The links between the energy transition and economic growth

E3Modelling & Cambridge Econometrics
June 2022

Authors:

Kostas Fragkiadakis, Dimitris Fragkiadakis, Panagiotis Fragkos, Leonidas Paroussos (E3Modelling)

João Gorenstein Dedecca, Liliana Guevara Opinska, Foivos Petsinaris (Trinomics)

Boglarka Molnar, Richard Lewney, Bence Kiss-Dobronyi (Cambridge Econometrics)

EUROPEAN COMMISSION

Directorate-General for Energy
Directorate A — Energy policy: Strategy and Coordination
Unit A.4 — Chief Economist Unit

Contact: Energy Modelling Team

E-mail: ENER-A4-MODELLING-TEAM@ec.europa.eu

European Commission
B-1049 Brussels

The links between the energy transition and economic growth

Manuscript completed in March 2022

LEGAL NOTICE

This document has been prepared for the European Commission however it reflects the views only of the authors, and the European Commission is not liable for any consequence stemming from the reuse of this publication. More information on the European Union is available on the Internet (http://www.europa.eu).

PDF	ISBN 978-92-76-52355-0	doi 10.2833/770957	MJ-07-22-268-EN-N

Luxembourg: Publications Office of the European Union, 2022

Table of Contents

Executive Summary

The objective of this report is to identify the channels through which energy promotes economic growth. The different channels through which energy impacts growth are assessed according to the findings of the relevant literature and to case studies on technology transitions as well as scenarios on energy transition. The review seeks to identify gaps between current and desired modelling features in GEM-E3-FIT and E3ME.

Technical change and the low-carbon energy transition

The low-carbon energy transition requires a major wave of technological and social innovations, with interdependent changes in multiple areas. The change from cheap fossil energy sources to renewable energy sources will impact GDP and welfare, in many different channels most of which models with detailed treatment of the energy system, like E3ME and GEM-E3-FIT, already capture.

The high financial cost of the enegy transition is only a part of the trasnformation process of the energy system. First, the falling cost of low-carbon technologies and increased adoption reinforce each other. Second, the energy transition is characterized by high uncertainty and imperfect information, affecting the decision making of private actors and requiring strong political commitment to minimize negative economic consequences. Third, energy innovation efforts have cross-sectoral and international spillover effects which reduce the cost of the transition (although this effect may be dampened) and may give (or not) first-mover advantages to certain countries.

In order to support and provide guidance to public and private actors, it is necessary to achieve a balanced representation of the energy-growth nexus (including innovation) through a number of modelling approaches. This will allow a robust analytical support for achieving the EU energy, climate and economic objectives.

Theoretical and applied analysis of the energy transition, growth and modelling

The approaches to model the macroeconomy fall under two broad paradigms. The equilibrium/optimisation paradigm, which is closely tied to the neoclassical school, and the non-equilibrium/simulation paradigm, which encompasses the (neo)-Keynesian and (neo)-Schumpeterian schools. The review of key schools of economic thought, modelling paradigms, innovation aspects and the relationship between energy and growth conducted in the first part of the study highlights that:

- The role of energy and exhaustible resources in promoting growth is gaining importance. All schools of economic thought concur that technical change is an important driver of economic growth. Economic thinking differs the main factors affecting growth and the main incentives to innovation.
- The main differences between macroeconometric and CGE models regard the capacity utilisation of production factors, the drivers of growth, the representation of money supply and the role of investments crowding out. These lead to different outcomes under certain conditions, and thus the models are not only relevant for different economic structures and stages of economic development, but also complementary for supporting policy making.

- Among the main drivers of innovation are supply push and demand pull mechanisms. Policy can affect both supply push and demand pull and thus have a significant impact on driving innovation and technological change. Characteristics of innovation include diffusion, increasing returns, learning effects, uncertainty and path dependence, human capital, bounded rationality and knowledge diffusion.
- Energy indirectly affects growth and is affected by it through the several interactions with other determinants of growth, such as human capital, trade openness, and infrastructure. Based on this analysis it is possible to conclude that energy has an influence on economic growth through a number of direct and indirect channels, including energy efficiency.

