intended Nationally Determined Contributions (INDCs), Europe has committed to 40% reductions of its domestic Greenhouse Gas (GHG) emissions below its 1990 level by 2030.[1] The EU already had this decarbonisation target included in its 2030 climate and energy framework, alongside two other inter-related targets, namely at least 27% share for renewable energy and at least 27% improvement in energy efficiency.[2]

These climate and energy targets can be achieved via different pathways and different combinations of supply-side and demand-side technological and socioeconomic responses. Significant debate exists on strategies for an efficient and cost-effective sustainable energy transition in Europe and across the world (e.g. IPCC 2014; Edenhofer et al. 2010; Stern 2007; Nordhaus 2010; Nordhaus 2015). Many experts have analysed the question, and many tools have been used for the purpose. It is clear that a certain quantity of decarbonisation will originate from technological change distancing from fossil fuel combustion equipment developments, for example replacing existing large coal electricity plants by renewable energy systems, 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 originate 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.

There is, however, a knowledge gap as to how and why consumers and firms adopt or do not adopt low-carbon technology (e.g. Gillingham and Palmer 2014; Gerarden, Newell, and Stavins 2015; Jaffe and Stavins 1994). Why do firms and consumers not invest in seemingly cost-effective solutions that will save them money in the long run? Is it lack of information, lack of access to finance, institutional constraints? The answer is complex and needs attention (Knobloch & Mercure 2016).

Analysis tools built for the purpose of providing insight for the design of energy and climate policies must, to be truly useful to the policy-maker, be able to realistically estimate what the outcome is likely to be, within some uncertainty bounds, of applying particular policy instruments, and combinations thereof, within certain given contextual settings. This can effectively only be achieved by accurate representation of: i) the statistical description of the economic-energy-enviroment system, ii) the behaviour of consumers and firms, and iii) the interaction among heterogeneous agents. Such representations are far from complete in current analysis tools (e.g. Mercure et al. 2016; Mercure et al. 2014). Furthermore, few or none of the current models used to analyse and assess energy and climate policies (IEA 2015; GEA 2012; IPCC 2014) have representations of the financial sector of national and the global

[1] See http://climateactiontracker.org/countries/eu.html
[2] http://ec.europa.eu/clima/policies/strategies/2030/index_en.htm
[2] http://ec.europa.eu/clima/policies/strategies/2030/index_en.htm

economy, and its relevance for a large scale decarbonisation transition. This is a major shortcoming because such a transition will require large-scale investment.

In the current economic context in Europe, it is of primary importance to determine whether a sustainability energy transition 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 2015b), and *this specifically includes low-carbon and energy innovation*, which could fuel future prosperity.

In this report, we review current analysis methods 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, at European level or at Member State level, 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 outcome of chosen policy instruments across the member states? This report represents only one deliverable amongst other inter-related deliverables planned for the on-going European Commission funded study on the macroeconomics of energy and climate policies.[3]

For this purpose, we first carry out an extensive literature review, covering energy innovation in economic theory, historically and contemporarily, in order to explain and assess how innovation is currently understood in models used to carry out analysis for the Commission, and more broadly (e.g. 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? We draw conclusions for the applicability of different types of models to the present project. By reviewing current methods of analysis and representations of the drivers, barriers and impacts of innovation, in particular low-carbon energy innovation, we conclude with a number of recommendations for existing models commonly used by the Commission for its impact assessments of policy proposals, for improving their accuracy in simulating the outcomes of energy, climate and environmental policies in Europe.

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 very well the theoretical underpinnings of the various existing implementations. In particular they do not link to the extensive research field of *Technology Innovation Systems* (TIS), and do not fully touch upon *how innovation is financed, adopted and diffused*. Here, we give particular focus to these aspects, which we consider key to our ability to inform effective energy-related policy-making.

In this report, Part II reviews innovation in economic theory (applying to energy and overall innovation), and how it is represented in contemporary computational economic models. This is followed by a discussion of the drivers and barriers to innovation in Part III, zooming into more explicit energy innovation aspects. Energy-related innovation takes place in tandem with systems of finance for innovation. For that reason, a brief review is given, as well, on its drivers and barriers of the finance of innovation. Most of this theory is not currently incorporated in models, which we consider significantly limits their ability concerning energy policy induced technological change and related economic impacts. We thus finish in Part IV by identifying the gaps

[3] For the Terms of Reference of this study, see the DG Energy website of the European Commission where calls for tender are listed: http://ec.europa.eu/energy/en/funding-and-contracts/calls-tender# (the call for this "Study on the Macroeconomics of Energy and Climate Policies" was closed on 22nd of June 2015).

that macro-sectoral models would need to tackle for better informing energy and climate policy formation and for supporting faster energy-related innovation uptake. Further information is given in an extensive appendix.

# Part II. Literature review on modelling innovation

## 2 Innovation in the history of economic theory and models

### 2.1 Motivation

The goal of this report is to assess how macro-models used by the Commission and other institutions involved in the energy and climate policy sphere can better describe, and provide insight on, policy strategy to better foster and support technological change for a sustainable future energy sector, and for improved European economic development. Macro-models have been used extensively to address how to reduce emissions, in particular through the IPCC process (IPCC 2014), and at the European level.[4] However, as argued below, while models are typically designed to produce technology or economic scenarios, they do not address key features of the policy frameworks that could lead to achieving particular scenarios, leaving a knowledge gap for actual policy application (Mercure et al. 2014; Mercure et al. 2016). Indeed, which policy frameworks or portfolios are likely to reach cost-effectively multiple energy and climate objectives: should a carbon price be used on its own? Should it be combined with technology subsidies and/or feed-in tariffs? Is pricing the externality sufficient, or should access to finance be improved? Do policy instruments interact (interfere, synergise) with each other? Can we model energy technology push policies? These are questions that the current modelling community continues to grapple with. There are several limitations to a more robust modelling of macro-energy interactions, which calls for radical improvements of their representations of policy instruments.

This situation is of course not simply because academics and researchers downplay these questions. Rather, it reflects 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 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.

The realism and accuracy of model representations of the effectiveness of policy instruments depend critically on the representation of the behaviour of the agents targeted by those policy instruments, whether firms, consumers or public entities (Mercure et al. 2014): do they optimise, what do they optimise when deciding, what do they know, are they homogenous or highly diverse, and crucially, how well do we know their contexts for decision-making, and how do we aggregate a multitude of different agents into a macro-theory and macro-models? Such questions will have to be addressed with the inclusion of a higher degree of detail to describe the energy-related behavioural response of different kinds of agents (Knobloch & Mercure 2016; Wilson et al. 2015) based on empirical evidence. However, such changes are likely also to require supporting changes in the structure of models.

Meanwhile, an important debate has taken place for many years on the macroeconomic impacts of an energy-related sustainability transition (Grubb 2014;

[4] 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

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 how to include innovation in models in order to better determine how productivity growth can be influenced by technology policy. This applies particularly to energy systems (supply, demand, infrastructure) and remains an unsolved question. In the context of the current recession and economic fluctuations in Europe and beyond, progress needs to be made in order to better inform policy-making and reduce the uncertainty of possible policy outcomes from the policy-maker's perspective (Mercure et al. 2016). For example, does technological change policy for addressing climate change strengthen or weaken Europe's economy and competitiveness in the global context? Or put differently, how can energy-related policies be formulated, such that they best incentivise growth and competitiveness?

This section of the report reviews methods used in contemporary energy-economy-environment macro-models deployed for energy and climate policy assessments. We raise issues in current models that pose challenges to effectively inform energy-related policy-making. We start with a description of innovation in general, as currently included in economic theory, because it applies directly to energy systems. In particular, R&D investments for end-use technologies do not typically seek solely 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). Meanwhile, R&D in energy supply technologies target process innovation for the production of improved machines and devices. These pertains characteristics specifics to innovation occurring in network industries.

## 2.2 Technology and innovation in the history of economic theory

It is hardly conceivable to discuss innovation in the history of economic thought without starting from the work of Schumpeter, which focused on the role of the entrepreneur and of the enabling financial institutions (Schumpeter 2014; 1934; 1939). This 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 (EE), (Freeman & Louça 2001), Sustainability Transitions Theory (TT, Geels 2002), Energy Technology Innovation Systems (TIS, Grübler & Wilson 2014), directed clean innovation, (Acemoglu et al. 2012) and planetary economics (Grubb 2014).

Meanwhile, the clarification provided by Keynes of the mechanisms that operate the macro-economy is also 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 1992). In fact, the Post-Schumpeterian and Post-Keynesian pictures could be seen as two different perspectives on the same broad theory (e.g. see in Perez 2001). These may be said to form together the non-equilibrium economics school.

Meanwhile, 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.

In Appendix A, we present an extensive review of innovation throughout the history of economic thought. We summarise it pragmatically here by stating how economic development takes place in each of two schools. The basic view of the equilibrium school is one of allocation of *scarce economic resources and capital accumulation*:

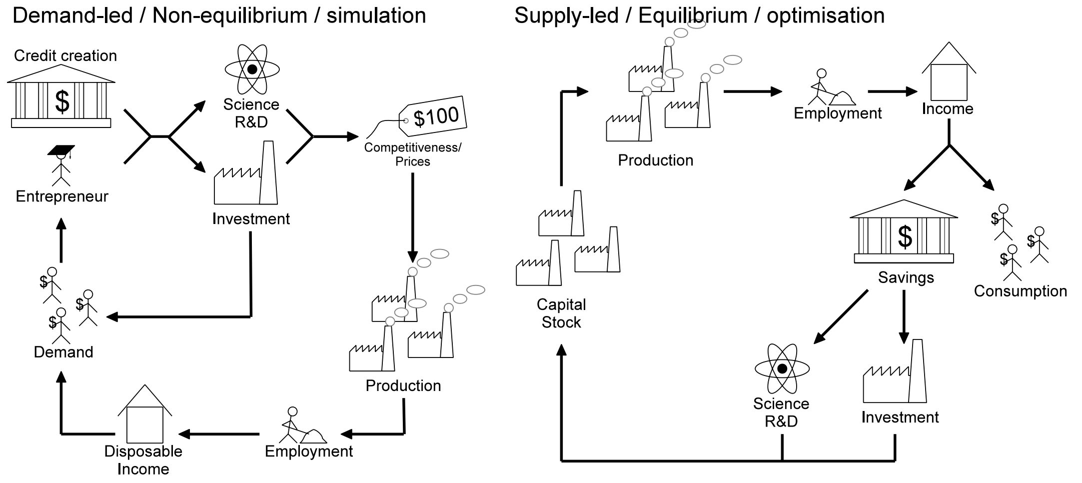


**Figure 1: Contrasting economic growth in the Post-Keynesian/Post-Schumpeterian (non-equilibrium) schools to the neoclassical (equilibrium) school.**

1. Given a finite set of production factors, technology options and households' preferences for consumption, firms produce by fully using resources (full employment)[5] to meet the intermediate and final demand of their products.
2. Firms seek financing for their investment from the capital markets.
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 the consumption (of various goods) and saving.
4. All savings are used to finance firms' investments. Investment accumulation defines the capital stock available for production, which includes: physical production facilities (e.g. replacement of retired machinery), and investments into knowledge stock (e.g. technical progress, R&D).
5. The increased amount of capital, labour (population) and productivity expand the production frontier and allows higher volumes of production.

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

1. Entrepreneurs see potential applications for their ideas, and apply to financial institutions to finance their innovative improvements to the existing capital stock. Banks create loans based on entrepreneur 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 increases 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 on 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).
5. Higher demand and profits incentivises firms to re-invest to innovate and expand their capital stock, leading to further expansions of the stock of knowledge.

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

These two representations are radically different in their key principles and lead to contrasting methodology when used 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. The difference in the modelling assumptions has deep consequences on the macroeconomic adjustment suggested by each school. Hence the clear exposition of assumptions is required to render analysis informative.

### 2.3 Contrasting assumptions, methods and current mainstream thought

It is widely accepted by all schools of economic thought that 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 10 schools and research areas in economics. These schools or fields do not generally exclude each other except whenever they are inconsistent. In particular, we see the Post-Keynesian and Post-Schumpeterian schools use significant amounts of concepts and data from the behavioural school. However, non-equilibrium schools tend to be at odds with equilibrium schools due to sheer methodological and theoretical divides.

**Table 1: Schools of economic thought**

| | School Name | | Micro-foundations: Rational | Micro-foundations: Agent | Money | Estimation method | Innovation Technology | Economic change |
|---|---|---|---|---|---|---|---|---|
| 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 | Capital & knowledge accumulation |
| Non-equilibrium | P-S | EE[4] | Behavioural[8] Heterogeneous | | Asset (Credit creation) | Dynamical sytems (EE), Historical approach[9] | Diffusion, learning curves | 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)

*Planetary Economics* (Grubb 2014) attempts to reconcile schools of thought for the climate change mitigation context by structuring the analysis in three different areas of focus solving different problems: the adoption of sustainability innovations, altering markets to support low-carbon innovation, and transforming infrastructure and institutions. For this, Grubb invokes methods from, respectively, behavioural, neoclassical and evolutionary economics. The problem of climate and energy policy-

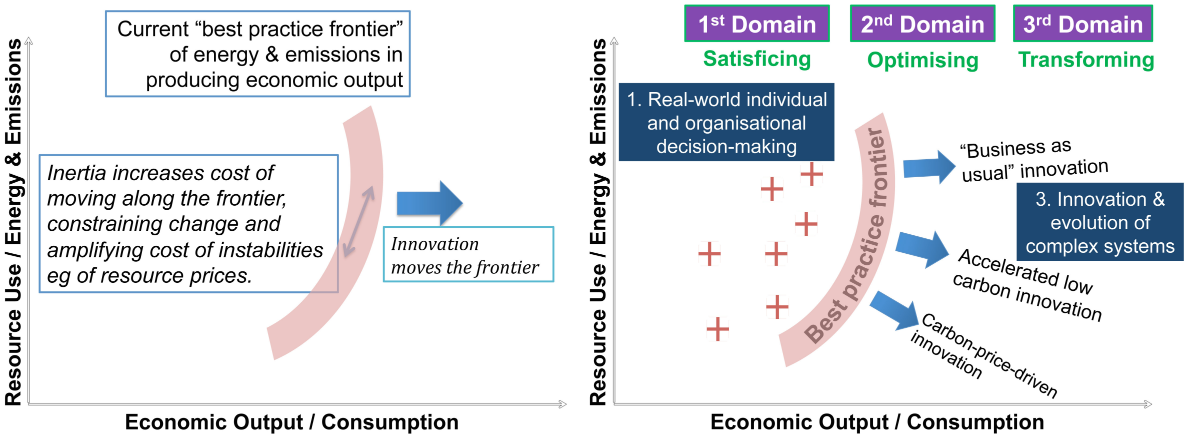


**Figure 2: Grubb and the three pillars of sustainable development (adapted from Grubb et al 2014 p. 60).**

making is described along the lines of three policy pillars for sustainable development (respectively): standards and engagement (pillar 1), markets and prices (pillar 2) and strategic investment (pillar 3).

Grubb depicts the evolution of the economy over time and as influenced by environmental policy, illustrated in Figure 2. In this figure (left panel), a productivity frontier is shown which shows the possible trade-offs between resource use and economic output, similar to the production frontier of classical economics. In efficient markets with ease of access to technology and information, in which no Pareto improvements are possible,[6] all agents and institutions situate themselves on the frontier. In practice, this position is not attained in the real world, a fact readily observable (Grubb 2014).

The productivity frontier represents current thought and understanding of efficient markets in mainstream 'optimising' normative neoclassical economics, in which improvements to productivity occur if they are regarded as utility-improving by agents optimising inter-temporally with rational expectations (i.e. with equal and complete information). In reality, most agents, institutions, countries, are positioned somewhere to the left of the productivity frontier (Figure 2 right panel), because the productivity frontier is represented by technologies, innovations, and systems that have been invented but not yet implemented across all firms and institutions, and this process of diffusion is not instantaneous. For example, with information technology, the fastest computers available are not what most people and institutions currently use, even though they exist, but they are those that may be used in the near future. In this picture, all agents, institutions, countries gradually move to the right towards the productivity frontier, and the productivity frontier itself moves to the right as science, knowledge and engineering develops.

The rate at which agents, institutions and countries catch up or lag behind the frontier depends on their *local innovation system,* as well as behavioural issues.[7] They may evolve in this plane in different directions, depending on the structure of incentives; some agents, institutions or countries may move towards higher resource and waste intensities, others towards lower intensities. This is indeed the case when observed at the national level internationally (Grubb 2014).

The rate of movement of agents and institutions in this diagram is determined in large parts by behavioural aspects, such as barriers to innovation and/or technology

[6] Increases in utility for some agents that do not take away utility from other agents.
[7] It depends on a set of behavioural, organisational, and cultural factors including education, governance systems and infrastructure. *It concerns a capacity for behavioural and organisational innovation to accelerate adoption of new technologies.*

adoption (the health and strength of the innovation system, see section 5), the local regulatory and policy structure, cultural dimensions, 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 perspective (e.g. electricity markets). However according to Grubb, innovation and the transformation of firms and institutions is typically best described by Technology Innovation Systems (TIS, see section 5), Evolutionary Economics (EE), and Transitions Theory (TT, for both see appendix A.5). The contemporary equilibrium school views this through knowledge spillovers and market imperfections (section A.4).

# 3 Macro-modelling methodologies

## 3.1 Current macro-models: a taxonomy of assumptions

Current models are typically classified along the categories of general equilibrium, partial equilibrium, econometric, systems dynamics and agent-based. Within each of these, sub-categories exist. We list those along with their types of assumptions regarding the structure of technological change, its representation at the micro and macro levels, as well as their representation of the entrepreneur at both levels.

Table 2 lists the main 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 as whole sectors). 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.[8] The unsurprising result was that investment costs related to technological change were mitigated over time as learning-by-doing and technological progress were 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 2014, ch. 11). Indeed, in some studies, cost are identified to total energy system costs, in others cases to additional investment costs, and yet in other cases, to 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 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 wait for certain future gains of productivity and refrain from investing in low-carbon energy, delaying action in the present. The presence of so-called back-stop technologies[9] also had the same effect,

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

[9] 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 | |
| Optimisation | 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 | |
| Optimisation | GE* | DSGE* | Can be linked to detailed technology models | Exogenous technological change | Heterogeneous stochastic representative agent | |
| Optimisation | 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 (fcn. of cumulative investment) | Can be linked to detailed technology models | Investment behaviour derived econometrically |
| Simulation | SD* | Stock-Flow[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 |
| Simulation | SD* | 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 |
| Simulation | 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 (Bouwman et al. 2006) [6] FTT (Mercure et al. 2014) [7] MATISSE (Köhler et al. 2009).

promising future solutions that would appear with certainty. This in general meant that pre-ETC model results were to a great extent determined by assumptions of 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. Thus an analysis of theory and assumptions is critical.

Endogenous technological change thus partly 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 respond to a change with prices, models would predict perpetual 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, such as more car journeys, Grubb 2014). It may perhaps be argued that investment behaviour is always driven by 'something', and cannot be brought into models as explained by 'nothing'.

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.

## 3.2 Innovation and technological change in macro-economic models

In contemporary theory, modellers can represent the economy using either of two paradigms, (1) equilibrium/optimisation and (2) non-equilibrium/simulation, which, as discussed in section 2.2, have opposite directions of causation:

(1) The representative agent chooses the proportion of consumption of income now and in the future, where saving (i.e. not consuming in the classical perspective) in the present implies an equal amount of investment that increases (with certainty) production capital for supplying consumption in the future, through the accumulation of physical capital and knowledge. Some of this investment goes to R&D in various sectors, increasing their productivity (the C-M-C economy, see Appendix A.6).[10] Investment resources are finite and determined by savings; due to assumptions of diminishing returns, displacing their use for less productive purposes (e.g. for climate change mitigation) will usually be harmful to the economy (unless it removes existing distortions).