The review of six technology transition case studies indicates that:

- The **case studies chosen illustrate technology development at different stages**. Two distinct outcomes for historical energy transitions can be identified for innovations which have been successful, or which have not (yet) achieved substantial market penetration despite technological maturity.
- For all six case studies, **policy and a combination of supply push and demand pull drivers have played an important role**. A combination of both types of driver seems to be optimal. Whereas economic drivers are often the underlying basis for technology development, other important drivers identified include technical, environmental and social ones.
- Innovation can arise at different speeds and in different forms with **incremental innovation being the most frequent type observed** in the case studies. Several innovation characteristics are identified in different degrees and forms, such as **increasing returns, learning effects and both purposeful and unintentional knowledge diffusion**.
- From the case studies, **the impact of the energy technologies on the macroeconomy as an economic activity is most visible**, while most reviewed technologies have not yet been able to systematically reduce the energy cost (except CCGTs). Of the unconventional roles, the impact on technical change, climate change, infrastructure and energy quality and development stages are most apparent.

The review of nine energy-economy-environment models (with a focus on macroeconomic ones) and of different energy transition scenarios highlights that:

- Following the overall trend towards combinations of models and the quest to a more detailed representation of the energy system, **many of the integrated assessment or macroeconomic models analysed are hybrid**, incorporating an energy systems submodule.
- **Main interaction mechanisms between energy and growth** can be identified, but no model represents them all. Mechanisms include the substitution between production inputs, endogenous innovation in energy technologies, available productive slack in the economy, the costs of climate action and climate damages, changes in household preferences, changes in wages (and their cross-sectoral effects), and investment in energy technologies.
- Which interaction mechanisms between energy and growth are represented (and how) directly influence the possibility for decoupling between growth and energy consumption or GHG emissions. Generally, given the use of limited substitutability between energy with capital and labour, **decoupling from GHG emissions (due**

to reduced fossil fuel consumption) is more frequently achievable in the models than from overall energy consumption.

- Generally, **energy efficiency, deployment of renewable energy and structural change of the economy enable the decoupling from fossil energy consumption**, facilitated by knowledge stocks and spillovers when represented in the models.
- The **models generally represent both supply push and demand pull drivers, incremental innovation and learning effects**, while there is less representation of human capital, radical innovation and increasing returns (on the contrary, decreasing returns are frequently modelled representing resource constraints).

This section identifies the central aspects in technology transitions and economic growth that ideally should be addressed in GEM-E3-FIT and E3ME. It follows the most important aspects as identified in the case studies, which are discussed in section 3.2.

Representing the **impacts of energy on growth or the reverse** is a challenge for macroeconomic models in general. Not all mechanisms have the same strength, or may conflict with the premises of a given economic school. Moreover, the unconventional channels discussed in section 2.3 are highly complex. The main aspects to consider are:

- The existence and intersectoral influence of labour and capital markets, and the possibility for under-utilization of production capacities. These aspects may be intrinsically connected to a certain modelling paradigm, but can still be implemented in others through various approaches.
- The substitutability between production inputs, which strongly influences decoupling possibilities, and will vary between the different energy inputs, capital, labour, and energy efficiency measures.
- The impact of energy technologies on technical change should be represented in the model, such as how the competition between energy technologies on economic, technical and environmental grounds influences technical change and hence growth. But there are also potential technology-specific complementarities such as between autonomous and fuel cell or battery electric vehicles.
- The feedback of climate change on the energy system was not observed in the case studies. Some models did represent it in a simplified form. Nonetheless, clearly private decisions are being currently affected by climate change due to individual considerations and public policy, and the impact of the energy system on climate will feed back to the energy system in the long run.

The energy technology transition case studies additionally identify the **most important innovation aspects** being the interaction of the supply push and demand pull drivers, the role of policy, the existence of increasing or decreasing returns, the relevance (and complexity) of learning effects, the importance of human capital and finally also of knowledge diffusion.

Bridging the gap: addressing remaining relevant aspects in GEM-E3-FIT and E3ME

Drawing on best practices from the models reviewed

The following best practices should be considered for GEM-E3-FIT and/or E3ME, taking into account the limitations imposed by the modelling paradigms, data availability and other practical considerations:

- **Costs of climate action and net climate damages(E3ME):** consider ways of internalizing climate damages. As macroeconomic models, if not coupled to integrated assessment models, GEM-E3-FIT and E3ME do not consider the feedback effect of climate change on the economy.
- **Public support to supply push(E3ME):** implement synergies produced by coordinated policies that promote R&D, investment, production and adoption of low-carbon technologies; develop endogenous public R&D which considers these policy synergies and defines priorities and allocates resources (e.g. R&D funds) across sectors; model targeted subsidies that increase the levels of private R&D (that is, leveraging);
- **Radical innovations (GEM-E3-FIT and E3ME):** represent backstop technologies/sectors and stochastic entrance of these in the economy, including the non-economic demand pull drivers (technical, environmental, social) which lead to increasing development and adoption despite an initial lack of economic competitiveness;
- **Learning effects (GEM-E3-FIT):** use more sophisticated learning curves, such as multi-factor curves highlighting learning-by-doing, learning-by-researching, and/or intersectoral spillovers, noting their different underlying drivers and implications for European low-carbon industrial strategy. There is also room for separation of the scope of the cumulative capacities used in the learning curves between the global and the regional levels as applicable (including lags);
- **Human capital (GEM-E3-FIT):** separate human capital stocks in general skills applicable to multiple sectors, and sector-specific skills. This includes considering the representation of the R&D sector, which requires highly-skilled workers with possibly limited skill transferability to and from industry;
- **Knowledge diffusion (GEM-E3-FIT and E3ME):** consider the relevant channels of knowledge diffusion (e.g. within industrial conglomerates, technology licensing and company acquisitions) which can vary per sector and which may not be accurately proxied by a single indicator such as bilateral imports or patent citation data. Include also time lags for interregional spillovers.

Improving GEM-E3-FIT and E3ME beyond identified modelling best practices

Although the models reviewed provide important improvement avenues, further advances can be made by novel approaches and drawing from other models not covered in this report:

- **Substitution between production inputs:** Consider the inclusion of endogenous energy efficiency measures, and comparing with other models the parameters determining the substitutability between specific energy inputs and with capital, labour and materials. The capacity of energy efficiency measures to reduce energy demand and hence substitute energy inputs is already addressed in both GEM-E3-FIT and E3ME;
- **Finance and crowding-out of investments:** Investigate the more detailed representation of financing conditions for specific energy technologies. This is one of the objectives of the ‘Representation and implications of the financing challenge’

task of the present project. Both GEM-E3-FIT and E3ME are able to represent the creation of money and thus the (partial) mitigation of the crowding out effect;

- **Intersectoral R&D supply push:** Represent investments by industrial conglomerates and cross-sector investments, such as digital technology or oil & gas companies investing in low-carbon technologies. This can be implemented by consideration of intersectoral variables for determining R&D expenditures, such as activity levels from other sectors;
- **National policy:** Implement coordination of national policies in multiple innovation aspects including supply push, demand pull (with support to investment, production and/or consumption), infrastructure and knowledge transfer, and the synergies between them. This could be done through sectoral indexes reflecting policy priorities and influencing public variables across these dimensions.

The recommendations addressed so far concern the development of model capabilities for the endogenous representation of various aspects. However, alternative strategies leveraging the model inputs (such as through scenarios) can provide important policy insights into the macroeconomic impacts of the energy transition. The use of coherently-designed scenarios applies especially to two challenging topics:

- **Uncertain radical innovations or group of innovations,** impacting multiple sectors through conventional and unconventional channels, for example the development of electric, connected and autonomous vehicles.
- **Coordinated national policy** given the challenges of adequately representing them across the various aspects necessary to innovation and industrial development in a country, such as knowledge transfer initiatives, guidance (e.g. through targets), and support to R&D, investments, production and demand.

Overall, addressing the various recommendations identified is challenging, requiring the selection of the best approach, either endogenously in the models, or exogenously. Nonetheless, the review conducted confirms that to an important extent the models are already capable of providing relevant insights into the macroeconomics of the energy transition, especially when complementary modelling approaches are employed for the same policy question.

Introduction

The main objective of this report is to review the channels through which energy promotes (and is affected by) economic growth. A second objective is to analyse how growth is driven by energy-induced technical change. The different channels through which energy impacts growth are assessed according to the findings of the relevant literature and to case studies on technology transitions as well as scenarios on energy transition. The review seeks to identify gaps between current modelling features and desired modelling features in GEM-E3-FIT and E3ME.