(2) 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 accept to give out loans, money is created where savings and investment both increase equally, leading to increased debt and income; when they do not, saving and investment do not increase. Collective effects lead to economic cycles. Individual investments may or may not lead to productivity improvements and profit; however at the aggregate level they may do so through an increasing body of knowledge (the M-C-M economy, see Appendix A.6).[11] Increasing debt leads to growth, but excessive debt levels can lead to speculative investments as opposed to productive investments, and even financial instability.

In the first instance, since the representative agent maximises utility by allocating fixed resources between possible uses, and the state of the economy in equilibrium does not depend on its states in the past, the methodology is tied to constrained optimisation (every point in time is optimal). In the second instance, since at every

10 Models of this type include GEM-E3-FIT (E3MLab 2013), IMACLIM (CIRED 2006), GEMINI (EPFL 2008).
[11] Models if this type include E3ME-FTT (Cambridge Econometrics 2014a) and GINFORS (Lutz et al. 2009).

time step the state of the economy depends on its states in previous time steps and expectations of the future, the methodology is tied to dynamical systems simulations.

Despite this, the current model zoology is not so clear cut, and many models are hybrid (e.g. IMACLIM. GEM-E3-FIT). 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 more realistic descriptions. Furthermore, when the foresight of agents is curtailed, models become ‘dynamic’ if agents do not correctly guess the future (often called the ‘myopic mode’). Finally, if a financial sector is introduced, investment funds can be brought to the present from the future (e.g. in GEM-E3-FIT).

In the general equilibrium world, models are optimisations, in which every configuration is a steady state. Productivity change takes place either exogenously or by knowledge capital accumulation. Models are based upon production functions, which are representations of firm technical choices and trade-offs in resource allocations, substituting between labour, physical capital and knowledge capital (R&D). The consumption choices of the representative agent maximise his or her utility, based on discounted present and future consumption, equal to income minus saving. 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 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, see appendix D.1), 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 optima. As famously described by Arthur (1989), any process that result 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 could have equally fallen into an onshore wind power future given early wind investments instead. Once the model solution has adopted one direction, the other direction will no longer be selected: it is trapped in a lock-in. An indeterminacy thus exists between possible futures at the starting time of the simulation. In fact, any feature that embodies increasing returns to investment lead models to become path-dependent (e.g. Köhler et al. 2006). This contradicts the assumptions of steady state equilibrium: several sets of commodity and factor prices solve the general equilibrium.

Increasing returns arise with the cumulative causation of knowledge accumulation, which can take many different directions. For instance, in technology models with many learning curves, sorting out all possible equilibrium points can become highly challenging to the modeller. But furthermore, it also opens the possibility of model flips and instabilities. This issue applies whether increasing returns are included at the micro (technology) or macro (sectoral) levels.

In the Post-Keynesian world, models are simulations, and productivity change also takes place through knowledge accumulation, using Kaldor’s technological progress function (Kaldor 1957; Lee et al. 1990). 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). This is consistent with both Schumpeter's and Keynes' understanding of economic development. Simulation models do not suffer from discontinuous flips. Instead, they assume that every model run unavoidably heads into a different path-dependent future.

## 3.3 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.[12] 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 benevolent '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 action. To obtain optimal configurations that reach certain objectives other than cost-minimisation, the modelling tradition follows a Pigouvian approach by internalising externalities: valuations are given to externalities such as $CO_2$ emissions and energy security (see McCollum et al. 2013).

Due to their optimisation foundation, partial equilibrium 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 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 (appendix A). 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 2012). 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.

[12] 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 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.

(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 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 EE (Mercure et al. 2014).

## 3.4 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*?

- **Normative:** models that make prescriptive judgements and attempt to identify best courses of action or optimal system configurations for reaching certain objectives.
- **Positive:** models that attempt describe an observed reality and extrapolate future events, based on theory parameterised with empirical knowledge.

It is also useful to distinguish positive 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). In this sense, models that assume types of agent behaviour that precisely result in optimal whole system outcomes (e.g. cost- or utility-optimal) are normative, not positive.

As discussed above, normative model results (e.g. cost-optimisation) are often interpreted in a descriptive paradigm (e.g. the pathway RCP8.5 in IPCC 2014, calculated using MESSAGE interpreted as a current policies baseline), resulting in a problematic scientific inconsistency. Normative models do not typically reproduce diffusion trends as reported in the empirical literature (Marchetti & Nakicenovic 1978). While this may be thought of as semantic, one clear drawback of this procedure is that such scenarios are difficult to interpret for policy-making, since these pathways were not created based on particular policy instruments or frameworks.

One clear danger exists in the use of normative models for descriptive purposes, 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 is to match 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.*

## 3.5 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 only 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, *emissions reductions* occurring with the introduction of low-carbon energy technology *only take place when the price of carbon increases*.[13] Technology diffusion stops if the (real) price of carbon or other incentives become constant, and reverses if they decrease.[14]

In a non-equilibrium perspective, models typically evolve even if the context does not change, in parts pre-conditioned by their history and momentum. Thus, technology diffusion does not solely take place when relative prices change. In this paradigm, taxes create incentives to re-orient an ever-changing system towards a new course. For example, the higher the value of the carbon price, the faster changes take place, but changes keep taking place (since it is non-equilibrium) irrespective of whether the carbon price changes. 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.

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 2014), which can lead to first-mover advantages. In this perspective, the price of carbon must be high enough

[13] With the exception of policy instrument 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.
[14] This in parts stems from that available learning potentials regarding technology are known by agents, and agents take optimal decisions based on this knowledge. Variations are explored using sensitivity analyses.

to provide a clear signal that communicates the 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.

### 3.6 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, the latter 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. It depends on the amounts of funds available in the economy for investment.

> ***Crowding out***: In the context of this report, we use the general meaning of the term, 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.

Theory and models again play a role here as to how this question is understood by modellers and policy-makers, and it is the subject of significant debate. While the subject of finance of low-carbon technology will be explored in section 6, we lay out here the differences between modelling schools of thought.

This subject is once more fundamental to economic theory, where we again have two paradigms, (1) equilibrium and (2) non-equilibrium. In 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 savings, which are determined by a proportion of income (the propensity to save). Entrepreneurs compete for this amount which takes the form of funds 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. 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. This is typically because the initial allocation of capital resources is assumed to be optimal, and any deviations from this would lead to less productive use of funds. Depending on the models, the cost to GDP varies: in some simple neoclassical models (Nordhaus 2010; Stern 2007), the cost to GDP exactly equals the investment in low-carbon technology itself. In multi-sectoral models, the outcome can be lower, due to trade and multiplier effects (e.g. IPCC 2014, ch. 6). The key outcome is that policies for a sustainability transition cannot lead to increased GDP globally as it necessarily crowds-out other key investments (This is different in GEM-E3-FIT, see section 4.1).

(2) Investment is determined only by the credit-worthiness of entrepreneurs, based on perceived risk by banks, unless the funds used were internally generated by the firm. Banks are not solely intermediates, but have a balance sheet and strategy. Banks borrow from each other to diversify risk and to the central bank to keep their balance sheet in order. Money, whether in paper form, or in bank accounts, is a form of asset-liability pair, between two entities, the bank (debtor) and the owner (creditor). Thus forms of money are financial instruments that can be *created* (see Fontana 2009; Lavoie 1992; Schumpeter 2014, Barker 2010).

In this perspective, investment also equals saving, but savings are determined by investments, rather than vice-versa. The process of loan creation is also one of saving creation, and the total amount of monetary assets in the economy is not constant, nor is it a commodity, and price levels evolve. Loans have a price and debt must be serviced, and high amounts of debt makes entrepreneurs less credit-worthy, and thus less likely to be awarded more loans. Money creation is limited by the supply of credible lucrative ventures. If loans are allocated on the basis of speculation on the value of existing assets (so-called 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 (Freeman & Perez 1988), 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). Models have, however, no endogenous representation of defaults.

In the perspective of climate change mitigation, under favourable policy frameworks (e.g. market-pull, technology-push policies), the return on investment for investment in low-carbon ventures can be attractive, and lead to prosperity for particular firms, and to loss of business in others. The outcome is context-dependent. Climate policy could create employment in areas of low income due to enhanced investment, but can also lead to higher 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).

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.

## 3.7 Conclusion: model outcomes 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 non-equilibrium classes discussed above (Figure 3). We also illustrate the behaviour of uncertainty in economic projections, which also stem from model theory.

In the case of equilibrium models, with crowding out of finance, 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. In the long run, with learning-by-doing, resource displacement eases, while lower expenses on fossil fuels are incurred, and GDP recovers.

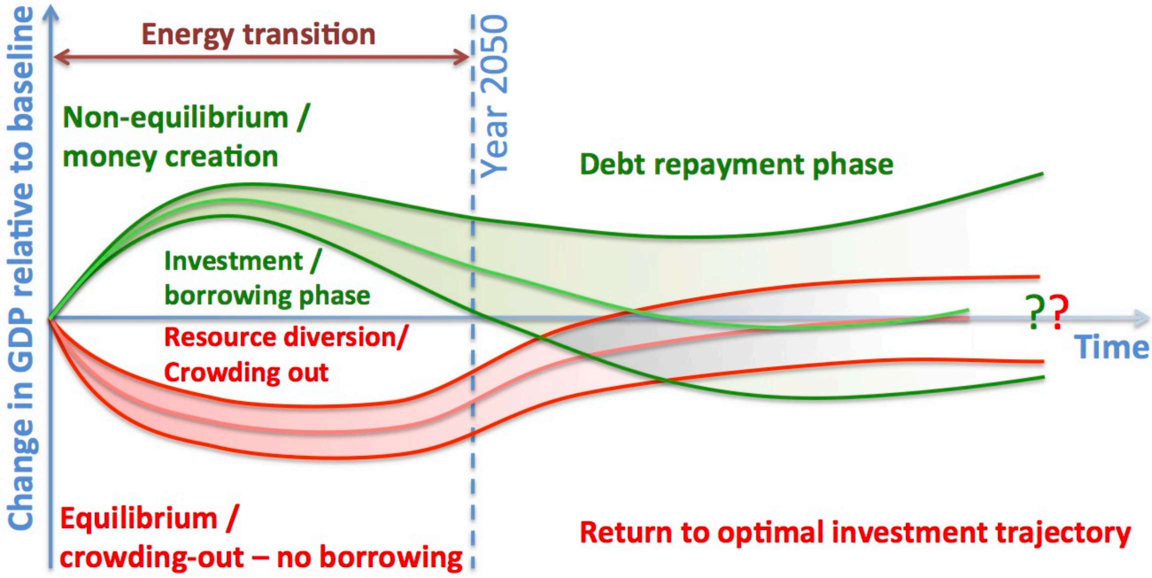


**Figure 3: Illustration of GDP changes, relative to a baseline, of a policy-driven sustainability transition for the two groups of modelling schools of thought, equilibrium and non-equilibrium. In this image, a sustainability transition is financed (self-financed or via borrowing) from time zero until the vertical dashed line, after which low-carbon finance stops. Upper and lower boundary lines display uncertainty ranges. Outcome uncertainty increases with modelling span in non-equilibrium models, property associated to path-dependence (figure co-designed by the authors).**

In the case of non-equilibrium models (green curves), an investment-intensive energy transition program results in creating additional employment and boosting GDP in the short to medium run, but a possible reduction in macro-economic gains or even decline in the long run depending on debt servicing conditions.[15] This is due to money being created in the early phase, which funds construction and results in activity across the economy, but also increases the debt burden, which remains in a 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 may remain in the long following cumulative investments in new technology and equipment. In the short run, if decarbonisation is carried faster than capital turnover rates allows, an additional cost is incurred related to scrapping capital earlier than it is able to pay for itself, 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. Uncertainty also behaves differently: in equilibrium, uncertainty with solutions is linearly related to the uncertainty in parameters. In non-equilibrium models, uncertainty on parameters leads to scenarios that diverge from each other, such that model outcomes in the far future are more uncertain those in the near future.[16]

## 4 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

[15] E.g. in E3ME-FTT, debt repayments for renewable electricity generators passed-on to consumers through an increased price of electricity affects the economy as a legacy of the transition (see Mercure et al. 2016).
[16] Lower apparent uncertainty bounds in equilibrium models should not be seen 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.

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.

## 4.1 The recursive dynamic CGE model GEM-E3-FIT

GEM-E3-FIT[17] 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 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 3.7. 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. Details are given in appendix D.1.

[17] 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.

## 4.2 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, see Appendix D.2).

# Part III. Drivers and barriers to energy innovation

## 5 Drivers and barriers to innovation: theory and evidence

### 5.1 Technology and innovation applied to energy as a network industry

Innovation and technological change for an energy sustainability transition concerns two distinct areas of industry and technology markets: energy supply and end-use of energy. We make this distinction because they function differently and innovation has different motivations and impacts. Energy is the most archetypical case of a network industry with clear lock-ins, spillovers and impacts to other industries. We review the relevant features to adapt general innovation concepts to the specific case of energy.

**Energy supply**. Supply is distinguished from end-use as the technologies that generate the secondary fuels used by end-use applications, and thus, are primarily energy conversion technologies (e.g. electricity generators, biofuel plants, refineries). In contrast to end-use technologies, relatively few supply technologies exist, each using very specific physical processes (e.g. photovoltaic, wind turbines), each of which are undergoing gradual incremental innovation that bring them ever closer to competitive energy generation markets. Few if any radical supply innovations are considered likely to have an impact during the current policy horizon (e.g. fusion).

**Energy end-use**. End-use is distinguished from supply in that the technologies in question are primarily energy-consuming and fulfil various functions not necessarily energy-related, and thus policies for emissions reductions concern primarily technological change or innovation for energy-efficiency change. End-use technologies are as important for emissions reductions as those for supply systems (Wilson et al. 2012). This includes the diffusion of electric vehicles, electric heat pumps, higher efficiency electric motors in industry, etc. Here, technologies are extremely diversified, diverse, and innovation sees significant spillovers since many end-use technologies that fulfil different functions actually use the same conversion systems. Often, innovation takes place in tandem with other unrelated changes in performance for the purpose of improving competitiveness and attracting consumers, and thus lies closer to product innovation.

*The network nature of energy systems* requires that supply and end-use technologies share a common distribution system managed by an operator under certain conventions (e.g. 50Hz AC current). This constrains all technologies to particular historically defined standards (from the 19$^{th}$ century), and important lock-ins. It also constrains supply to match demand in real time, leading to grid balancing challenges. This makes it necessary that innovation revolves around existing standards (e.g. inverters), while other innovations arise to change existing standards (e.g. micro-grids, demand management) and some radical innovations are precluded by the system itself (e.g. superconducting DC lines). Thus many innovations are developed solely for the purpose of integrating new technologies into old locked-in networks.

### 5.2 The energy technology innovation system (ETIS)

When leading to lower production costs or to market new products, innovation allows firms to gain competitive (temporary monopolistic) advantages, and increase their profits - a potentially powerful driver for innovation that is acknowledged across economic schools of thought (Appendix A). In particular, the study of Technology Innovation Systems (TIS) provides significant insights on how this takes place, applied (section A.7) here to energy technology. Appendix B provides an extensive review of indicators for measuring innovation. Economists also agree that firms underinvest in innovation in the energy sector (Grubb 2014).

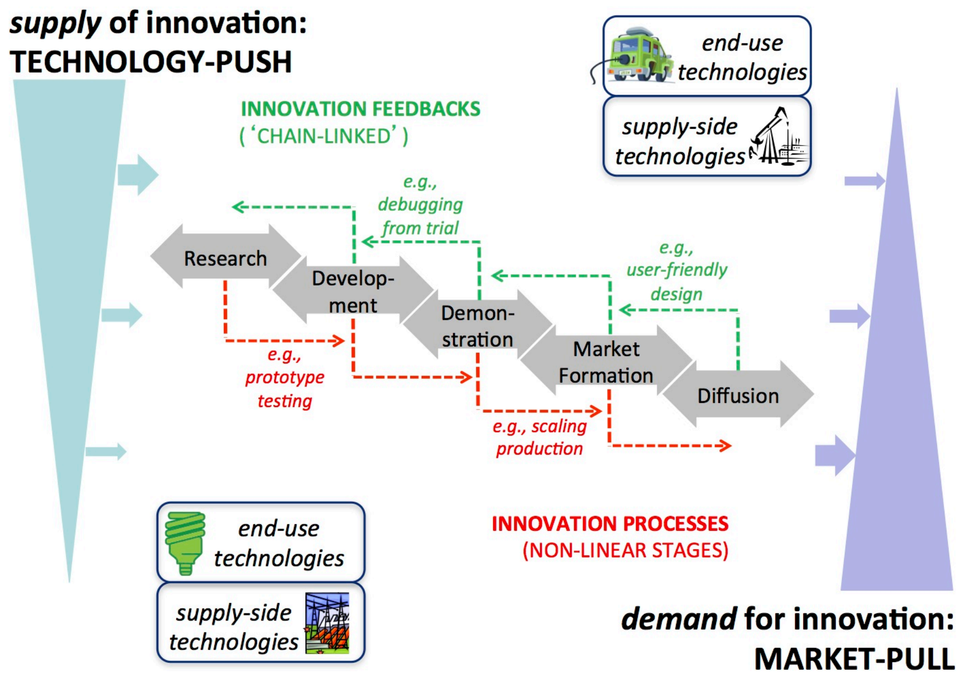


**Figure 4: The Energy Technology Innovation System (ETIS, reproduced from Grübler & Wilson 2014) p. 8, with permission from the International Institute for Applied Systems Analysis).**

Policies for supporting successful innovation are classified along two types:

- *Technology push*: public policies supporting the development of ideas into products,
- *Market pull*: public policies that create market space for new technologies.

For successful innovation, as we see below, 'technology push' must meet 'market-pull'. In the energy sector (as opposed to e.g. biomedical or information technologies), this proves to be difficult: barriers leave a substantial gap between promising ideas and economic rewards, and many innovations never reach the market.

The path from basic research to a product profitably sold in the market can be long, tortuous and risky, and is commonly described as the innovation chain. Schumpeter (1939) first established a differentiation between the *invention*, *innovation* and *diffusion* stages of new technologies, concepts elaborated by the EE, TT and TIS schools (see appendix section A.7). The standard representation of the innovation chain is given in Figure 4, with emphasis on the fact that the path is not a simple linear path but rather interacts with other levels of the chain (see also Grubb 2014). Indeed, steps within the innovation chain are not independent from each other, but highly interrelated. For example, if the uptake of energy-technologies is limited by some barriers (a reduced 'market-pull'), this directly lowers firms' incentive to engage in the development and commercialization of such products. The other way around, a technology that is never developed (missing 'technology push') never diffuses into the market despite favourable market-pull policies. For reviews of related empirical studies, see Popp et al. (2010) and Grübler & Wilson (2014).

Drivers and barriers to these processes occur at all three of the traditional stages of innovation but differ significantly between them, consequently we consider in turn:

- *R&D,* including appropriability, spillovers, extent of market, opportunities,
- *Innovation,* including issues at both technology push and market pull,
- *Diffusion*, including issues related to the adoption of innovations by consumers

We discuss these in the next sections.

## 5.3 Drivers and barriers to invention: R&D in the energy sector

As the innovation chain's first step, the *invention* stage describes the "*origination of an idea as a technological solution to a perceived problem or need*" (GEA 2012 ch.24, p.1673). This involves basic research, and may result in a patent. Exploring the question as to why private firms may want to invest in research activities (R&D), Dasgupta (1987) refers to three determining drivers to invention:

- the degree of appropriability of R&D benefits (Arrow 1962),
- the extent of the market (Schmookler 1966),
- and the existence of innovation opportunities (Rosenberg 1976).