The energy transition and the Energy Union

The low-carbon energy transition will involve substantial further innovation to develop and lower the cost of a wide range of key technologies for renewable electricity, low-carbon gases, energy storage, fuel cells, heat pumps, energy efficiency, low-carbon industry feedstocks, and possibly carbon capture, utilization or storage (CCU/S) and nuclear electricity. The transition will also involve the development of supporting network infrastructures (primary and secodary) for various energy carriers. Moreover, increased system flexibility will be required, including through the coupling of electricity, gas and heat systems.

A major programme of refurbishment or rebuild of the housing stock and the stock of industrial and commercial buildings will also be required. This may not involve much technological innovation, other than improvements in e.g. heat pumps, but it is likely to involve policy innovation to establish the regulatory framework and incentives for action.

Moreover, because the transition involves the substitution of capital for fossil energy, it requires a shift towards more up-front capital spending in return for lower operating costs. This, in turn, requires an effective market for project and consumer finance for firms and households, and new business models for the delivery of energy and mobility services. It will also require changes in consumer lifestyles and behaviour.

The cost of the energy transition

In summary, the transition requires a major wave of technological and social innovations, with interpendent changes in various areas. One view of the future regards the transition as a shift from an economy reliant on low-cost fossil fuels to one reliant on higher-cost renewables (or CCU/S) alternatives. Technological and behavioural change come about in response to policies that raise the cost of carbon in some markets and regulate to prevent or limit the use of fossil fuels in others; those changes in effect allow for selecting from a range of possibilities that are already well-known but not previously attractive given existing and expected fuel and technology costs. The economic impacts of this future are:

- to raise the price of energy to all users, with the higher cost ultimately paid by final consumers for products according to their direct and indirect energy content;
- to require firms and households to choose more expensive options for energy-using applications (for example, heat pumps instead of natural gas boilers);
- to change the structure of the economy away from extraction and processing of fossil fuels to low-carbon products, services and associated capital;

- to increase investment in energy production and use during the transition (because the low-carbon technologies are more capital-intensive); possibly diverting (or not) investment from other projects or curbing consumption spending.

The net effect of these impacts may be to reduce GDP and welfare compared with a future in which cheap fossil fuels continue to be used[1]: in this view of the world, in which actors have the information and are able to make choices optimised over a long time horizon, the intervention to cut out the use of fossil fuels forces firms and households to make second-best choices. For economies that are net importers of fossil fuels and which are not capacity-constrained, there may be offsetting impacts from the substitution of domestic production of the new technologies for imported fuels.

Potential factors affecting the cost of the energy transition

Macroeconomic models with a detailed treatment of energy products, like E3ME and GEM-E3-FIT, already capture these cost impacts of the energy transition well. But this high cost future is unlikely to be the whole story.

First, the cost of the key technologies will fall, albeit at an uncertain rate of decline, as the demand for them grows, due to economies of scale, more learning-by-doing and R&D efforts. Lower costs then drive faster take-up, producing a virtuous cycle (as seen, for example, in solar PV). This kind of innovation is well captured in E3ME and GEM-E3-FIT (and other models) through the use of learning curves for each technology, which relate the cost of the technology to the cummulative production.

Second, there are economic consequences of the uncertainty and imperfect information that characterise the transition, particularly given that investors need to commit to investment in capital-intensive assets with a long life, while the viability of those investments depends upon sustained political commitment to decarbonisation policies across many countries. E3ME and GEM-E3-FIT rely on forward-looking calculations for the relative attractiveness of alternative power plant technologies discounted to net present values, but in reality the costs, prices and volume of sales that enter those calculations are not known with certainty. E3ME's treatment of power sector investment choices (FTT:Power) has an inertia property that penalises technologies with a low market share, to try and capture power companies' (and financial investors') reluctance to commit to less familiar technologies even if the net present value calculation favours them. GEM-E3-FIT's treatment of the power sector investment takes into account the risk premium of a project that is directly linked to the overall enabling conditions.

Third, the investment in knowledge production stimulated by the prospect of higher energy costs may have spillover effects both across countries and across sectors: production in one country can learn from the best-practice technology applied in leading countries, while sectors that use a related technology can gain from the technological advances in the sector driving innovation (as, for example, CCGT technology benefited from turbine developments in aerospace in the case study described in this report). Models that include explicit R&D spillover effects like E3ME and GEM-E3-FIT seek to capture this by gathering evidence of important channels of knowledge diffusion between countries and

---

[1] This assumes that the time horizon is limited to a period over which any climate damages are driven by past greenhouse gas emissions; otherwise the fossil-fuel future should include the impact of damages and the cost of adaptation measures.

between sectors through the use of patent citation data. This allows the models to explore questions of how quickly a country's first-mover advantage might be eroded (as innovation in the first mover spills over to other countries), and to extend the economy-wide impact beyond the sector that leads the innovation.