Although each factor on its own involves a set of complex considerations, the resulting principle may be summarized as follows: given technological opportunities and constraints (innovation opportunities), firms' incentives for R&D investments increase with expected benefits (extent of market), but are limited by a potential spillover of these benefits to competitors and the wider society (degree of appropriability). Within the context of energy technology, the neoclassical analysis of R&D is usually framed in terms of two distinct classes of 'market failures' (Jaffe et al. 2005): knowledge and environmental externalities.

*Knowledge externalities* refer to the public good character of knowledge (Arrow 1962): once a new discovery has been made public, more than one firm can potentially use it with little additional costs. Benefits of R&D may therefore *spill over* to other firms, both to direct competitors and to firms in entirely different sectors of the economy. This leads to *limited appropriability* of R&D benefits by innovating firms. Private profits of R&D activities are then lower than the full extent of social benefits. For this reason, a firm may underinvest in research if, when deciding on its R&D budget, it does not take into account any positive knowledge externalities. This public good character underpins important support for active government involvement in funding research.

*Environmental externalities* relate to the impact that energy technologies have on the environment, such as pollution originating from the burning of fossil fuels. If such negative externalities are not accounted for in the price of energy, they constitute a market failure: from a social perspective, the price of carbon-based energy is too low. As a result, this decreases the potential competitive advantage of low-carbon technologies. In the absence of internalisation policies such as carbon pricing, firms' incentives for low-carbon R&D are lower than socially optimal (Jaffe et al. 2005). It remains under debate whether a carbon price both effectively internalises the costs of climate change (Nordhaus 2010) while incentivising R&DD (Grubb 2014).

## 5.4 Drivers and barriers to innovation: the 'technology valley of death'

*Innovation* is about "*putting ideas into practice through an (iterative) process of design, testing, and improvement*" (GEA 2012 ch.24, p.1673). In the neoclassical market failure analysis of R&D barriers, there is no obvious need for explicitly focusing on the innovation stage: once all market failures are corrected (say, by combining a strong system of intellectual property rights with a carbon tax), market forces are expected to incentivise firms to provide the desired level of energy technology innovation. In reality, the road from basic research to successful diffusion is long and tortuous, and can easily be more costly/risky than the invention as such. "*Invention takes brain and imagination. Innovation takes time and money*" (Grubb 2014, p.316).

For innovation to work, all steps of the innovation chain have to be connected. The prospect of profits has to be clear and large enough to connect *'technology push'* and *'market-pull'*. If the expected returns on innovation are large (such as in IT or the pharmaceutical industry), market forces may bridge both ends of the chain on their own. If expected profits are low (such as in the energy sector), the chain can have missing links, and promising technologies might never make it to the market - even if the social benefits are potentially substantial. This is a common observation in the energy sector, in which homogenous products largely have little scope for profitable product differentiation by means of innovation (Grubb 2014).

Murphy and Edwards (2003) analyse the innovation chain for electricity production technologies. They diagnose a chronic lack of finance for the expensive process of demonstration, commercialisation and market accumulation, which they name the '*technology valley of death':* a potentially deadly gap between early stage public finance (government sponsored energy R&D in public laboratories or universities) and subsequent private finance (by a profitable commercialisation). "*While clean energy investments can be very profitable, they are still perceived as high-risk, large-dollar investments by much of the investment community.*" (p. 4).

In the context of the "valley of death", Grubb (2014, p.332) summarizes six barriers to innovation, three each that counteract the necessary finance by either 'technology push' or 'market-pull'. With respect to 'technology push', they are:

- *Uncertainties and knowledge divisions around risks and rewards:* due to uncertainty and the low probability, albeit high consequence, characteristic of potential payoffs, investors may prefer to wait and see what emerges.
- *Transitions from technical to management and commercial skills:* researchers in the initial technology development team may only have a limited business expertise, and may be unable to formulate a convincing business plan. Investors' money becomes easily diverted to firms with inferior technology but better sales pitches.
- *High capital costs and long timescales*: the more investors have to commit up front and the longer they have to wait to see a return on investment, the greater the uncertainties (including around government policies) and risks, deterring investors.

For the 'market-pull', they are:

- *Economics of scale and experience*: there is insufficient volume to fuel enough learning-by-doing to reach a sustainable market. A capital-intensive scale-up amplifies risks for investors, even when aware of learning and scale effects.
- *Misalignment of private and public goals*: investors may conclude that technologies backed by governments have been motivated for reasons not aligned with commercial interests and are thus more risky.
- *Incompatible public policies and understanding of the full innovation chain:* establishing new industries requires the coordination of many elements, including associated infrastructures and regulatory frameworks.

Evidence on the "valley of death" can be broadly divided into two categories: reports that refer to potentially successful technologies that have never been commercialised due to a missing link between "technology-push" and "market-pull" (Narayanamurti et al. 2011), and case studies that describe how policies helped certain technologies to traverse the "valley of death" to the stage of successful commercialisation (EC 2009; Jenkins & Mansur 2011).

Jenkins and Mansur (2011) point to various advanced energy technologies that are trapped in the "valley of death": carbon capture and sequestration plants, small modular nuclear reactors, advanced solar manufacturing facilities, engineered/ enhanced geothermal, various utility-scale energy storage technologies, advanced biofuels production facilities and new manufacturing for advanced batteries. Narayanamurti et al. (2011) present seven case studies that illustrate the key barriers to commercializing new energy technologies. These case studies indicate that the "technology valley of death" is real, and can eventually be overcome by targeted policies. However, the available evidence is typically limited to qualitative descriptions, which lack counterfactuals: we do not know what would have happened to a specific technology in the context of other policies (or lack thereof).

## 5.5 Drivers and barriers to diffusion: the limited uptake of new technologies

Once an innovation has crossed the 'valley of death' and is developed into a mature product, it reaches the stage of *diffusion*: the "*widespread uptake of a technological innovation throughout the market of potential adopters*" (GEA 2012 ch.24, p.1673).

According to standard neoclassical economic theory, firms and households should adopt a technology when doing so is objectively beneficial for them. However, studies based on engineering data regularly report that the uptake of energy technologies is far lower than what is considered as cost-effective by third parties (Gillingham & Palmer 2014). One example frequently cited is a report by McKinsey and Company (2009), stating that an increased uptake of profitable technologies could substantially reduce global $CO_2$ emissions, which is not currently happening. The gap between market outcomes and a hypothetical benchmark of cost-optimisation is probably largest for energy efficiency investments, which fuels an on-going debate about the *'energy efficiency gap'* (for a discussion, see Jaffe & Stavins 1994).

There exists an extensive academic literature on potential 'barriers' to the adoption of energy technologies. While often framed in terms of energy efficiency investments, most can be easily generalised to other kinds of innovations. Within mainstream economics, a commonly applied distinction is between 'market barriers', 'market failures' and 'behavioural failures' (Gillingham et al. 2009). Sorrell et al. (2004) define a barrier to energy efficiency as "*a postulated mechanism that inhibits a decision or behaviour that appears to be both energy efficient and economically efficient*". Sorrell et al. (2011) review the literature on barriers in industry, and present an overview that summarizes them into six categories: risk, imperfect information, hidden costs, access to capital, split incentives and bounded rationality. Here, we follow loosely Gillingham and Palmer (2014), and separate two broad questions: (1) how large is the energy efficiency gap? (2) what causes the gap?

### 5.5.1 How large is the gap: the dynamics of technology diffusion

Not adopting a new technology does not necessarily indicate an efficiency gap or barriers to uptake. Diffusion is a gradual process, which can be explained by a combination of information availability, heterogeneous adopters and decreasing costs over time (for an overview, see Allan et al. 2014, Rogers 2010). First, potential adopters have to learn about a new technology's existence and benefits, and then decide whether to adopt or not. Second, firms and households are not identical, but differing situations, desires and perspectives. They differ in economic fundamentals (such as income, access to finance and expected usage patterns) as well as individual preferences, risk aversion and perceptions. As shown in textbook theory of diffusion of innovations by Rogers (2010), this implies different thresholds to their decisions, and is partly responsible for the gradual diffusion: various processes may change perceived costs and benefits over time, such that the adoption becomes increasingly attractive. With learning-by-doing, gradual cost reductions occurring with cumulative adoptions lead to a self-reinforcing phenomenon (Arthur 1989). Many studies show that the process recurrently follows logistic curves (Fisher & Pry 1971; Grübler et al. 1999; Mansfield 1961; Nakicenovic 1986; Marchetti & Nakicenovic 1978).

Young (2009) points to three primary mechanisms driving diffusion dynamics:

- *Contagion*. People adopt when they come in contact with others who have already adopted; that is, innovations spread much like epidemics.
- *Social influence*. People adopt when enough other people in a social group have adopted; that is, innovations spread by a conformity motive.
- *Social learning*. People adopt once they see enough empirical evidence to convince themselves that the innovation is worth adopting, where the evidence is generated by the outcomes among prior adopters.

If individual uptake depends on decisions by others (e.g. because this provides valuable knowledge about the new technology to others), observed diffusion can be slower than optimal even in the absence of any barriers. From a market failure perspective, such positive 'adoption externalities' are not considered by 'early adopters', so that they have less incentives for uptake than socially optimal (Mulder et al. 2003). When agents partly base their decisions on adoption behaviour observed in others, possible emergent consequences are 'information cascades' and 'herd behaviour': depending on hierarchical position of agents in a chain of information, agents may rationally ignore their own information, and make decisions based on information obtained from observed decisions (Bikhchandani et al. 1992; Banerjee 1992). Depending on initially available information and first observable decisions, such 'cascades' can either result in an innovation's widespread adoption, or rejection.

### 5.5.2 What causes the gap: market barriers to diffusion

'Market barriers' are economic factors that explain why agents may reject seemingly profitable technologies for rational reasons: overestimated savings, risk and uncertainty, imperfect information, access to capital and split incentives.

**Overestimated savings***:* engineering estimates of potential benefits such as energy savings may be inaccurate, and hence overestimate the economic attractiveness of technology uptake. For example, calculations may be based on hypothetical cases of perfect installation and average usage patterns. Realistic saving potentials can be both lower (e.g. due to a sub-optimal set-up) and deviate from the representative mean that is analysed in cost-optimisation studies (e.g. due to different load patterns, Hausman & Joskow 1982). Engineering studies may ignore 'hidden costs' (or benefits), such as installation costs, disruptions in the production process or varying technology characteristics (Jaffe et al. 2004).

**Risk and uncertainty:** future benefits of technology uptake are not guaranteed, but subject to risk and uncertainty. In the case of energy efficiency investments, potential savings depend on technical reliability as well as uncertain future variables such as energy prices. Such risks represent real costs (Sutherland 1991). It can be rational to adjust expected future savings downwards, and to put more weight on initial investment costs. Furthermore, expectations on future energy prices across agents may be misrepresented in studies of technology uptake (Jaffe et al. 2004).

**Imperfect information:** for making decisions on technology uptake, consumers need to rely on information about a technology’s performance. Information may either be absent or unreliable: if buyers cannot reliably observe promised benefits and sellers cannot credibly communicate them, they might be rationally ignored in purchase decisions, resulting in adverse selection (Akerlof 1970). The credibility of promised cost-savings is likely to be higher if a technology’s advantages are proven or certified, and lower if not directly observable. This is referred to as asymmetric information.

**Access to capital:** households and firms are heterogeneous with regard to income and how easily they can access the necessary capital for technology uptake. Even when the credit supply is ample, its access can be constrained (Golove & Eto 1996). One explanation is asymmetric information: if lenders cannot reliably distinguish between high and low risk investments, they may reject credit applications. Another concerns poor credit records, even for investing in low-risk, high-payoff energy saving tech (Palmer et al. 2012). For firms, capital may also be restricted due to organisational structures within the firms themselves, such as internal budgeting procedures that impose certain criteria on the evaluation of potential investment projects (see Graham and Harvey 2001).

**Split incentives:** profitable technologies may not be adopted if the agents investing are not the same as those benefiting from the investment. Split incentives for adoption can result from a limited appropriability of potential payoffs. Within firms, for example, incentives for beneficial long-term projects are limited if the employee is evaluated based on short-term goals, or if different divisions are in charge of energy bills and investment accounts. In energy efficiency investments in the building sector, the landlord pays (and chooses the level of energy-efficiency), while the savings benefit the tenant (who pays for energy use Davis 2011; Gillingham et al. 2012).

#### 5.5.3 What causes the gap: behavioural aspects of technology adoption

Market barriers can explain parts of the gap in innovation uptake, but not all of it. Empirical studies indicate that observed investment decisions are partly inconsistent with the standard assumptions of rational maximisation (Gillingham & Palmer 2014). For example, it is a recurrent empirical finding that the uptake of energy-efficiency technology is much more sensitive to upfront costs than to future cost savings (Hausman 1979; A B Jaffe & Stavins 1994; Hassett & Metcalf 1995; Anderson & Newell 2004). While at times challenging to distinguish from economic barriers (such as risk aversion), the relevance of behavioural factors for energy policy is now widely acknowledged (Allcott & Mullainathan 2010; Pollitt & Shaorshadze 2012). Gillingham et al. (2009) identify three key behavioural themes most relevant for energy policy: *bounded rationality*, *heuristic decision-making* and *Perceptions of gains and losses*.

**Bounded rationality and heuristic decision-making:** since time and attention for decision-making is not endless, they represent a scarce resource. Firms and households may decide rationally, but have to rationalise on their cognitive limits (Simon 1955). Theories of bounded rationality replace unbounded utility maximization with concepts of satisficing behaviour. Manifestations are heuristics in the form of rules of thumb or the replacement of an originally complex decision problem with a simpler, approximately accurate one. For investments, this may explain why many firms use simplified methods as key decision criteria (e.g. payback times instead of more elaborate evaluation methods such as net-present-value calculations).

**Perceptions of gains and losses:** Kahneman and Tversky (1979) systematically map apparent 'biases' in human decisions, and conclude that optimality considerations are less relevant than the question, “What course of action seems most natural in this situation?” (Kahneman 2003). Prospect theory (Tversky & Kahneman 1992; Kahneman & Tversky 1979) is based on psychological foundations and empirical observations. Overall, it helps to explain various behavioural biases that are potentially relevant for technology uptake. For example, losses are typically weighed roughly twice as much as gains — termed as 'asymmetric loss aversion'. Further relevant biases include the 'endowment effect' (humans value things that they already possess relatively more), the 'status quo bias' (humans are reluctant to changes and tend to stick to default choices) and the 'salience bias' (people give more weight to facts that are prominently visible, relative to known facts that are not as visible).

Integrating known complexities of real-world human behaviour into models of technology uptake allows a more reliable analysis of policy instruments (Mercure et al. 2016). Concepts of bounded rationality are at the core of evolutionary theories and models of technological change (Metcalfe 1988; Saviotti 1991), enabling quantitative considerations to be made. Greene (2011) applies prospect theory for a simulation of fuel-efficiency choices in car purchases. Knobloch and Mercure (2016) combine elements of bounded rationality, prospect theory and heterogeneity into a model of energy-efficiency investments, which can be used for quantitative policy simulation.

### 5.6 Drivers to innovation: connecting 'technology-push' and 'market-pull'

There clearly is no scarcity of barriers along the innovation chain. Nevertheless, innovation remains the primary driving force of economic growth. In many sectors, markets successfully sustain innovative activity - such as in the pharmaceutical or IT industry, where R&D intensities are between 5-15% (global averages, see Grubb 2014, fig. 9.3, p.321). In such sectors, the innovation chain is well connected, so that market forces are sufficient drivers to bridge the 'technology valley of death'.

In comparison, R&D intensity in the energy sector is below 1% (global average, *ibid*).[18] The presence of the various barriers discussed above drives a large gap between promising inventions and self-sustaining innovations. For harnessing the potential of markets as a driver to energy innovation, the gap has to be closed in a way that accounts for the sector's characteristics regarding incentives for innovation. Foremost, there is a relatively low potential for profitable product differentiation, alongside a high potential for societal benefits (such as environmental benefits) which are hard to appropriate for innovating firms in the absence of regulatory frameworks. This leaves firms with few profit expectations related to energy innovation.

To close the gap, demand or market-pull policies (such as carbon pricing or renewable obligations) must be aligned to technology-push policies (Grubb 2014). Both work best in combination: demand-pull policies create space in the market, but need something to pull on (existing marketable products, resulting from successful R&D activities), while supply-push policies support innovation, but need something to push toward (existing markets for innovations) as well as a sufficient demand. Aligning both sides enables to bridge the valley of death. Importantly, the combined policies are more than the sum of their parts: individually applied, each can fall short of its aim.

# 6 Barriers to finance in the EU for low-carbon innovation

Access to finance is one of the key barriers cited in section 5; however its impact is not typically quantified in models. In fact, many models assume that access to finance is curtailed by the cost of finance (the interest rate), which is thought to clear the money market. This is not accepted by all academics (notably not by Post-Keynesian economists), and furthermore, the evidence for 'crowding out' of finance for green innovations is not substantial or convincing. *Whether investment in new technology takes place does not only depend on investor attitudes: it also involves lender behaviour and their perceptions of borrower credit-worthiness.* However, lenders are truly heterogeneous, and hence, we review here barriers to finance in Europe for low-carbon innovation. Here, we expand the abovementioned issue of *access to capital*.

## 6.1 Finance barriers to clean energy technology investments

From the investor's perspective, risk and return are crucial decision factors for any investment finance decision. However, there are typically also institutional barriers embodied in the investment practices of financial institutions. For example, rules exist that restrict the kinds of projects or borrowers that are considered as candidates for lending. With respect to returns, low-carbon investments will be hindered by: factors that make the return of renewable energy and energy efficiency projects low, factors that make fossil fuel projects higher, and factors that reduce the return to foreign investors compared to national ones. With regard to risk, lenders can be deterred by risks that cannot be hedged or avoided through contractual arrangements.

Conventional economic analysis identifies market imperfections as a general source of impediments to the matching of resources to needs (in this case, the need for low-carbon energy). Market failures for investments in renewable energy and energy

[18] This is the case in the current energy sector structure for centralised power generation. Decentralised structures and institutions for renewables could lead to a bi-polar situation, where new renewables have comparatively high R&D intensities while the mature fossil technologies have such low R&D intensities.
Atomic power is an unusual case, because the through life safety costs are very high, but it also involves high R&D intensities

efficiency are mainly associated with emissions externalities, technological spillovers, imperfect financial markets and asymmetric information.

First-of-a-kind demonstration projects in new energy technologies present a number of particular issues that make it difficult to structure project finance. Firstly, energy demonstration projects usually take a long time to mature and some sectors (e.g. fuel cells and hydrogen) are only likely to generate stable cash-flows during operation in the medium term, well beyond the usual grace period provided by banks. Moreover, even when technologies are validated through demonstration, their subsequent market deployment may require substantial supporting infrastructure investments, which present additional risks for investors.

The following sub-sections identify barriers to raising finance for investment in clean energy that arise (1) from the nature of projects, and (2) from the decision-making framework adopted by lenders. These are distinct from the above (section 5.5) by emphasising that they apply to financial institutions/lenders, not project developers.