But it is possible that the spillover model parameters have the property that the impact is successively dampenened as it spreads from the leading sector, and so the models may not capture the dynamics of major historical innovations. Also. since the transition entails widespread technological and social innovation, this prompts the question as to whether both the transition costs and the cost reductions originating from innovation are well captured in macroeconomic models. Such wider innovation futures are notoriously difficult to predict, and entail limitations on what can be represented within the model. One way to address this difficulty would be to develop narrative scenarios describing illustrative examples of pervasive technological and social innovation in the transition and to represent those scenarios in the quantified modelling.

Representation of the interactions of the energy system with the economy

Therefore, in order to support and provide guidance to public and private actors, it is necessary to achieve a balance in the representation of the most important interactions of the energy system with the economy. This to provide an adequate assessment of the costs of the energy transition, the potential cost reductions arising from innovation and the impact on the quantity and quality of growth.

An adequate representation of the interactions will allow analytical support to be given especially to the dimensions of the Energy Union focused on the decarbonization of the EU economy, competitiveness, and the promotion of research, innovation and competitivenness. Hence, this report conducts a review of economic and innovation theory, technology transition case studies, models and scenarios both from a general and an EU perspective. The report makes recommendations for developments to GEM-E3-FIT and E3ME that would further improve the models' relevance for policy analysis to inform decisions on these Energy Union dimensions.

Structure of this report

The report is separated into the following sections, as illustrated in Figure 1:

Section 1 - Review of economic schools, modelling paradigms and aspects of innovation: First, the key macroeconomic schools of thought and the associated modelling paradigms are reviewed, analysing the consideration of energy and innovation within each school and paradigm as well the main determinants for the differences in model results. Finally, innovation aspects for the analysis are reviewed.

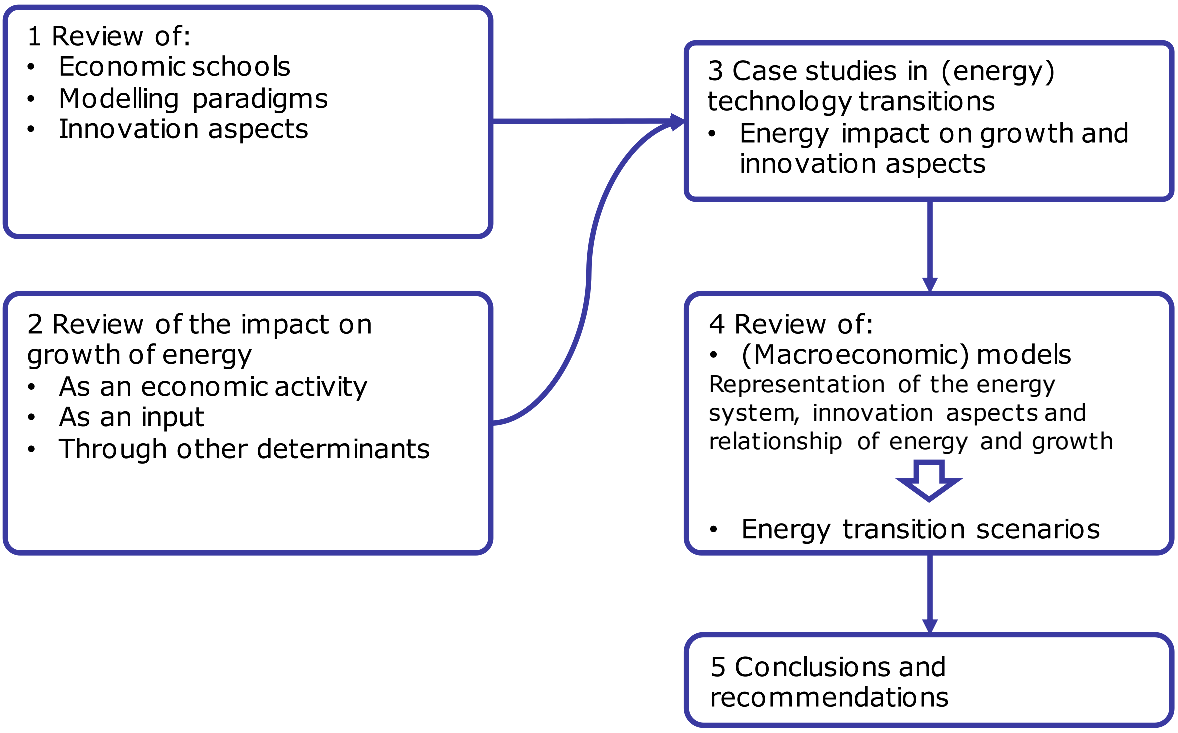
Section 2 - Review of energy as a factor of economic growth: The section presents the main channels through which energy can drive economic growth, addressing both conventional channels (energy as an economic activity and as an input) and unconventional channels (energy influence on other determinants of growth).