### 6.1.1 Financial barriers typical for innovative clean energy technologies/projects

- **Lack of a clear market opportunity**: eco-innovation is driven by environmental policy. If the policy does not clearly require action in the short to medium term, there will be no market demand for the new technologies.
- **R&D uncertainty:** Development of new energy technologies is subject to the same uncertainties as other R&D investment: development can be costly, there is great uncertainty over the time required for successful commercialisation and achievement of financial closure; in that time, market conditions (either demand or competing technologies for supply) can change;
- **High capital costs and long-lived assets**: Renewable technologies are generally characterized by relatively high up-front capital costs and low operating costs. Such projects require long-term finance and a willingness to bear the risk of construction cost overruns; otherwise investment decisions may become biased towards conventional technologies that can be financially viable with shorter loan terms;
- **Availability and volume:** Financial instruments/investment products (e.g. green bonds), even for mature energy technologies, are not readily available and, if they are, the overall lack of volume of projects remains an issue; equity markets lack "blue-chip" climate-friendly investment opportunities. The market poses a liquidity risk (being able to sell rapidly when required), making more easily-tradable bonds (with higher issuance levels) and equities (with higher market capitalisation) more attractive. This creates a bias against some types of less tradable clean energy assets, such as project finance;
- **Risk-return related to regulatory (political) stability:** Many types of climate-friendly investment opportunities often have – or are perceived to have - lower returns and higher risk compared to carbon-intensive projects in more established sectors, unless there is strong low-carbon policy support, such as subsidies or carbon taxes. Particularly for long-term projects, this makes policy risk particularly important for investors, in case the support is modified in the future in a way that reduces returns;
- **The high-risk nature of First-Of-A-Kind projects:** Due to their pre-commercial nature and unproven technologies, such projects are usually too risky for commercial finance and therefore considered as "not bankable". Structuring First-Of-A-Kind projects requires considerable know-how and skills to assess and allocate the risks properly. Some international financial institutions such as the EIB provide this type of service, but institutional investors and most commercial banks generally do not have the internal expertise to address these risks;
- **Lack of coordination and complementarity** between financing instruments from EU, Member States, and technology promoters;

- **Lack of financial and technical advice** to technology developers and investors, respectively;
- **Capital intensive:** First-Of-A-Kind demonstration energy projects are usually too capital-intensive for venture capital investments and too risky for private equity financing, while the lack of historical data prevents the insurance industry from designing products which could contribute to the de-risking of such projects;
- **High transaction costs:** Transaction costs are higher when investing in smaller assets, a typical characteristic of climate-friendly project finance. Tools like securitisation can address this issue by bundling assets, although barriers to securitisation remain. These include lack of standards for loan contracts for climate-friendly assets and warehousing infrastructure. In addition, due diligence transaction costs related to lack of comparability of non-financial, climate-related data and transparency remain.

#### 6.1.2 Financial barriers arising from investors' decision-making framework

- **Time horizon of decision-making:** Despite the long-term liabilities of pension funds and insurance companies, most fund managers have a time horizon of three years or less (and rely on the liquidity of their investments to adjust their portfolio to meet these short-term targets). The short time horizon reflects partly regulation that imposes a liquidity requirement, and partly the institutional aspects of fund managers such as remuneration systems that involve short-term targets, investment mandate design, and a lack of long-term risk assessment models;
- **Lack of integration of climate risks into fiduciary duty and engagement practices:** The relationship between climate-related risks and benefits and institutional investors' fiduciary duty is not clearly established. Additionally, assessments of investment managers' engagement practices with companies do not sufficiently include climate-related concerns;
- **Lack of relevant climate-related risk and performance methodologies:** Current climate risks (physical impacts) and carbon risks (structural policy changes) face methodological shortcomings. The assessments done to date are not easily integrated into mainstream investment tools and practices. Investors currently cannot easily measure the climate and carbon performance of their portfolios.

### 6.2 Financing of clean energy technology innovation chain

The promotion of clean energy technologies requires investment at each step of the innovation chain (Figure 5): (1) investments are needed to support basic research, develop a technology concept, prove its feasibility, and validate the technology, (2) investments in "first-of-a-kind" clean energy projects are required in order to demonstrate feasibility, (3) investments bring the technologies that demonstrated marketability to the market, (4) investments in proven clean technologies ensure their replication and increase market uptake and (5) investments in mature technologies.

Different types of lenders typically finance each stage of the innovation chain. The first stage of technology development is generally supported by public investors because of the high degree of uncertainty and the potential for knowledge spillovers. This includes research and innovation funding and public financial institutions (such as the UK Green Investment Bank, the European Investment Bank, the European Bank for Reconstruction and Development see Cochran et al. 2014). The second stage is also predominantly public, also reflecting the high degree of uncertainty, and typically takes the form of grants. Public support plays an important role in de-risking very innovative and risky projects and can leverage private capital (Burnham et al. 2013).

An example of funding instruments providing demonstration support is the EU's NER300 programme, which funds large-scale demonstration of low-carbon energy technologies in Europe (EC 2016). Some private investors will support demonstration

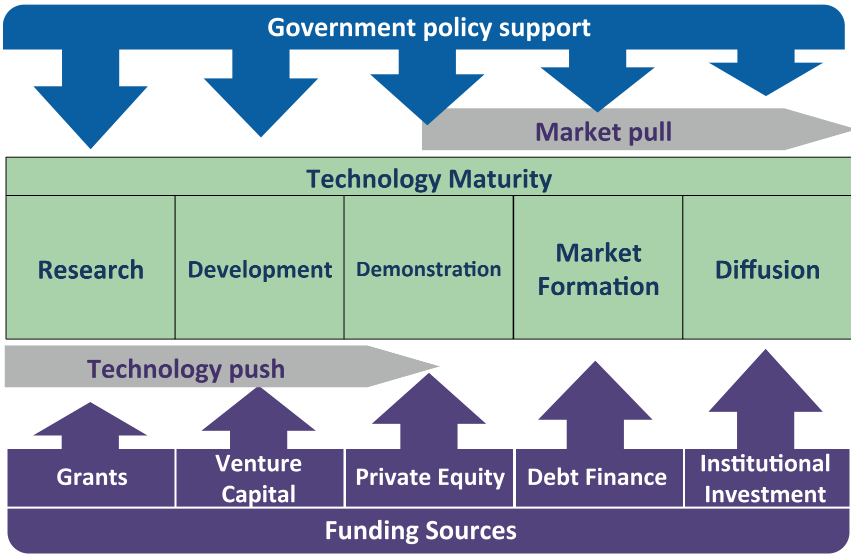


**Figure 5: Funding sources through the innovation chain (source: Leete et al. 2013; adapted from Wüstenhagen & Menichetti 2012).**

if they see a clear link to their business. The next stage may attract high-risk investors (such as venture capitalists, hedge funds) provided that innovations are of sufficient interest to them. Once the technologies reach the commercialisation stage, various types of private investors become involved, including banks, corporations, individual investors, and institutional investors (insurance companies, private funds, investment managers, foundations and endowments, sovereign wealth funds, and non-fund pension assets OECD 2015a).

## 6.3 Influence of macroeconomic conditions on availability and cost of capital

In contemporary economies, the major component of the money supply (97% in most advanced countries) is created by commercial banks extending credit and expanding their balance sheets (McLeay et al. 2014). Post-Keynesian theory advances that, when a bank makes a 'loan', it does not borrow money from anyone else as is the case in capital markets (see section A.6). It adds an accounting entry to its ledger in the form of an asset (the loan, money the borrower owes to the bank) and a liability, (a deposit, which the bank owes to me). When a loan is paid back, this money is destroyed. This means commercial banks create new purchasing power in the economy and direct where it goes via their lending decisions. This is not the view taken by equilibrium economists (and equilibrium models), which assumes a competition for loans.

In modern, deregulated financial systems, Post-Keynesians insist that central banks have limited ability to control credit creation by banks (Lavoie 1992). This is important because the modern credit creation framework is subject to a major market failure, as even in the presence of profitable investment opportunities, the private banking system may not be willing to provide the amount of credit the economy requires to move closer to full capacity utilization (see sections A.5 and A.6, and references therein). Under certain economic conditions, of which the current historical period is a clear example, banks are more concerned to adjusting their balance sheets by constraining credit and securing safe assets rather than pursuing the highest rates of return on investment (Koo 2014). In such circumstances, fiscal interventions, such as the introduction of a price on carbon - may not be enough to achieve a low-carbon economy, thus requiring the implementation of additional policies targeted at the credit market. Consequently, the state of the macroeconomic cycle has a substantial influence on the willingness of banks to take on risk and create money, depending on their perception of risks. This does not take place in equilibrium economic theory and models, which does not give an important role to fundamental uncertainty.

# Part IV. Recommended steps for improved analysis

## 7 Summarising the gaps for better policy impact assessment

Following the discussion in the previous parts of this report, 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, as well as specifically to both case study models E3ME-FTT and GEM-E3-FIT. 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.

Undoubtedly, some of these issues cannot be easily solved in models. In part, this is due to data availability or reliability (see appendix B), 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).

The problem of representation of the assessment of projects by financial institutions or other investors is clearly a difficult question, which relates directly to Keynes' so-called 'animal spirits', where it is not always clear how decisions are taken. The presence of multiple finance sources as seen currently in Europe (see appendix C.1) reflects the fact that different institutions and asset holders have different requirements for managing their risk portfolios, and have different tolerances regarding uncertainty. Thus what non-banking sources of finance fund is not typically the same as what banks fund. In order to fully understand the relationship between policies targeting improved access to finance, and the pace of innovation and the adoption of new technology, risk and uncertainty, as perceived by the decision-makers concerned, need to be better characterised.

Section 3.7 concludes by illustrating typical model outcomes for GDP impacts of a sustainability transition towards low emissions in the global economy. These differ strongly between equilibrium and non-equilibrium models, for the theoretical reasons given above in section 2 (and appendix A). 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.

### 7.1 Current gaps in the macro-modelling of energy innovation

a. Market-pull is modelled at the bottom-up scale in technology models, not in aggregate (e.g. technology-specific policies: carbon price, subsidies, feed-in tariffs, regulations). This means that economy-wide effects are difficult to model (models of economy wide technology diffusion are required).
b. Technology-push is modelled at the sectoral level, but not bottom-up (e.g. R&D investments). This makes difficult to model the push of individual technologies.
c. No connection is made between demand-pull and technology-push policies. This means that evaluating the impacts of aligning market-pull and technology-push is not currently possible in models (i.e. policies for bridging the valley of death).
d. Models do not include the impacts of intellectual property regulations on productivity, efficiency and technological change (e.g. first mover advantages).

e. Models do not have representations of the limits to innovation activity (institutional capabilities that could be crowded out, e.g. scientists, universities, skills formation).

f. Models do not have representation of the capacity of a sector to absorb innovation produced elsewhere (usually spillovers come at no cost and independently of human capital availability).

g. Models focus on modelling the *rate* of innovation and not the *direction* of innovation. R&D expenditures and payoffs are usually modelled in a deterministic way whereas risk and its determinants are key factors in modelling innovation.

h. Models do not have representations of unknown possible game-changing technologies, and thus are tied to their technological assumptions. This, however, is part of the modelling working structure, and furthermore, completely new technologies are not likely to progress through the innovation chain so quickly as to really change the game within most policy horizons.

i. At the aggregate scale, models have no clear representation of the clustering of technological developments (Freeman & Perez' (1988) great surges), and their long-term view is biased by present perspectives (e.g. see Perez 2001).

j. Models do not include the increase in demand from environmental policies. Models do not include the multiplier effects and lead market effects of eco-innovations.

## 7.2 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 (it is partly explicit in GEM-E3-FIT, not explicit in E3ME-FTT, as they currently stand).

b. It is not determined whether crowding out takes place or not and to which degree. This includes crowding out at the level of the labour force, production capacity and financial markets.

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 the proper incentives for innovation.

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

## 7.3 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. Very few studies provide results on this matter.

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

d. Equilibrium models typically predict losses of GDP in a sustainability transition due to the displacement of capital, labour and investment resources from their baseline assumptions (unless a distortion existed in the baseline which is alleviated in the transition). This eases in the long run due to combinations of learning-by-doing and lower reliance on energy imports. This model outcome requires further research and empirical validation.

e. Non-equilibrium models project, for an investment-intensive sustainability transition, GDP increases in the short-to-medium run, due to the use of unused or underutilised production capital and labour resources, and higher levels of investment and finance through credit creation. GDP is then affected by costs in the long term when the economy is slowed down by servicing the debt accumulated during the short-term high investment phase. These model outcomes require further research and empirical validation.

f. No limit to finance is fully determined in either types of models, and the mounting of debt is not fully kept track of, nor of debt servicing (debt servicing in E3ME-FTT is partially assumed implicitly through price effects). Stock-flow models of finance are needed, requiring further research and model development.

## 7.4 Possible model improvements that could address the gaps

Novel developments in some models have been made that address some of these gaps. Other developments are possible and currently considered by some researchers. And naturally, for some of the gaps, no clear solutions are currently in sight. We again focus on E3ME-FTT and GEM-E3-FIT, particularly in the context of this study commissioned by the European Commission.

(1) The development of a financial sector in the equilibrium GEM-E3-FIT model is a highly welcome one, since as it is widely known, financial aspects are of key importance in drawing policy for energy system transformations and decarbonisation. This is due to the fact that low-carbon technologies are, on average, more investment intensive than fossil fuel-based ones, albeit with the advantage of lower maintenance costs later and often no fuel costs at all. This means that higher amounts of finance are likely necessary in a low-carbon future, even in the long terms, in comparison to a high-carbon future. Analysis of the financial aspects of energy and climate policies will likely be a standard component of any future commissioned study. Therefore, the development of a financial sector in E3ME-FTT should be a priority. They key aspect that needs improvement in both models is *to represent the perception of risk and the perceptions of future markets by investors and financial institutions in different types of ventures* (e.g. low-carbon vs high-carbon), and whether/how the cost of finance varies across the types of investments.

(2) The representation of an increasing diversity of policy instruments for incentivising sustainable, secure and competitive energy developments is a welcome development in both models, and in particular in E3ME-FTT, which puts it ahead in the modelling community. These policy instruments, however, are almost exclusively of a demand-pull nature; this restricts significantly the analysis in comparison to what policy-makers really face in the real world. Where does policy for R&D and energy infrastructure innovation fit in the picture? This in fact causes the problem that the policy debate can become biased towards the exclusive use of demand-pull solutions (e.g. carbon pricing, a key point of discussion in Grubb 2014). Thus future developments must allow the analysis of *the alignment of demand-pull with technology-push policy and its impact on the economy* i.e. support for R&D and environmental policies from the innovation policy literature.

(3) Models and theory have been classified in this report along the categories of equilibrium and non-equilibrium, and the root of this difference ultimately lies with how we understand investor behaviour, the creation of money and the role of commercial banks and the central bank. In a pragmatic methodological sense, the outcomes of analyses using the two classes of models *hinge on whether crowding out takes place or not.* It is thus natural that an empirical determination of this phenomenon should be undertaken, and its result be implemented in the models. This is the key point upon which convergence between the models and schools of thought can be achieved and the resulting uncertainty in the range of likely macroeconomic impacts of energy-related policies could be reduced. Significant research exists in the

Post-Keynesian and evolutionary traditions on the subject, which are not generally included in current E3 models.

## 8 Conclusion and outlook to the future

Policy assessment is a process in which a bridge is created between science and policy in order to analyse and suggest, to the best of scientific knowledge, what could be the outcomes, desired or undesired, of proposed policies or policy portfolios. Such an exercise 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 report presents the outcome of an important effort towards this very goal:

(1) to explain why one obtains particular results out of particular models for the analysis of 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 history of development of economic theory underpins the various types of models that exist today, in which 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. For this, we used two case study models, GEM-E3-FIT and E3ME-FTT, as representative examples of each model class, equilibrium and non-equilibrium. These represent state of the art modelling that tends to lead to some convergence in the results of the two otherwise disparate schools of economic thought. This convergence in modelling approaches will be further explained, tested and refined in the next phases of this study to demonstrate how the analysis could be taken forward for advancing energy and climate policy impact assessment.

(2) to review current knowledge on what, in the real world, constrains the pace of transformation of current society towards sustainability, and in particular, what constrains the development of new technologies and their mass adoption in markets. This has involved barriers to energy innovation and the finance of innovation.

(3) to list what improvements to current models, used by the Commission and more broadly, could lead to better informed analysis of the impacts of energy, climate and energy efficiency policy adopted or contemplated by Member States or the Commission itself. We have identified current gaps in models, and highlighted what is feasible to implement in a short term.

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, both at the European Commission and member state level, as well as in the climate change research community (including the next IPCC report). We trust that the knowledge reviewed here can help build a new research agenda, but also, shape the direction of enquiry in policy assessment by the Commission and Member States.

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# Appendix: further material

## A. Technology, innovation and diffusion in the history of economic theory

When debating the mechanisms of policy-induced innovation and technological change, one must almost unavoidably refer to a theory of the behaviour of the entrepreneur, and a theory of the behaviour of the consumer, for the simple reason that economic change almost invariably takes place through the role of firms seeking economic opportunity in ever evolving markets, and consumers making consumption choices. We first make a distinction between *invention*, *innovation*, and the *diffusion of innovations*. We define here *innovation* as any step taken by a firm, whether change in management, use of resource (capital, labour, material, energy) and/or use of finance that leads to securing higher economic returns. Changes in the policy, governance and/or regulatory context in which firms operate can incentivise innovation primarily because such changes can create economic opportunities for entrepreneurs.

Innovation is at the root of economic growth (Solow 1957), and thus policy-induced innovation or technological change fundamentally entails economic transformation. We briefly review in this section how the entrepreneur and the consumer, and their roles in the innovation process, have been represented in economic theory historically. Since models are representations of theory, and that theory is divided between radically different schools, it is unavoidable to go back to the origins of modern theory. When discussing innovation and the role of the entrepreneur, the works of Schumpeter are at the root of most modern theories of innovation. We then discuss how Schumpeter is not incompatible but rather complementary with Keynes (and eventually represented in macro-econometric models), and indeed, both authors strived to explain the business cycle by ascribing it to fluctuations led by speculation over returns on investment, which is typically tied to innovative activity. Walras, upon which neoclassical theory and Computable General Equilibrium (CGE) models were originally built, did not emphasise the role of the entrepreneur, and productivity growth is explained differently.

Schumpeterian and Keynesian theory both led to their respective successors, the Post-Schumpeterian (or evolutionary economics, used here interchangeably) and Post-Keynesian approaches, each looking in a different direction: innovation, transitions and business management, in the case of Post-Schumpeterians, and the macroeconomy, monetary policy, investment and the financial sector, in the case of Post-Keynesians. However, both schools attempt to explain the business cycle, economic recessions and financial crises resulting from innovation, expectations, finance and investment uncertainty. Together with Post-Walrasian neoclassical economics, these three schools strive to explain the mechanism for economic growth.[19]

Post-Walrasian neoclassical theory takes a different approach, focusing on the allocation of existing scarce resources. Models based on this theory adopt a supply-driven perspective, and so the direction of causation between many variables runs opposite to that of Post-Keynesian and Post-Schumpeterian demand-led models, as we explain below. As an equilibrium theory, Post-Walrasian economics does not attempt to explain business cycles or unemployment endogenously.

In neoclassical theory, investment is understood as taking a share of fixed national income, where a choice is made by households between consuming scarce resources

[19] We differentiate between normative and descriptive schools of economic thought, and only review descriptive theories for their applicability at explaining observations. We do not discuss the missing Marxian/Marxist school here, primarily since it is not particularly relevant to the issue at hand, namely innovation and technological change.

immediately for increasing utility now, or saving these for the future by investing. Households are assumed to make choices that optimise their welfare, and so this approach is associated with the use of *optimisation* as a methodology, as we see in CGE models. In Post-Keynesian and Post-Schumpeterian theory, finance is created and allocated according to the creditworthiness of entrepreneurs, as long as adequate returns are expected, and the incomes from production accrue to households whose collective behaviour generates aggregate demand, feeding investor expectations. Expectations are not necessarily realised and outcomes are not necessarily optimal, and so this approach is associated with the use of *simulation* of behaviour as a methodology, which is applied in macro-econometric models. We explain below the important implications this has for practice in the field.

## A.1 Schumpeterian theory

The core of Schumpeter's theory is contained in his *Theory of Economic Development* (Schumpeter 1934)[20]. It covers three main areas: (1) the role of the entrepreneur in generating corporate profit, economic growth and development through innovation, (2) the role of credit creation and of the financial institution in enabling the entrepreneur's activities, and (3) how the clustering of innovative activity leads to the business cycle. In a nutshell, *The Theory of Economic Development* puts forward a self-consistent theory of entrepreneurial activity, a basic monetary theory and a macroeconomic theory. Further writings by Schumpeter explore in more depth the subjects already addressed in *The Theory* (Schumpeter 1942; Schumpeter 1939; Schumpeter 2014). Of note is his work on the monetary system, "A treatise on Money", a theory of money creation, inflation and finance (Schumpeter 2014).[21] Schumpeter's theory is not a neoclassical or equilibrium theory; although his approach starts from Walras, the role of innovation makes it demand-led, not supply-driven.

The Schumpeterian entrepreneur is a person with ideas for making money, seeking liquid capital in order to develop those. Entrepreneurial ideas consist of unproven methods to improve a firm's productivity or lower its production costs, in order to secure temporary monopoly rents, by inventing "new combinations of economic resources" (Schumpeter 1934), whether human, capital, knowledge or material. In the hope of securing profit, the entrepreneur applies for finance at a financial institution, whose awarding decision is based on the entrepreneur's creditworthiness, and the credibility of their business plan. The venture may fail, in which case the entrepreneur may file for bankruptcy (for which the entrepreneur and the lender suffer the loss), or succeed, in which case the loan is repaid and the entrepreneur secures a profit (after costs). The expectation of profit is the factor motivating both the entrepreneur and the financial institution. Innovation therefore involves two key actors, the profit-seeking entrepreneur and the financial institution.

Economic development for Schumpeter comes about through innovative activity, through the following three processes. (1) The profitability of the entrepreneur has a limited duration as competing entrepreneurs and firms strive to match their gain in competitiveness (including by imitation), and any productivity-enhancing innovation is eventually diffused across the economy. Sustained profits are only achieved through continuous successful innovation (sometimes termed the 'red queen hypothesis' in evolutionary theory[22]). (2) Successful innovation depresses real prices over the long term as higher productivity methods and technology are diffused, leading to lower production costs (which are passed on to consumers as a result of competition

[20] The Theory of Economic Development - An inquiry into Profits, Capital, Credit, Interest and the Business Cycle" (Schumpeter 1911, translation from German in 1934).
[21] Written in the 1920-30s, but only published posthumously in German 1970 and in English in 2014.
[22] Name originating from Alice in Wonderland, referring to a perpetual arms race between competing evolving opponents.

between entrepreneurs). (3) Households can therefore benefit from higher real incomes (for the same wage income), while entrepreneurial profits augment income for this group.

The business cycle in Schumpeter arises due to the "clustering of innovative activity", because technically related successful innovations emerge clustered in time, leading to eras of important technical expansion and economic prosperity, interrupted by periodic eras where much innovative activity fails to deliver, and unemployment and economic instability or depression arise (Schumpeter 1939; Freeman & Louça 2001). Because investment is stimulated by innovation in Schumpeter, in periods when innovative activity fails, investment declines, leading to economic recession. Schumpeter analyses in great detail the various lengths of economic cycles (3, 9 and 55 years), the longest commonly called 'Kondratiev waves'. These are linked to "great surges of innovative activity" (Freeman & Perez 1988), related to particular important technological developments. Fluctuations in decisions by financial institutions to make financing available, tied to expectations (Schumpeter 1934; Schumpeter 1939; Schumpeter 2014), are key factors in the mechanism of the business cycle.

### A.2 Keynesian theory

Keynes was a contemporary to Schumpeter, with a similar goal to explain the business cycle, in a post-Great-Depression era. Keynes emphasised the role of entrepreneurs in aggregate to drive macroeconomic dynamics, and sought to explain inflation and unemployment in his General Theory (Keynes 1936)[23]. As in Schumpeter, income depends on investment, rather than the other way round. The economy evolves at a certain growth rate, which is not always the fastest rate at which it could possibly grow, depending on aggregate demand, in contrast to neoclassical models. The economy can be, but typically is not, operating under full employment of economic resources (physical capital, labour). Keynes invoked a gap between existing output and maximum theoretical output according to existing capital equipment. The level of effective demand determines the actual level of output, and demand does not necessarily tend to a level consistent with the maximum potential level of output. This opens the possibility of the economy exhibiting cycles.

In Keynes, aggregate investment depends crucially upon entrepreneurs' expectations of returns, the future state of the economy, and what other entrepreneurs are planning. Both risk (quantifiable probabilities) and uncertainty (unquantifiable probabilities) play a key role. Expectations, a process in which entrepreneurs interact, trying to guess each other's plans and to anticipate the outcome for the economy, gives rise to a self-reinforcing property of macroeconomic behaviour: in an economic decline, entrepreneurs delay investment, which leads to further decline, while an upturn encourages further investment, leading to bubbles. In Keynes, these 'animal spirits' (entrepreneurial psychology) explain the business cycle. However, the role of money in the behaviour of entrepreneurs is not completely clarified.

It is clear, however, that profit-seeking entrepreneurs, supported by financial institutions, invest in ventures in which they expect high returns, and this naturally includes investing in innovative activity. However, Keynes does not put any emphasis on the entrepreneur as an *innovating* agent, nor on *innovation* as a driver of economic growth.

### A.3 Walras and traditional neoclassical theory

Walrasian theory, upon which the neoclassical school and CGE models draw, conceptualises the economy in terms of the efficient allocation of scarce resources

[23] "The General Theory of Employment, Interest and Money" (Keynes 1936).

across sectors and time. Its arguably normative foundation[24] is the maximization of utility by individuals, who decide how to best use their life-time endowments of resources to satisfy their individual preferences (including their degree of impatience). It is individuals who own firms, which transform inputs (capital, resources and labour) into outputs, the latter consumed by individuals. Both the demand for outputs and inputs depend on relative prices, which in turn depend on relative scarcity, preferences and production technologies.

In *Elements of Pure Economics* Léon Walras (1874), laid out a mathematical framework that conceptualises how all factors relate to each other as a system of simultaneous equations. The fundamental analytical result is the existence of a *general equilibrium*: in an economy with multiple goods, the maximization of utility by individuals and minimization of production costs by firms should resuclt in a state in which all markets are cleared simultaneously, i.e. demand equals supply for all goods and production factors. Crucially, in equilibrium firms' profits will be zero.

The Walrasian standard framework is a powerful tool for analysing the functioning of markets from a "bottom up" perspective, and in his *History of Economic Analysis,* Schumpeter (1954) acknowledged it as the most significant contribution to economic theory. Indeed, Walras' approach remains influential as a particular representation of Adam Smith's 'invisible hand', the force that leads producers to respond to the needs of consumers. In Walras' approach, prices and quantities tend towards an equilibrium, extensively used in contemporary Computable General Equilibrium Models (CGE, more on this below). By defining markets for future consumption, it is possible to extend the concept of *general equilibrium* to apply across time, as in the Arrow-Debreu model (Arrow & Debreu 1954), the primary reference of most contemporary microeconomic models.

However, Walrasian theory does not account for *changes* in technologies (and the related changes in productivity). Effectively, in a steady state equilibrium, no dynamics exist: "By requiring profits to be zero, Walras shut the door to the market rewarding entrepreneurial activity" (Makowski & Ostroy 2001). This is in part due to an assumption of perfect competition with free market entry, so that firms are purely price takers.[25] Individual firms compete with identical productivities determined by the given technological frontier, and cannot influence the market outcome: firms maximise profits *given* market-clearing prices. Furthermore, the framework of general equilibrium focuses on competition in a given and finite set of goods, and does not include a process for entry of new commodities or technologies.

## A.4 Innovation and productivity change in early and modern neoclassical theory

The neoclassical school *does* acknowledge the relevance of entrepreneurial innovation and "creative destruction" for capitalist growth (Nordhaus 1969), and sees technical progress as central for economic development. There are numerous attempts to reconcile the dynamics of innovation with the Walrasian standard framework of static utility and profit maximization (Makowski & Ostroy 2001). But the extension of neoclassical models in this direction requires additional assumptions, and ways of incorporating these mathematically mostly result in more complex (and sometimes analytically challenging) models. As is the case generally in modelling, greater realism (here with respect to innovation) is often associated with a loss of simplicity.

[24] Depending on context, neoclassical economics is sometimes normative, sometimes descriptive. Broadly speaking, normative neoclassical economics advocates removing barriers to agents maximising their utility.

[25] Firms are assumed small with respect to the market such that their actions are assumed not to influence prices.

The first hallmark growth model of neoclassical economics, the Solow-Swan model (Solow 1956; Swan 1956; Solow 1957), focuses on the relative roles of labour, capital and productivity changes for economic growth. It is defined at the aggregated economy level, and has no focus on microeconomic foundations. Changes in productivity (i.e. innovation), changes in the stocks of labour (population growth) and capital (savings and depreciation rates) are exogenous. Labour and capital are substitutable inputs of economic production, represented in an aggregate production function. Causation runs from optimal labour and capital employment choices by firms, which with exogenous productivity, determines supply, all of which (following Say's law) is consumed by households. Thus in Solow-Swan, the level of inputs determines the output - it is supply-driven, and any level of production will be consumed by households.

With decreasing returns to scale, a long-term *steady state* arises when capital accumulation just replaces depreciation, without further growth per capita. Long-term growth is thus only possible due to exogenous technical change, which allows a more effective transformation of the input factors into economic outputs (the *total factor productivity*, TFP). With exogenous TFP, the Solow-Swan model represents (but does not explain) innovation as an outside process, independent of the economic context.

One of the model's strengths was to allow the first empirical estimations of TFP at the macro-level: by means of growth accounting, it was estimated that increases in TFP accounted for more than half of GDP growth in many countries - the other fraction being attributed to increases in capital per hour of labour (Easterly & Levine 2001; Solow 1957). Besides innovation, parts of TFP may be attributable to an increased use of environmental resources (e.g. in the form of energy), which are not considered as explicit inputs in the original model formulation (Solow 1974; Solow 1986). The model did not attempt to explain the underlying dynamics, and crucially, how they may be influenced by policies.

Taking inspiration from Ramsey's (1928) normative theory of optimising growth, Kydland and Prescott (1982) and Prescott (1986) pioneered RBC (Real Business Cycle) theory. RBC established the widely used dynamic stochastic general equilibrium (DSGE) models, with emphasis on explaining growth and the business cycle through series of exogenous (technology, policy, historical) shocks. These models are different from the Solow-Swan model mainly for their claim to micro-foundations: deriving collective macroeconomic identities out of utility-maximizing choices of a population of agents, relying on the principle of the *rational representative agent*. These reproduce the Walrasian *general equilibrium*: full employment and potential output are maintained by price and wage adjustments that clear markets.

However, DSGE models lack a micro-foundation for *innovation*, maintaining the assumption that technological change is exogenous. This remains the case in the most recent family of DSGE models, referred to as the "New Keynesian" Model (Clarida et al. 1999; Galí & Gertler 1999): firms are assumed to have access to, and use, identical technology, subject to exogenous random shifts. By introducing monopolistic competition and nominal rigidities ("sticky prices" make price changes costly) into the framework, they instead allow insights into the potential *consequences* of innovation: as the economy cannot adjust to (monetary or technological) shocks instantaneously: in the short term positive "technology shocks" can lead to increased output, but reduced employment (Galí & Rabanal 2004).

The literature on "endogenous growth models" (Romer 1994) seeks to incorporate an explanation of changes in TFP into the neoclassical paradigm. Explicit models of TFP incorporate some form of technological change, economies of scale, the role of externalities, changes in an economy's sector composition, and the adoption of lower-cost production methods (Nordhaus 1969; Easterly & Levine 2001). Models of endogenous growth can be broadly divided into two categories: those that explain technological progress as a result of experience in production, or those that explain it as a result of investment in research. Conceptually, they extend the concept of capital accumulation to include knowledge accumulation, which changes productivity over time through the following steps:

1. Given a limited set of production factors and households' preferences for consumption, firms produce by fully using resources (full employment).
2. Households receive payments for their production factors (labour), as well as firms' profits (according to their shares). They choose how to spend their income between the consumption of produced goods, and saving.
3. All savings are invested into firms' capital stocks for production, which includes: physical production facilities (e.g. replacement of retired machinery), and investments into productivity change (e.g. improved machinery, R&D).
4. The increased amount of capital and productivity allows higher amounts of production for the same given set of production factors.

Arrow (1962) explains TFP as resulting from workers' increasing experience in the production process - "learning by doing".[26] Decreasing unit costs imply (directly or indirectly) increasing returns to scale, leading to multiple possible equilibrium solutions, and economic dynamics become path and decision-dependent (Arthur 1989). Romer (1986) and Lucas (1988) proposed endogenous growth models that link the concept of knowledge as a result of "learning by doing" to the economy-wide stock of capital, including human capital. However, this form of "innovation" is thought of as a process external to the individual firm. As a public and non-rival good, it is available to all firms in the economy at no cost. Consequently, individual firms cannot gain competitive advantage from innovation, and perfect competition is still assumed. Hence, the role of patents (for example) is excluded, and there is no room for a Schumpeterian entrepreneur. The process of "innovation" remains unintended at the firms' micro-level, and is only an externality of their investment activities. Since knowledge accumulation takes place at the economy level, the model abstracts from the adoption of innovation by firms: productivity increases are a deterministic function of output.

By contrast, in imperfectly competitive general equilibrium models (Romer 1987), innovation is seen as the result of intentional microeconomic activities aimed at profit maximization: if individual firms can appropriate some gains from newly discovered knowledge (e.g. because it gives them a temporary monopolistic position), firms have an incentive to innovate. The concept is made more explicit in multi-sector models, which integrate a routinized R&D sector in addition to the pure production sector (Grossman & Helpman 1991). Investments into R&D are determined by their expected return, and modelled on the lines of the patent race literature in industrial organization: profit-maximizing firms compete to discover an invention, so that they can obtain patent protection and exclude competitors (Shapiro 1985; Aghion & Tirole 1994). Finally, "neo-Schumpeterian" models of endogenous growth attempt to represent the process of "creative destruction" within a neoclassical framework (Aghion & Howitt 1992): entrepreneurial firms engage in research activities with an uncertain outcome, which may result in disruptive innovations. If successful, the firm can make a profit and gain market share at the expense of firms that lack the innovation, and the old production capital is made obsolete.

[26] Learning-by-doing was reported one of the first times by the Wright brothers, makers of airplaines (Wright 1936), in which it was observed that the time required to make an airframe declined with the cumulative number *N* of airframes previously made by a factor $N^{-1/3}$ (with an exponent of minus one third). This is now widely observed in many contexts, products, technologies (Köhler et al. 2006; Weiss et al. 2010; IEA 2000).

While general models of endogenous growth are mainly concerned with the role of innovation in raising TFP, a sub-category of neoclassical models focuses on the *direction* of innovative activities. If the resources required for R&D are finite (e.g. scientists), trade-offs (crowding-out) exist between innovation activity in different sectors, i.e. *directed innovation*[27] takes away scarce resources for innovation from other sectors. Ahmad (1966) proposed that there exists a historical "possibility frontier" for technological change, representing all possible combinations of innovations that can be realized with limited social resources. Acemoglu (1998; 2002) shows that innovation investments in different sectors are influenced by both market size (which encourages innovation in larger sectors) and price effects (benefiting innovation in sectors with higher prices). Popp (2004) presents a model with *directed innovation* in the energy sector, suggesting it can lower the costs of environmental regulation. Acemoglu et al. (2012) introduce a model of endogenous growth with environmental constraints, in which research can be directed towards either a "clean" or a (substitutable) "dirty" production sector (which degrades the environment). It is shown that in the presence of an environmental externality, the optimal policy should combine a carbon tax and an immediate redirection of R&D investments into the "clean" sector (e.g. by introducing a research subsidy).

In essence, if innovation is to be fostered or directed by policy within the neoclassical framework, this has to be carried out by influencing firms' expected profits. Policy can either lower the cost of research activities (e.g. R&D subsidies), or influence relative prices in a way that increases expected demand for the resulting product (e.g. carbon pricing). The latter was proposed by Sir John Hicks as early as 1932, in what is known as the induced innovation hypothesis (Hicks 1932): "a change in the relative prices of the factors of production itself is a spur to invention, and to invention of a particular kind - directed to economizing the use of a factor which has become relatively expensive" (pp. 124-125). The proposed link from relative prices to technological change is empirically supported by an extensive literature (Lanjouw & Mody 1996; Jaffe & Palmer 1997; Newell et al. 1998; Popp 2002).

### A.5 From Schumpeter through Evolutionary Economics to modern Transitions Theory

Post-Schumpeterian research has drifted away from the mainstream to establish a field of its own, evolutionary economics, focusing on both Schumpeter's plea for adopting a historical approach, and on the barriers and enabling factors to 'creative destruction'. The key figure in this field, Christopher Freeman[28], led the research to establish the methodology, data and indicators for measuring science and innovation. He reinvigorated the Schumpeterian tradition with multiple books, and his influence gave birth to several new branches in the field.

In a highly detailed historical account, Freeman & Louça (Freeman & Louça 2001) follow Schumpeter (Schumpeter 1939) to unearth key factors in the evolution of five 55-year cyclical "Great Surges of innovation" that have taken place since the first industrial revolution. A consistent picture is built of recurrent phases of great technical advances with far-reaching consequences for productivity, interrupted by periods of instability and economic fluctuation and depression. Each of these involved particular 'constellations' of linked, related innovations (Freeman & Perez 1988): Schumpeter's *clustering of innovation*. For example, the steam engine not only allowed railways to be built (among other important applications), but also, through new access to mobility, allowed new business models to be developed and dramatically changed

[27] Term used in the literature meaning innovation promoted by specific policy.
[28] Founder of the highly influential Science Policy Research Unit at the University of Sussex, UK.

access to markets. Thus innovation builds on itself in the way of a complex network (Arthur & Polak 2006).

In each of these Great Surges, expectations of large productivity changes and high returns attracted large financial investment, and thus rapid expansion in infrastructure and industry was seen. Technological developments always occurred together with enabling financial innovation. Each Great Surge fuelled rapid economic development. The clustering of innovation also meant that opportunities for profitable investment were eventually used up (e.g. covering all of Great Britain in railways), limiting the scope for further innovation and expansion, and lowering the return on further investment. At this point ventures became less successful, failures multiplied, uncertainty for the investor increased, and investment slowed down, sometimes dramatically. This led to periods of high unemployment, low output, and painful adjustment. The recurrent phenomena is a replacement of old technological systems, or constellations, by new ones, Schumpeter's 'creative destruction'.

Freeman's work was carried further by Perez (2001) in its financial dimension, reconstructing the financial history of the Great Surges. It is consistently found by Perez that (1) innovative activity in systems related to each surge began well into the previous surge, but took decades to emerge into mainstream use, (2) investment activity multiplies until a bubble forms, in which asset prices soar and investment activity becomes purely speculative, (3) a financial crash takes place, and several firms in the race go bankrupt, and (4) a peaceful development allows the technology to consolidate its applications across the economy, until (5) most applications are in place, and investment drops to a low level leading to spare capacity and unemployment (e.g. idle construction workers).

The early work researchers under Freeman at the Science Policy Research Unit of Sussex University, and other evolutionary work elsewhere (Nelson & Winter 1982), led to new fields being established, focusing more specifically on technology, technological change and innovation. Following the same historical approach, some researchers in these new fields have adopted purely qualitative methods, as opposed to the classical evolutionary school. Others have kept a strong empirical base. We describe below the areas of modern Evolutionary Economics (EE), Technology Innovation Studies (TIS), and Technology Transitions research (TT). With increasing interest in climate change and sustainability, these fields have found natural application, and mainstream attention, in studying public policy for sustainability. Their relevance however goes beyond sustainability.

### A.6 From Keynes to the Post-Keynesian tradition

The Post-Keynesian tradition (e.g. King 2015, Lavoie 1992) has followed a different approach to innovation and productivity change in comparison to the Post-Schumpeterian, keeping a closer focus on productivity, economic growth and cycles. Following Keynes, a macroeconomic explanation for demand deficiency and unemployment was sought (Harrod 1939; King 2015). Economists such as Kaldor, Thirlwall, McCombie have explained growth and international competitiveness through the concept of "cumulative causation" associated with knowledge accumulation (Kaldor 1970; Kaldor 1972; Arthur 1986; Arthur et al. 1987; Kaldor 1957; Arthur 1989). Cumulative causation refers to a path-dependent virtuous cycle where growth leads to increasing productivity which itself leads to growth, a self-reinforcing process (or a vicious circle in the opposite direction). This opened the way to path-dependent theory and modelling.

In Kaldor, since every new capital stock addition originates from a new vintage (latest technology), technological progress becomes implemented with new investment, and is thus function of *cumulative* investment.[29] Kaldor's so-called technology progress function is similar to then well-known learning curves for individual products (Arrow 1962), however applied at an aggregate economy-wide or sectoral level. Increasing the stock of knowledge itself affects the productivity of the capital stock; but the stock of knowledge only grows when investment takes place, and thus it is self-reinforcing and path-dependent, as follows (see Figure 1, top panel):

1- Entrepreneurs see potential applications for their ideas, and apply to financial institutions to finance their innovative improvements to the existing capital stock. Banks create loans based on entrepreneur 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, increasing 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 on 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).

5- Higher demand and profits incentivises firms to re-invest to expand their capital stock, leading to further expansions of the stock of knowledge.

The Post-Keynesians built models without production functions. Kaldor went further and even took out the notion of capital entirely, dealing only with effective demand, productivity and money. While the notion of short-run capacity constraints exists, which can lead to inflationary pressure, these are not represented with reference to the capital stock, not least because of the difficulty of measuring that stock when different vintages on investment incorporate different innovations and when innovation can render some equipment economically obsolete before the technical end of its life.

Causation in Post-Keynesian economics runs in the opposite direction than in neoclassical theory. Production is not primarily driven by choices of firms as to how much capital and labour to employ; it stems from choices of consumers as to what to consume (demand-led). Consumers choose to consume in the present; firm decisions in the present regarding capital always concern planning for future production.[30] This difference typically leads to a contrast of language and acute misunderstanding across the schools.

Setterfield (1997) reviews various formalisations of Kaldor's ideas. Dixon & Thirlwall (1975), Thirlwall (1980), McCombie & Thirlwall (1994) explore international competitiveness in relation to Kaldor's technological progress function, and determined that it confirms Verdoorn's law that competitiveness is an increasing function of output (a form of increasing returns). Through increasing international competitiveness due to improved productivity and/or increasing product variety, markets expand and economic growth is fuelled (Barker 1977; Dixon & Thirlwall 1975).

Keynes described this perspective as the M-C-M' view of the economy, in which money is invested first, which trickles down through the economy leading to consumption,

[29] In theory it should be the cumulative number of units produced since the first, e.g. as in Arrow (Arrow 1962), who uses an illustrative product 'serial number' that increases by 1 for every new unit. In practice, since investment typically increases exponentially in early phases of diffusion, some uncertainty on numbers in early phases can be tolerated without much impact on the outcomes.

[30] We thank Terry Barker for providing us this very clear formulation of the issue.

which itself incentivises further money to be invested (King 2015). This contrasts to the C-M-C' view from the neoclassical world, where consumption arises first, and leftover income not consumed (saved) is invested, which leads to further production to be consumed in the future (Figure 1, left panel).

In the demand-led view, banks award loans based on entrepreneur creditworthiness, incorporating the short-term interest rate determined by the central bank within the loan rate charged to borrowers; planned investment is not matched to planned saving by a market-clearing interest rate as in neoclassical theory. In the M-C-M' perspective, money, even central bank money ('high powered money') is not a commodity that exists in a finite quantity decided by the central bank; money is both an asset (to the holder) and a liability (to the central bank), similar to any other type of financial asset, and in modern economies the central bank supplies money on demand to commercial banks (see Fontana 2009) at the short-term interest rate. Commercial bank money (bank deposits)is created each time a loan is awarded by a bank to an entrepreneur or a consumer, and is destroyed when the loan is repaid. Since the 2007 banking crisis, this is a fact increasingly acknowledged by banking institutions, as explained for example by the Bank of England (McLeay et al. 2014). This is equivalent to Schumpeter's description of credit creation (Schumpeter 1934; Schumpeter 1939; Schumpeter 2014).

Finally, it is to be noted that Post-Keynesians do have a microeconomic theory, which is strongly based into behavioural economics. They integrate works on bounded rationality by Simon (1955), on prospect theory by Kahneman & Tverski (1979), and institutional economics, in order to derive a non-optimisation basis (Lavoie 1992).

## A.7 Sustainability transitions studies and technological innovation systems

Three main schools have emerged since the 1990s studying technology and innovation in relation to the economy, in addition to neoclassical and Post-Keynesian efforts (which we discussed separately above). These are Evolutionary Economics (EE), Technology Innovation Studies (TIS), and Technology Transitions research (TT), and we review their main features here.

EE follows the early efforts of the evolutionary school (Freeman & Perez 1988; Nelson & Winter 1982), merging ideas from Post-Schumpeterian analysis and theoretical elements from the Darwin's Theory Of Evolution (TOE), which is highly successful experimentally and empirically in biology and other fields. TOE maintains that evolution takes place naturally, statistically, whenever three processes are present simultaneously: reproduction, mutation and selection. In biology, a group of individuals within a species has a genetic bath characterised by diversity, with the frequency of genetically transmitted traits evolving due to selection (different relative survival success rates across variants) in response to changes in the environment.[31] With the addition of mutation of genes (innovation in economics), the species (socio-technical systems in economics) gradually evolves over time. Without mutation, genetically static species would fail to adapt to the changing environment and gradually go extinct in the long run. This provides a framework to analyse for example R&D investment competition for competitiveness (i.e. the Red Queen Hypothesis), as well as the co-evolution of regulation and markets.

These characteristics are unavoidably highly dynamic and non-linear, as they involve population dynamics (dynamics of life and death of technologies in economics, Mercure 2015). The dynamics of genetic populations are well described by mathematical models (Hofbauer & Sigmund 1998). Some behavioural questions in

[31] I.e. every individual has a different combination of genes, and some genes recur more frequently than others, and frequencies of recurrence evolve over time, giving rise to an evolving population.

ecology led to the development of the field of Evolutionary Game Theory, developed for biology by authors such as Maynard Smith (1982), but it had always been clear that the theory was equally applicable in economics (see e.g. Hodgson & Huang 2012). That is, it applies to the process of *technology* evolution, the generation and combination of ideas, market selection and adoption of innovations (Safarzynska & van den Bergh 2012; Safarzynska & van den Bergh 2010), and the evolution of institutions. These ideas are supported by a large amount of empirical data on the actual dynamics of technology evolution (Sharif & Kabir 1976; Marchetti & Nakicenovic 1978; Mansfield 1961; Fisher & Pry 1971; Grübler et al. 1999; Wilson 2012; Grübler & Wilson 2014), and lend themselves well to the construction of innovative quantitative models (Safarzyńska et al. 2012; Saviotti & Mani 1995; Mercure 2015).

In an alternate pathway, the theoretical foundation in EE, in particular from Freeman & Perez (1988), directly led to the development of TT. Building alongside earlier work from the normative Dutch school of Transitions Management (Rotmans et al. 2001), using methodology from traditional EE contributions (Freeman & Perez 1988), Frank Geels puts forward historical case studies of successful past transitions of socio-technical regimes, in which technology only takes meaning in relation to its users (e.g. Geels 2005; Geels 2002). Using a Multi-Level Perspective (MLP) framework,[32] Geels constructs a detailed qualitative picture of the various societal elements influencing and regulating the evolution, or resistance to change, of socio-technical regimes (i.e. what people do with technology systems). This includes regulatory structures, policy landscapes, economics, but also technology networks and infrastructure, and finally, culture, preferences, social influence. New socio-technical regimes emerge from existing niches, where technologies exist but for alternate, smaller scale, applications. TT is evolutionary in the sense that changes in socio-technical regimes can be brought about through changes in the wider environment (the economy, policy, regulation, markets, demography). The MLP has been severely criticised (Genus & Coles 2008) but is also evolving and improving in response (Geels 2011). Its predictive power remains to be fully demonstrated empirically, restricting its normative applicability. The field is now sizeable and influential.[33] With some exceptions (Köhler et al. 2009; Turnheim et al. 2015; Holtz 2011; Holtz et al. 2015), while compelling conceptually, TT is not extensively used in modelling; the literature retains a strong qualitative component.

TIS is a different type of research field, focusing on the nature of innovation systems, with a strong empirical foundation: what are the contextual factors responsible for the success and failure of innovation systems? It was allocated a full chapter in the Global Energy Assessment (GEA 2012), in recognition of the importance of studying policy frameworks for the development and improvement of low-carbon energy innovation networks. We review briefly the features of the Energy TIS (ETIS) in section 5.

A TIS is a network of interrelated actors and institutions involved in the development of innovations: scientists, research institutions, firms, technology transfer offices, policy-makers, investors, venture capitalists, and most critically, users. The quality of interaction between these actors determines to a large degree the degree of success in the TIS to bring ideas to the market, generating profits to various actors involved (e.g. entrepreneurs and capitalists). Hekkert et al. (2007) review the functions of TIS actors and provides a methodology to map TIS networks. (Bergek et al. 2008) proposes a method to link policy functions to the functions of TIS. The GEA (2012) as well as Grübler & Wilson (2014) provide a full account of the ETIS and its functions.

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[32] Here we do not mean to say that Geels developed the whole MLP framework, as many other scholars have been highly influential, including (Rip & Kemp 1998; Kemp et al. 2001).

[33] Some European funding calls have now been formulated using a TT-consistent language, which is gradually making its way to debates in scientific and policy circles.

Finally, innovations can enable firms, and even nations, to gain competitive advantage internationally. In a manner consistent with the Post-Keynesian analysis of trade and competitiveness (e.g. McCombie & Thirlwall 1994, see section A.6) in relation to growth, a specific literature has emerged exploring potential economic impacts of the diffusion of eco-innovations through first-mover advantages, the so-called Lead Markets approach (Rennings 2014). In this perspective, policy for the development and diffusion of innovations in foreign markets leads to extensive global markets for goods and services with reduced environmental impacts, and these goods and services require large-scale investment. The investment costs and potentially reduced operating costs (e.g. through reduced energy consumption) change considerably over time due to learning effects.

## A.8 Multi-sectoral quantitative models

Applied economic research to estimate the macroeconomic impacts of environmental or technological change policies (e.g. carbon pricing, environmental taxes) generally uses whole-economy macrosectoral models, either in the Computable General Equilibrium (CGE) tradition (e.g. Wing 2004) or in the macroeconometric post-Keynesian tradition (e.g. Cambridge Econometrics 2014). CGE models compute a *general equilibrium* of the entire economy, the prices and allocation of resources that clear all input and output markets simultaneously. Post-Keynesian macrosectoral models typically determine prices as a mark-up on unit costs and allow output to adjust to demand changes; wage rates are determined by a wage-bargaining rule that does not guarantee market-clearing. The CGE approach was first applied in a 22-sector model of Norway (Johansen 1960), while the post-Keynesian macrosectoral approach was pioneered by the "Cambridge Growth Project" model of the UK (Stone & Brown 1962).

Both CGE and post-Keynesian macrosectoral models simulate an economy with several production sectors (e.g. 10-100), distinguishing inputs, outputs and flows of intermediate products between sectors using input-output tables (represented in a detailed social accounting matrix).

In CGE models, profit-maximizing firms are represented by sectoral production functions; the representative agent who owns firms and factors of production maximises his utility inter-temporally. Calibrated to economic data in the form of input-output tables, the models numerically calculate the equilibrium levels of sectoral production, relative prices and social welfare (in the form of aggregate consumption).

Because of their sectoral detail, both kinds of models have been applied to questions that require a sector-specific model resolution, such as the impact of environmental or border taxes, tariffs and regulations on particular sectors. The introduction of policies affects relative prices, activity levels and demand. To determine distributional and welfare effects, CGE models determine new ("distorted") general equilibrium points, which can be compared to a baseline. In practice, a CGE model forms a system of numerical equations to optimise under constraints, which is typically solved using commercially-available optimization software - foremost the PATH solver (Dirkse & Ferris 1995) and the Generalized Algebraic Modeling System (GAMS, Brooke et al. 1998). Post-Keynesian macrosectoral models also simulate the outcome of alternative policies, but without the presumption that the baseline is 'undistorted'. Whereas in a CGE model, departure from the baseline (say, as the result of the introduction of a tax) typically necessitates a reduction in welfare by assumption, in a post-Keynesian model the outcome may be better or worse (measured, say, by the impact on GDP or household consumption) depending on the details of the policies being modelled.

Standard CGE models are comparative-static in nature. They focus on allocations, while processes leading from one equilibrium to another take place without any representation of time (but usually with the implied assumption that in practice the adjustment would occur reasonably rapidly). The Walrasian condition of market clearance implies that in their most common type of closure[34], factors are efficiently allocated by trade, and households consume all outputs. Prices are defined in real terms relative to a numeraire good, and there is no explicit representation of money or the financial sector. Wages adjust to ensure that labour markets clear in standard CGE models: if production is lowered in one sector, excess labour is absorbed by other sectors. Perfect competition and constant returns to scale ensure the zero-profit condition. As in many other neoclassical models, standard CGE models abstract from innovation or entrepreneurial activity.

Post-Keynesian macrosectoral models have their roots in Leontief input-output modelling which also, typically, had no time dimension, but the incorporation of the Keynesian approach to the determination of output was accompanied by the explicit inclusion of time and a dynamic adjustment process. The approach typically assumes that money is created endogenously by banks and that there is no financial constraint on spending (other than that represented by the cost of borrowing), so that finance for investment is not represented explicitly. Technological progress is assumed to be embedded in investment, so that more rapid investment is associated with faster productivity growth (as in Kaldor's technological progress function), but innovation is not represented explicitly (see separate section below).

CGE models have been adapted for many purposes, resulting in a variety of variants (Dixon & Jorgenson 2013). In "recursive-dynamic" CGE models, results are presented for a time path, but solved for as a discrete sequence of static equilibria (connected by endogenous or exogenous external functions for investment, savings, population etc), without rational expectations (i.e. "myopic" expectations). In contrast, "dynamic" CGE models assume that (infinitely lived) agents have perfect foresight, and optimize their decisions consistently across time (Ramsey 1928). The approach allows analysis of dynamic normative policy questions, such as the temporally optimal allocation of carbon abatement investments. However, it significantly increases model complexity. Because the model cannot be solved for an infinite number of periods, it relies on the exogenous specification of long-term variables such as growth and technological change (Babiker et al. 2009).

Many state-of-the-art CGE models aim at a more realistic representation of their respective policy questions, and therefore diverge from the assumptions of Walrasian equilibrium - e.g. by including imperfect competition or involuntary unemployment. When modelling energy system transitions within CGE, endogenous technological change is considered one of the most complex and salient issues, and many major CGE energy models were modified accordingly. Endogenous technological change is represented by means of price-induced innovation, endogenous learning curves ("learning by doing") and endogenous investments into a stock of R&D knowledge ("learning by searching"). Grubb et al. (2006) and Gillingham et al. (2008) review the integration of these mechanisms into energy-economy models, providing an overview of achievements and obstacles.

Meanwhile, Post-Keynesian macrosectoral models allow to explore the dynamics of a sustainability transition in a path-dependent perspective. Here, due to technological progress functions, which change the intensity or productivity of sectors based on investment trajectories in the past, different policy frameworks lead the model towards increasingly different futures diverging from each other, for example in

[34] The closure corresponds to the choice of exogenous and endogenous variables. Many different closures can be and have been used with CGE models, depending on the aims of the modellers. For example, employment can be maintained full with a changing wage, or wages can be kept fixed with variations of total employment arising. The same can be done with other factors. Full employment is the most common closure choice, closer in spirit with neoclassical theory.

energy consumption, or GDP trajectories. This property is the same as in climate models: model outcomes increasingly differ from one another as the modelling time span progresses, for arbitrarily small differences in starting parameters. This characteristic model uncertainty is an expression of the so-called “butterfly effect”. It differs starkly from models with exogenous productivity changes in that there is no “preferred” income trajectory; each different trajectory is one of many plausible futures (Mercure et al. 2016).

## B. Indicators for energy innovation

### B.1 The demand for innovation indicators

For analysing energy innovations, evaluating related policies or calibrating models of technological change, it can be useful to condense the underlying process of invention, innovation and diffusion into simple indicators. Ideally, these identify comparable attributes of interest, while allowing for a large degree of heterogeneity among analysed innovations. To obtain quantitative indicators, this involves carefully specifying measureable aspects of the R&D process: there needs to be at least some level at which innovations and related activities are qualitatively similar, so that comparisons can be made in quantitative terms (Smith 2005). They can either be intangible (knowledge, ideas) or tangible and human (Freeman & Soete 2009).We review here the most common indicators for energy innovation, and largely built on Wilson (2014), Grubler et al. (2012), Gallagher et al. (2006) and Smith (2005). Following Wilson (2014), innovation indicators can be categorized into *input, output* and *outcome* metrics (see Table 3):

- *Input* metrics describe financial, labour, and other inputs to the innovation system
- *Output* metrics describe defined products of the innovation system and innovation processes
- *Outcome* metrics describe the broader energy sector or economy-wide impacts of the successful diffusion of innovations into the marketplace

### B.2 Community Innovation Survey (CIS)

The limitations of traditional indicators of innovation lead to the development of new indicators in the 1990s. Originating in a joint initiative of Eurostat, the OECD and Stats Canada, a common framework for measuring innovation was designed that allows to link individual firm innovation data to relevant firm level performance data (see OECD 1992 for the original version; and OECD 2005 for the third edition). The initiative resulted in a set of detailed and internationally comparable innovation surveys, carried out in OECD countries as well as China, Brazil, India, South Africa and Argentina (Freeman & Soete 2009).

Based on the "Oslo Manual"[35], the European Commission implemented the "Community Innovation Survey" (CIS) (Arundel & Smith 2013),conducted in 1993, 1997, 2001, 2005, 2007, 2009, 2011 and 2013. For the CIS, member states collect highly disaggregated information about product and process innovation, as well as organisational and marketing innovation. It covers the following data (Smith 2005):

- Expenditure on activities related to the innovation of new products (e.g. R&D, training, design, market exploration, equipment acquisition and tooling-up). There is therefore a unique focus on non-R&D inputs.
- Outputs of incrementally and radically changed products, and sales flowing from these products.
- Sources of information relevant to innovation.

[35] The "Oslo Manual: Guidelines for Collecting and Interpreting Innovation Data".

**Table 3: Commonly used metrics of innovation inputs (adapted from Wilson 2014).**

| Metric | Description | Characteristics & Issues |
|---|---|---|
| **Input indicators** | | |
| R&D Expenditure | • Expenditure on R&D.<br>• "R&D intensities" | • Typically available; time series data.<br>• Private R&D data, can be difficult to obtain; difficult to isolate energy R&D. |
| Investment | • Investment in innovation.<br>• Includes R&D, demonstration, early deployment, and diffusion.<br>• Can be normalised (early stage venture capital as % of total venture capital). | • Broader categorisation of investment can avoid disaggregation issues<br>• Underrepresent later stage innovation activities (e.g. R&D vs demonstration).<br>• Compile into specific technology sectors by investor type, databases mainly cover industrialised markets. |
| Human Resources | • Number of scientists and engineers engaged in R&D.<br>• Can be weighted by education or training type.<br>• Absolute terms, by sector, or per capita. | • Proxy for "tacit" knowledge embodied in labour input to innovation process.<br>• Does not account for quality or efficiency, or differences in research infrastructure.<br>• Difficult to isolate labour input specific to energy innovation |
| **Output indicators** | | |
| Publications | • Numbers of publications.<br>• Weighted by citations or impact factors.<br>• Workshops and conferences. | • Readily available information, but English-language bias.<br>• No clear system boundaries for energy technology innovations:<br>• Useful metric for programme evaluation if quality or impact weighted. |
| Patents | • Number of patents filed or granted.<br>• Can be weighted by citations. | • Readily available, but difficult to define system boundaries.<br>• Biased twds industrialised countries and sectors with higher propensity to patent.<br>• Bias R&D vs than later stage innov., not always good predictors of diffusion. |
| Technologies | • Number of technologies commercialised.<br>• Plants, production lines, product variants, process improvements, companies, turnover, etc. | • Most visible measure of ultimate success of innovation process.<br>• Difficult to define clear system boundaries (e.g. multi-component systems)<br>• Fails to capture non-codified knowledge (e.g., energy-efficient building design). |
| Technology Character-istics | • Ratios of technical to service characteristics. | • Indicate directionality and variety of innovations, prox. to technology frontier.<br>• Technology specific: not possible to use in meta-analyses. |

- Technological collaboration.
- Perceptions of obstacles to innovation, and factors promoting innovation.

The CIS data proved to be a rich source for research: the number of English-language academic publications based on the CIS have increased from less than 10 per year in the 1990s to more than 50 per year after 2008 (Arundel & Smith 2013).

Eurostat merges the CIS survey data with other sources to calculate the "European Innovation Scoreboard". Combining 25 metrics into a single composite indicator, it aims at measuring and comparing the innovative performance in individual member countries, as well as selected benchmark countries outside the EU (e.g. Japan, USA).

**Table 3 (continued)**

| Metric | Description | Characteristics & Issues |
|---|---|---|
| **Outcome indicators** | | |
| Market penetration | • Number or capacity of technologies sold or used.<br>• Market share or penetration rate | • Generally available data.<br>• Bias towards "successful" innovations that have diffused widely. |
| Learning Rates | • Rate of cost reduction of a technology.<br>• production plants, orgs or technologies. | • Learning rates change over the stages of the innovation chain.<br>• Data generally available,<br>• Sensitive to data-fitting issues. |
| Economic Benefits | • Cost-benefit analysis.<br>• Can be aggregated as net social benefit, or left disaggregated | • Costs generally easier to quantify than benefits, which can include externalities, knowledge stocks and spill overs, option values of technology portfolios |
| Energy / Emissions Intensity | • Energy or emissions per unit GDP.<br>• Normalisation can also be more defined per sector or per plant. | • Readily available data; meaningful as part of time series trend.<br>• Aggregate impact of innovation only, subject to structural change, non-price-induced changes, and fuel substitution. |
| Project / Programme Evaluation | • Size and number of programmes in terms of employees, turnover, investment, outputs, etc. | • Difficult to assess quality, so need to complement with case study or survey research.<br>• Similar issues with tacit knowledge as for technologies (see above under outputs). |

## B.3 Input indicators for energy innovation

Indicators of the input dimension aim to quantify financial, labour, and other resource inputs into the innovation process. While *R&D expenditure* and *human resources* largely focus on initial research activities as such, *investment* also includes expenditures for demonstration and deployment.

Among input indicators, *R&D expenditure* has a substantial advantage in terms of data availability. R&D data for many countries have been collected consistently over decades, and often include detailed sub classifications (Smith 2005). R&D data are relatively consistent across countries. OECD states apply a standardized statistical manual for R&D data collection, which clearly defines research-comprising activities.[36]

However, data is difficult to obtain and disaggregate for private R&D expenditures. As noted by Sagar and Holgren (2002), major players in energy-technology are diversified industrials (such as GE and Siemens), whose R&D budgets are particularly hard to disentangle and allocate at national level. Also, the indicator is biased against industries that rely on innovation methods other than R&D (Hirsch-Kreinsen et al. 2003). As argued by Rosenberg (1982; 1976), relatively small-scale changes in product performance can be as important for long-term innovation as the development of radical novelties, but are not necessarily related to explicit R&D expenditures. In particular, there may be a systematic undercounting of innovation activities in small firms (Kleinknecht et al. 2002).

To account for inter-industry flows of innovations, a modification of the R&D indicator includes "acquired technology": based on input-output tables, R&D embodied in capital and intermediate goods used in industry is calculated (Smith 2005). It is assumed that

[36] The "Frascati Manual: Proposed Standard Practice for Surveys on Research and Experimental Development", see OECD (2002) for the most recent version.

embodied R&D equals the capital good's value multiplied by the supplying industry's R&D intensity.

For energy technology innovation, macroeconomic statistics do not normally report specific relevant RD&D data (Dooley 2000). Grubler et al. (2012) review the availability of data sources. Energy and technology-specific RD&D expenditures are available for public sector spending in IEA member countries (IEA 2016), but "extremely fragmented and sparse" for non-IEA countries such as China and India, as well as private sector activities. According to their estimations, the IEA public sector data only cover around 25% of global energy-related RD&D.

Data is even scarcer on investments into market-formation and diffusion, such as feed-in tariffs, tax credits and public procurement: many transactions are unreported, existing measurements not harmonized, and attempts to track such investments are relatively recent (Grubler et al. 2012). While investments into energy-supply diffusion are estimated by means of modelling and surveys, data on investments in energy end-use is almost entirely lacking.

Another frequently used indicator for measuring the inputs into research activities is *Human Resources,* which can be used as a proxy for "tacit" knowledge embodied in labour - resulting from education, training, and learning from past innovative efforts (Gallagher et al. 2006). In its simplest form, the indicator can be constructed as the number of scientists and engineers engaged in R&D activities (in aggregate, by sector, per capita). To account for different productivities of human resources, it can be weighted by the type of education or training obtained by individual R&D workers. However, this is only a very rough approximation. The indicator does neither capture the true quality or efficiency of R&D labour, nor differences in research infrastructure and capital equipment. These drawbacks make it particularly hard to compare research activities between countries, which may widely differ with regard to labour costs and available research infrastructure. Furthermore, it is difficult to differentiate which scientists and engineers should be counted towards a specific research domain, such as energy innovation.

### B.4 Output indicators for energy innovation

Indicators of the *output* dimension aim to describe defined products of the innovation process - the most common ones being *publications, patents, technologies* and *technology characteristics*. While the metrics *technologies* and *technology characteristics* are more technology-specific and can capture specialised innovation attributes of interest (such as improvements in energy efficiency), the more abstract nature of *publications* and *patents* allows for a (challenging) sector-wide or economy-wide aggregation.

Particularly popular for empirical studies of innovation systems are *patents* (filed, granted or cited), which are used as a proxy for knowledge codification (Wilson 2014). As with R&D, one reason is the comparably good availability of patent data: technological information on inventions is continuously stored in public and freely available records, using a detailed and slow-to-change classification system (Smith 2005). Since many patent systems cover several centuries, the data offers unique time-series of innovative activity, which can be used to quantitatively analyse even long periods. Furthermore, citations within patents allow linking them to each other, as well as to academic publications. Major sources are the European Patent Office and the US Patent Office.

However, the patent metric mainly captures inventions, and is blind to non-patented technological change (Nagaoka et al. 2010). The information in patent databases largely depends on incentives to file a patent, which may be unrelated to innovative technological characteristics. As argued by Hall and Ziedonis (2001), increased patenting activities (such as in the 1990s) may as well be related to reduced patent costs or strategic firm behaviour (e.g. filing patents not to use them, but to exclude competitors from a market). Furthermore, preferences for patenting differ between economic sector as well as countries, and are shaped by economic incentives as well as cultural and institutional factors (Gallagher et al. 2006).

Both *Patents* and *Publications* are at the heart of bibliometrics, which is the statistical analysis of the composition and dynamics of scientific publications (for reviews, see Moed et al. 1995; Okubo 1997). Based on articles, patents and the citations therein, a measure of output can be constructed for individual researchers, research teams, institutions, and countries. In their most basic form, such "productivity" indicators classify and sum up all *Patents* and *Publications* that were published by the unit of interest (e.g. an academic or a R&D department). With regard to the dynamics within science and innovation, the analysis of citation indexes and co-citations can help to identify research networks (nationally and internationally), and give insight into the development of and linkages between new fields of research.

*Technologies* as an output indicator aims to quantify the number of technologies that were commercialised - for example the number of product variants or process improvements that resulted from a specific research process. Although it is surely the most visible measure of ultimately successful innovation, it often proves difficult to implement. Many new technologies are not well defined and hardly separable (particularly for complex multicomponent systems), which constitutes an obstacle to counting and evaluating them. Furthermore, the indicator does not capture increases in learning and know-how for technologies based on tacit or non-codified knowledge.

If interested in specific technologies, *Technology Characteristics* can be a useful indicator for evaluating changes in particular functions that are performed by a technology, measured as the ratios of technical to service characteristics. For example, innovation in the development of new electric motors can be evaluated by comparing the energy efficiency of different motor versions. While useful for analysis on the technology level, *Technology Characteristics* are mostly too specific for the purpose of meta-analysis.

### B.5 Outcome indicators for energy innovation

*Outcome* metrics aim to describe the broader energy sector or economy-wide impacts of the successful diffusion of innovations into the marketplace. *Market penetration* and *learning rates* quantify how an innovation's uptake and relative economic advantage changes within the energy system (e.g. falling costs, as captured by *learning rates*). *Economic benefits* and *Energy/emissions intensity* are attempts to quantify how an innovation's diffusion may impact the wider economy (e.g. carbon emission reductions or jobs created), by setting it into relation to different kinds of economic data (such as economy-wide energy use or the change in environmental indicators).

Of particular relevance for models of energy technology innovation are *learning rates*, usually expressed as the percentage reduction in unit costs per doubling of cumulative production. By linking innovation inputs (learning as a result of increased use and production) to outputs (cost reduction), they can be used to assess the overall performance and (at least some) dynamics of the innovation system (Wilson 2014). As with R&D and patents, their popularity is partly owed to data: necessary information on production and costs are generally available, and have been extensively used to construct learning curves for various energy technologies (Grübler et al. 1999).

However, it is not always clear which underlying processes are responsible for empirically observed cost reductions. It can therefore be problematic to separate learning from exogenous technological change in a theoretically sound way, which could overestimate the effect of increasing returns to scale (Nordhaus 2009). Furthermore, learning rates can suffer from data fitting issues (Nemet 2009).

*Economic benefits* are of large interest for policy analysis, but in many cases challenging to measure. While costs can often be quantified in relatively straightforward ways, the estimation of benefits largely relies on indirect estimations (e.g. by means of regression analysis). Besides direct economic effects, benefits may include environmental, national security, option value (of new technologies available for commercialization) or knowledge benefits (such as spill-overs to other sectors and countries, Gallagher et al. 2006). Additional complications arise when estimated benefits (such as reduced pollution) have to be converted into monetary units, for example as part of a cost-benefit analysis.

*Energy/emissions intensity* can be a useful metric to estimate the aggregate impact of energy-efficiency technologies (on *energy intensity*, e.g. energy use/GDP) or low-carbon energy-supply technologies (on *emissions intensity*, e.g. carbon emissions/GDP). While necessary data is readily available, such metrics can only approximate the aggregate effects of energy technologies (e.g. all energy-efficiency technologies). Empirical estimations are likely to be cofounded by external factors, such as structural changes in the economy. For similar reasons, it is usually not possible to disentangle the data in a way that allows clearly identifying relative impacts of individual innovations (Gallagher et al. 2006).

### B.6 Limitations of energy innovation indicators

**Mechanistic concept:** it should be noted that the categorization of indicators into input, output and outcome is purely instrumental, and does not imply that innovation indeed resembles such a clear-cut linear process. As discussed within the context of innovation systems, interrelations along the innovation chain are multi-fold as well as multi-directional. While possible, correlations between *inputs* and *outputs* or *outcomes* do not necessarily point towards causation. Furthermore, any indicator may be subject to "Goodhart’s law": once made a policy target, it could lose most of its original meaning (Freeman & Soete 2009). Policies specifically aimed at an innovation indicator face the risk of artificially inflating it without impacting the true process characteristic, of which the indicator is only an empirical proxy.

**Unclear system boundaries:** with regard to energy innovation, it is often unclear what should count as energy-relevant research and innovations (Sagar & Holdren 2002). It includes basic research (such as on turbulence, which can later help to improve combustion engines), applied research (such as improved designs for fuel-efficient turbines) and development (such as production methods for lighter cars). Such system boundaries can be particularly hard to draw in the energy end-use sector. This difficulty in obtaining data and indicators may be one reason that many energy assessments focus on energy-supply innovations, and often leave aside end-use technologies (Wilson 2014).

**Lack of integrated metrics:** available indicators are confined to certain attributes of a technology, or certain phases of the innovation chain. There is no single indicator that represents the overall success of a technology. Reliably connecting inputs to outputs and outcomes is complicated by a mixed involvement of both public and private resources, combined with undefined time lags between an entire set of interlinked processes. While learning rates may be an exception by linking inputs to outputs, they are still restricted to the diffusion phase (Wilson 2014). Furthermore, many appropriate indicators for energy technology innovations tend to be technology specific, which complicates cross-technology comparisons.

**Underrepresentation of demonstration and deployment activities:** indicator use is largely determined by data availability, and suffers from a composition bias by focusing on easy to measure attributes - "the drunk searching for his missing keys under the lamp-post effect" (Freeman & Soete 2009). On the input side, this favours R&D, patents and early stage investments. As for outcomes, data availability is best for diffusion metrics (such as learning rates and market penetration). Resulting from a lack of data, the demonstration phase and early market deployment activities remain largely underrepresented from an indicator perspective, although they are highly important to overcome the "technology valley of death" between R&D and widespread technology diffusion (Gallagher et al. 2006).

# C. Barriers to innovation, supplementary information

## C.1 The climate finance landscape in Europe

### *The German Climate Finance Landscape*

The climate finance assessment in Germany reports that at least EUR 37 billion (or 1.5% of German GDP) was invested in 2010 to support the German transition to a low-carbon economy (CPI 2012). About half of this amount was supported by public banks (in particular KfW) via concessionary loans, and so the public sector played an important role in supporting private investments. About EUR 26,6 billion of total capital investment went into renewable energy generation, with households (37%), the financial sector (25%) and industry (16%) being the main investors. Among the key factors driving these climate-friendly investments are the significant public incentives, like the Feed-in Tariff (FiT) system in Germany, which paid approximately EUR 13.1 billion to households and corporate renewable energy generators in 2010.

### *The French Climate Finance Landscape*

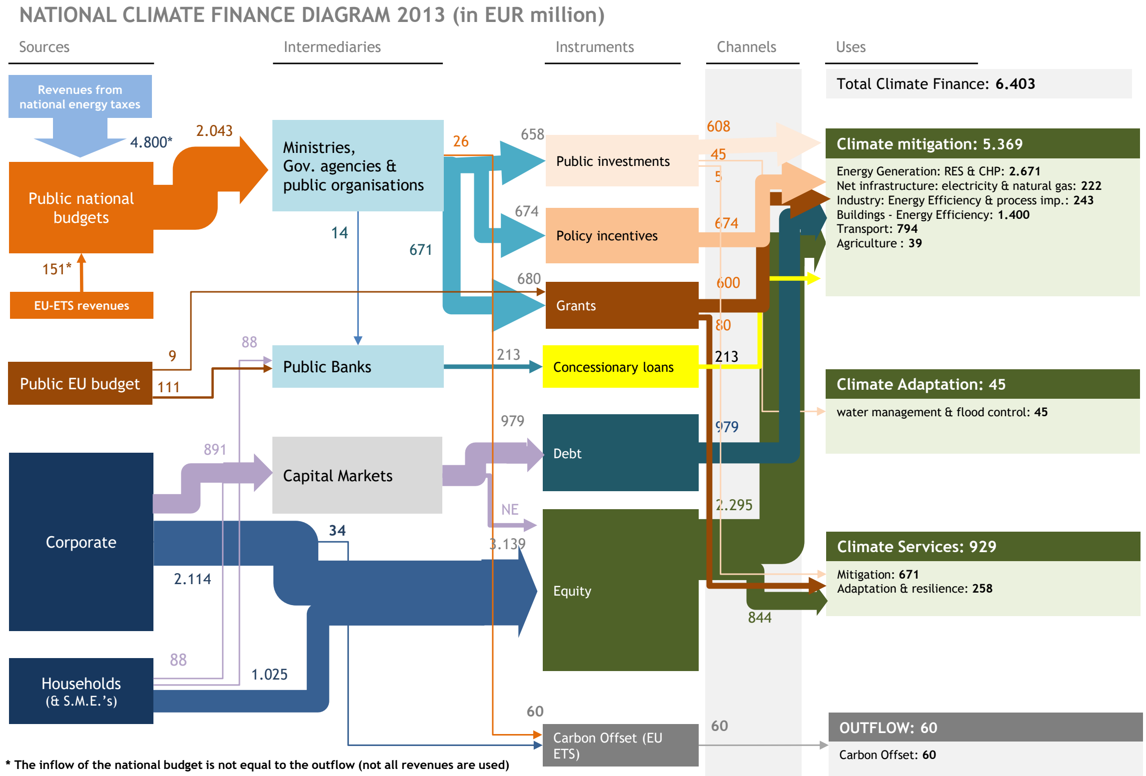
The climate finance assessment in France reports that up to EUR 36 billion of investment went into climate mitigation in 2013, of which EUR 17,6 billion was invested in energy efficiency, EUR 5,1 billion in renewable energies and EUR 12 billion in sustainable transport infrastructure (I4CE 2015). Moreover, EUR 1,4 billion was invested in new nuclear plants and GHG emission reductions from non-energy sources. As in Germany, households were the main investor category (EUR 13,6 billion, or 38% of investment) investing in the building sector. About 50% of the overall climate investments in 2013 (i.e. EUR 18,7 billion) were driven by the public sector, in particular via grants, subsidies and transfers (in total EUR 10 billion).

### *The Belgian Climate Finance Landscape*

After having identified all investment streams, an amount of EUR 6,4 billion was calculated in the climate finance assessment for Belgium in 2013, of which 84% (or EUR 5,4 billion) was used for climate mitigation purposes (Trinomics 2016). The remaining Belgian climate finance was used for climate services (15%) and climate adaptation (1%). The climate services are mainly (national) R&D programs and climate-related corporate services.

Climate mitigation efforts were made in the following sectors: renewable energies and CHP (54%), industry (4%), building sector (26%), sustainable transport (15%) and agriculture (1%). The main providers of climate finance in Belgium in 2013 were corporations (47%), public sector (including EU contributions; 34%), and households & SMEs (19%). The main instruments used for climate financing have been: equity (49%) and debt (16%) by private investors, grants (10%), public investments (10%) and policy incentives (11%). This is shown in Figure 6.

**Figure 6: The Belgian Climate Finance Landscape in 2013 (source: Trinomics 2016).**




### *The wider EU perspective*

Although the magnitude of climate-related investments, the sector focus, the use of instruments and the role of (semi-) public financial institutions are different between at least Germany, France and Belgium, the bulk of the clean energy technology investments are concentrated in the demonstration, commercialisation and up-scaling stages of the technology lifecycle, with only small percentages (and mainly public funding) being invested in research and development of new clean energy technologies. For example, in Belgium, R&D expenditures accounted for only around 2-3% of the climate-related investments. Hence, when it comes to financing the development of new clean energy technologies (as opposed to the take-up of technologies that have been brought to market), these investments are mainly funded by national and EU public budgets.

In order to support the research and innovation in Europe for a broad portfolio of clean energy technologies, the Commission has several instruments and programmes in place to support energy technology development. These are:

- **Horizon 2020:** under its challenge-based approach, Horizon 2020 includes the Energy Challenge - Secure, Clean and Efficient Energy, which is designed to support the transition to a reliable, sustainable and competitive energy system. The first work programme (2014-2015) was split into the following focus areas: energy efficiency, low-carbon technologies, and smart cities and communities;
- **Strategic Energy Technology (SET) Plan:** a strategic plan to accelerate the development and deployment of cost-effective low-carbon energy technologies. It proposes a new governance structure based on joint strategic planning which allows decision-makers in the Member States, industry, and the research and financial communities to jointly and strategically plan energy research and innovation efforts in alignment with EU energy policy goals;

- **New Entrants Reserve (NER300) programme:** aims to catalyse innovation and implementation of low-carbon technologies and is a funding programme for the demonstration of low-carbon technologies at commercial scale and innovative renewable energy technologies.

## D. Model characteristics

### D.1 The CGE model GEM-E3-FIT

GEM-E3-FIT[37] is a global, multi-region, recursive dynamic 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 and at each time step economies are found in equilibrium.

The model represents all major public finance aspects and it accounts for all substantial taxes, social policy subsidies, public expenditures and deficit financing. The model is dynamic as projections change over time. Model properties are manifested through stock and flow relationships, technical progress, capital accumulation and expectations of agents, which are modelled as myopic.

The regions of the model are linked through endogenous bilateral trade following the Armington specification. The labour market is modelled through a labour supply curve which allows for non-voluntary unemployment and flexibility in wages. The model is able to compare the welfare effects of various environmental instruments, such as carbon taxes, auctioning, various forms of pollution permits and command-and-control policy in the context of climate and energy policies. In GEM-E3-FIT it is possible to consider various ways of recycling of carbon revenues. The model includes a bottom-up representation of power generation technologies and it calculates endogenously the energy-related emissions of CO2 per economic sector.

Technical coefficients in production and demand are flexible. Production functions consider the use of intermediate products and three primary factors: capital, natural resources and labour. Production mix is flexible on the use of primary production factors and intermediate goods. Total demand (final and intermediate) is optimally allocated between domestic and imported goods which are treated as imperfect substitutes. Consumer demand is set endogenously and it distinguishes between durable and non-durable goods and services.

In GEM-E3-FIT the mix of factors in production, i.e. capital, labour, material and energy, and the mix of goods and services in consumption, are the result of substitutions driven by relative prices. Substitution possibilities in production sectors are captured with Constant Elasticity of Substitution (CES) functions, first proposed by Arrow et al. (Arrow et al. 1961) that follow a nested scheme, involving the various production factors. Substitution possibilities in consumption sectors are represented using a Stone-Geary utility function, also called a linear expenditure system, first proposed by Stone (Stone 1954).

The functional form of the model is determined by data availability and the theoretical context of model development. Exogenous parameters used include the Armington demand function elasticities, production substitution elasticities (substitution among production factors) and consumer preferences. Price and income elasticities in demand

[37] 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.

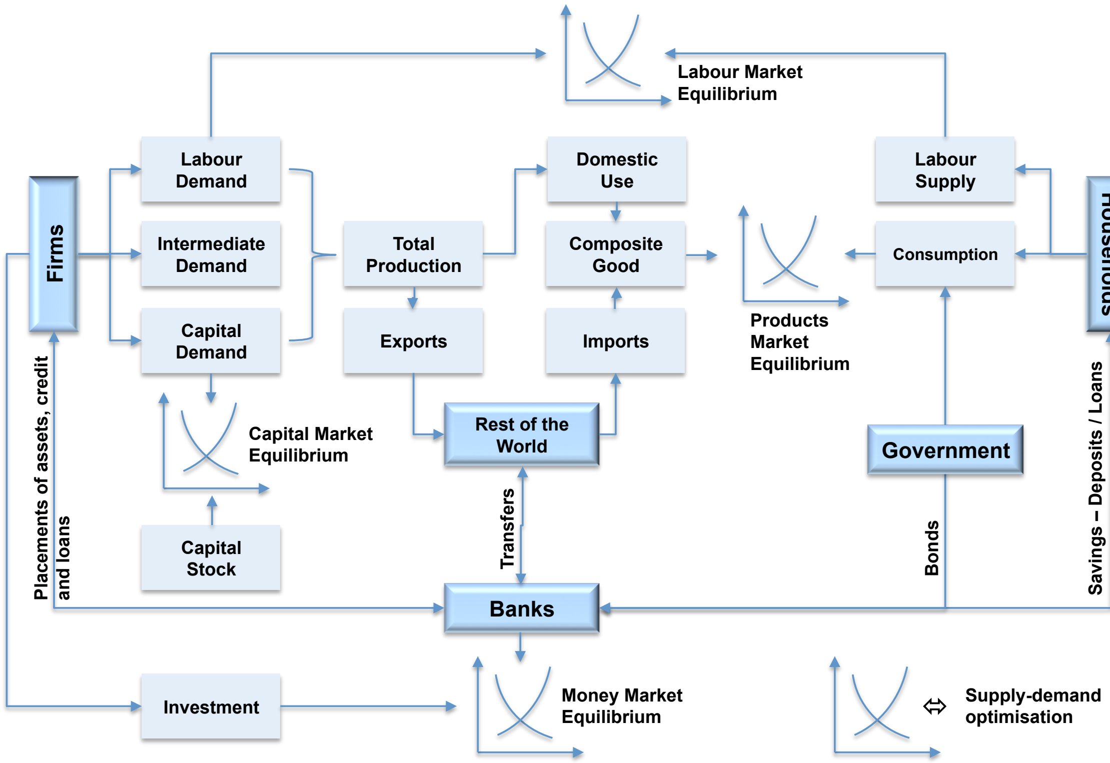



**Figure 7: GEM-E3-FIT economic circuit, circular flow of funds and market clearing. Supply demand intersection graphs indicate the operation of a price adjustment mechanism that is market clearing.**

of households for commodities are based on econometric estimations documented in the literature and are detailed in the technical documentation of the base GEM-E3 model (Capros et al. 2013).

The model does not produce forecasts as it makes use of exogenous assumptions on productivity and population. As it is usually the case with the CGE models, a baseline or reference scenario is modelled by dynamically calibrating projections to hypothetical trajectory aggregated figures of GDP, emissions, current account, consumption over investment ratios, etc. The model is calibrated on a base year data set of detailed Social Accounting Matrices for each country/region represented in the model. Bilateral trade flows are also calibrated for each sector represented in the model taking into account trade margins and transport costs. Representation of consumption and investment are based on consumption matrices linking consumption by purpose to demand for goods and investment matrices linking investment by origin to investment by destination respectively.

The model is calibrated to three base years i.e. 2004, 2007 and 2011, using the latest GTAP 9 dataset release, where each year reflects a different economic and trade structure and can be used alternatively. The calibration methodology ensures consistency between IO tables, energy volumes and GHG emissions. GHG emissions have been updated so as to match the latest inventories published by EUROSTAT and UNFCCC (2012 for most countries). The model runs yearly up to 2020 and then reaches 2050 in five year time steps.

### *Representation of the financial sector in GEM-E3-FIT*

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; given the finite nature and the full employment of capital resources increasing investment in one sector requires the decrease in others). Depending on the capital market clearing assumption, higher demand for investment will increase, sectoral, economy-wide or international interest rates. 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. In the light of these limitations it becomes evident that the explicit inclusion and representation of the financial sector in a CGE context can moderate the short-term stress on capital markets by allocating capital requirements over a longer period (long-term financing schemes/loans).

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. Model development draws on Bourguignon (Bourguignon et al. 1989; Capros & Karadeloglou 1991) and (Dixon & Rimmer 2014). A bank has been included in the model that collects the savings from the economic agents and it 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.

The money supply in GEM-E3-FIT can either be fixed with endogenously determined interest rates (money multiplier theory) or be adjustable (endogenous theory money) at a given interest rate (i.e. bank reserves adjust as needed to accommodate loan demand at prevailing interest rates). In the model the base year net lending/borrowing position of the agents is calculated in detail according to the institutional transactions (full sequence of National Accounts that include all secondary transactions like property income, income from deposits, and interest rate of all economies) that have been collected from EUROSTAT.

The net lending position of each economic agent has been built from bottom-up data (all sources of income including dividend payments, interest rates, debt payments, bond interest rates etc.). Data regarding the structure of the bilateral debt by agent (domestic-foreign) and country (who owes to whom) have been constructed according to current account and cumulative bilateral trade transactions.

Dynamically the net credit position of each agent depends on a number of endogenously determined variables like households' disposable income, firms' sales, consumption, saving and investment. The financial assets considered in the model include: Public Bonds, Corporate Bonds, Household Loans, Deposits and Time Deposits. The model is based on a matrix of flows of funds, involving, all economic agents (i.e. household, government, firms, banks and the foreign sector).

The financial behaviour of households is based on a portfolio model, which is derived by maximising expected utility. A household allocates its disposable income to consumption and financial assets on the basis of expected yields. Firms and the Public sector are represented only with respect to the financing of their deficit. Total public debt is updated dynamically by accumulating deficits. Public debt further influences interest rates and annuities which determine the net savings of the public sector.

The banking system, comprising the Central Bank, and private sectors, are represented following an "assets-liabilities balance" approach. On the assets side of the private sector, total wealth is evaluated, dynamically by private net savings, a variable coming from the real part of the model. Assets-liabilities balance in the banking sector serves to evaluate the capacity of banks to lend to the private sector.

Interest rates are derived from the equilibrium of financial supply and demand flows. The model determines endogenously two equilibrium prices:

i) Demand/supply equilibrium in financing public deficits serves to determine the rate of interest of government lending, i.e. interest rates of bonds

ii) Demand/supply equilibrium of the capital flows addressed to the private sector serves to determine the private lending interest rate

Inclusion of the financial sector in the GEM-E3-FIT model improves model capabilities with regard to:

- The creation of payback schedules that span over many periods and countries moderating considerably the crowding out effect
- Book keeping of stock/flow relationships of debt accounting (domestic and external Private and Public debt)
- Endogenous computation of interest rates for alternative uses of financial resources (deposits, bonds, household and business financing, etc.)
- Income availability by sector is adjustable depending on borrowing behaviour
- Lending capabilities depend on accumulated debt and on leverage assumptions. Thus demand and supply of money/deposits, bonds and securities determine interest rates
- Financing options that include: i) own financing from savings and/or lower consumption, ii) borrowing from domestic or international agents (domestic or/and from abroad), or iii) a combination of own financing and borrowing.

***Representation of technical progress in GEM-E3-FIT***

GEM-E3-FIT allows for the detailed representation of endogenous innovation and technological change, while maintaining all the features of a large-scale CGE model. The approach adopted draws on the endogenous growth theory developed in Romer (Romer 1990), Aghion and Howitt (Aghion et al. 1998) and Acemoglu (Acemoglu 1998; Acemoglu 2002). Technological change is modelled as productivity improvement by production factor and/or as total factor productivity in the production of goods, resulting from R&D spending. The model includes a discrete R&D supply sector that undertakes and provides R&D services. Spending in R&D is carried out by both the public and the private sector.

The output production function adopted in the GEM-E3-FIT model is the standard KLEM production function extended to account for the impacts of endogenous technology innovation. A discrete R&D sector is modelled in order to produce innovation for each activity included in the model. R&D expenditures by sector are translated into innovation that is associated with both spillover and fishing out effects. International spillover effects are captured through endogenous bilateral trade flows.

Investments in R&D, technological change and innovation lower the cost of clean energy technologies, especially of those technologies being at early stages of development and commercial uptake (i.e. electric vehicles, carbon capture and storage, renewables and novel appliances) as they improve sectoral total factor productivity. $CO_2$ emission costs, due to carbon pricing (resulting from markets for emission allowances, such as the EU ETS) lead the increase in R&D spending, which in turn enables productivity gains in the production of clean technologies and alternative fuels. Also, high fossil fuel prices imply substitutions towards clean fuels and technologies but also higher spending in R&D to mitigate costs. Higher R&D spending induces productivity gains along the learning potential curves, which exhibit diminishing returns to scale. The gains take place primarily in the region or the country pursuing carbon pricing. Gains are also “spilled over” at a certain degree in other regions, which do not pursue carbon pricing, as a result of technology diffusion, assumed to take place in addition to equipment trading.

In GEM-E3-FIT, firms decide on the input mix to production that includes capital, labour, energy, materials and R&D simultaneously. Firms' expenditures on R&D are modelled as firms' R&D demand for services addressed to the R&D supply sector. Improved productivity as a result of R&D expenditures imply lower factor prices and/or higher quality and lower prices of products. This further implies higher demand for the improved factors and products. Therefore, R&D induces higher demand and lower prices for the targeted products. This is a learning-by-doing process, which numerically in the model is calibrated to follow learning-by-doing potential curves specified for each type of advanced technology or alternative fuel.

Firms' R&D expenditures do not alter their production capabilities (this is the result of investments in capital) but they impact on product quality (improves) and production costs (lower). Quality improvements and cost reductions improve the market prospects and induce higher investments in the long term (higher quality and lower costs imply better possibilities to use the limited resources of the economy in the short term, and increase investment in the long term).

### D.2 The macroeconometric-diffusion model E3ME-FTT

E3ME is a macroeconometric model that derives aggregate economic behaviour in many sectors (69/43), countries (59), fuel users (22) and fuels (12), using regressions carried out on yearly data going back to 1971, and projects the global economy until 2050. It is based on around 20 regressed equations governing various areas (the energy sector, prices, investment, output, employment, etc).

E3ME can be used to explore the impacts of policies, typically by exploring differences to a baseline, itself harmonised to that of other models (GEM-E3, PRIMES) for comparability. E3ME is broadly consistent with Post-Keynesian and Post-Schumpeterian theory in its structure; however, it does not have explicit representation of the financial sector, and credit creation is implicit.

The bottom-up component FTT (Future Technology Transformations) is a technology diffusion model that explores specific sectors of application for energy or climate policy, currently including the power and personal transport sectors, while it will include a representation of land-use in the near future. FTT is a diffusion model that scales bounded rational decisions by heterogeneous agents on investment choices to the macro level of E3ME. Its decision-making basis makes it appropriate to explore the impacts of technology specific (market-pull) policies. The model is dynamically integrated to E3ME (sharing the same computer code).

The impacts of climate policy instruments in the model are depicted in Figure 8. Here, technology-specific policies are chosen and implemented in FTT, which influences the uptake of power technologies, and the model projects technology diffusion with learning-by-doing. The resulting S-shaped diffusion curves have timescales parameterised by a combination of policy-influenced technology preferences, lifetimes and deployment times.

The dynamical integration of FTT to E3ME is done through four variables: (1) the price of electricity, which is influenced by the cost of generation, (2) investment, which creates employment and income, (3) government policies including the price and income from the sale of emissions permits and (4) fuel use (incl. imports/exports).

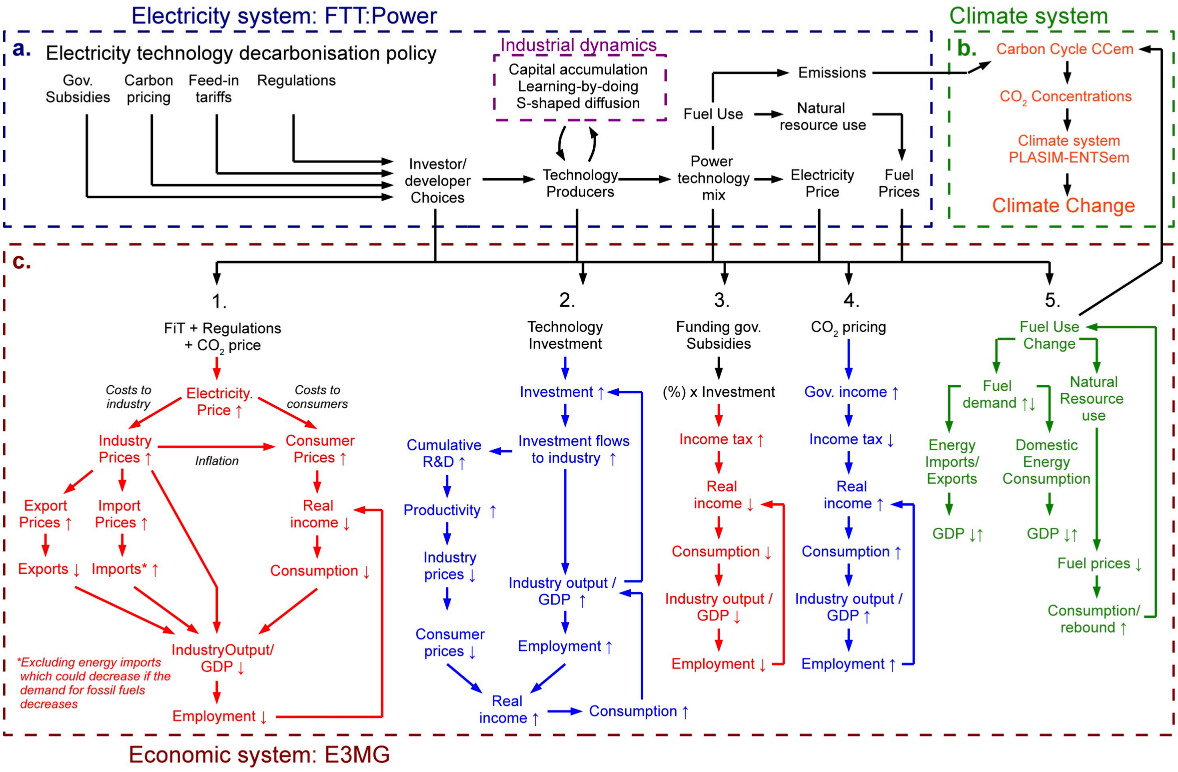



**Figure 8: Flows of information and causation in the macroeconometric-diffusion model E3ME-FTT.**

Increases in (1) stems from higher levelised costs involved with renewables, and is detrimental to the economy as it reduces the competitiveness of electricity intensive sectors (in a vicious cycle from reduced income to reduced employment). When new generators are built, the investment implicitly assumes a creditor institution, and thus private debt increases; the higher price of electricity is representative of the presence of implicit finance, since loans are repaid during the lifetime of these assets, i.e. debt is paid by selling more expensive electricity. Increases in (2) implies increasing debt which creates employment and income in all sectors involved in the construction of new assets (in a virtuous cycle), connected by input-output tables. This takes place in the first few years of the lifetime of assets. Increases in (3) implies either government expenditure or income. The latter can be very large with the sale of emissions permits if the price is high (e.g. 100€/t$CO_2$ means around €0.4tr per year in Europe). Recycling this income to reduce income tax can significantly increase income. Changes in (5) can make winners (low-carbon industry) and losers (fossil fuel industry) within nations; however in general, reducing expensive fossil fuel imports in Europe tends to increase income.

The overall impact of policies for a sustainability transition in E3ME-FTT can either be beneficial or detrimental, depending on geography and context (Lee et al. 2015; Mercure et al. 2016; Barker et al. 2015; Ekins et al. 2011). While the balance of these effects is different in every country, they tend to be changes in GDP from the baseline within the bounds of ±1-2%.