Section Error! Reference source not found. **- Case studies in (energy) technology t ransitions:** The section presents case studies on energy technology transitions selected according to their importance to central energy technology and industrial priorities of the EU. This serves to define which of the energy-growth interactions and innovation aspects can be observed in the technology transitions. This provides evidence of the relevance of the aspects identified in the theoretical review, which provides a prioritization of the aspects which are most important to be represented in the models and scenarios reviewed.

Section 4 - Models and scenarios for the energy- growth nexus: The section first reviews a select number of models representing different modelling paradigms (section 4.1). The section analyses how they represent the energy system and endogenous technical change, as well as the impact on economic growth. Second, a number of select energy transition scenarios are presented and reviewed. The scenarios chosen are based on the models covered and aim to illustrate the effect of different ways of modelling innovation and endogenous technical change on modelling outcomes.

Section 5 - Conclusions and recommendations: The section draws on the best approaches to modelling the impacts of energy on growth and innovation aspects identified, in order to provide recommendations to GEM-E3-FIT and E3ME.

Figure 1 Literature review on technology transitions and growth structure



1. Review of key economic schools, modelling paradigms, energy and innovation

The study of the key drivers of economic growth and technical change has long been a centrepiece of economics. In addition to that, the analysis of the relationship between energy supply and demand on one side and economic growth on the other has developed for several decades now, and is receiving increasing attention due to the need to decarbonize the global economy while maintaining growth. Economic activity has been one of the main drivers of greenhouse gas emissions, and its decarbonization has profound macroeconomic consequences.

Several drivers of growth have been identified in economic theory, such as technical change, population growth, trade or use of natural resources such as fossil fuels. Economic schools assign more importance to some of these drivers and growth dynamics through which they act, while paying less attention to others (or disregarding them entirely). As the main aspects identified in economic schools drive the modelling choices of macroeconomic models, this chapter focuses on how three main economic schools of thought have studied the relationship between the macroeconomy and energy production and use, and on the connection to the equilibrium and non-equilibrium modelling paradigms.

The chapter starts with a review of the basic theoretical foundations of each school (Section 1.1) together with their approach in integrating energy considerations. As technology is considered a main driving force of macroeconomic dynamics and a key factor in mitigating climate change, the role of technical change within each school is also examined. Subsequently, the main economic modelling approaches are presented distinguishing between the equilibrium and the non-equilibrium paradigms (Section 1.2). In the field of economic analysis of climate change and energy use policies, two macroeconomic models, one from the equilibrium tradition and the other from the non-equilibrium, have been very influential. These are the computable general equilibrium model, GEM-E3, and the macroeconometric model, E3ME, which are both reviewed in Section 1.3. Due to the importance of technological change for both economic growth and climate change mitigation, Section 1.4 presents a brief overview of the mainstream theories on innovation, adoption and diffusion of energy technology by presenting the different innovation taxonomies and concepts (such as learning effects, learning curves, path dependence and lock-in).

1.1. The key schools of economic thought, energy and technical change

In this subsection, three main schools of thought are reviewed in relation to their macroeconomic theory and their view on the role of energy and technological change in economic growth. The analysis starts with the neoclassical school, followed by the (post-)Keynesian and the (post-)Schumpeterian. Their main elements are summarized in Table 0-1.

Table 0-1 Summary of key elements of the three schools of economic thought

Paradigm	School of economic thought	Key theory elements	Energy-growth relationship
Equilibrium	Neoclassical	Supply-driven economy transformed over time through changes in technical progress, consumer preferences, capital accumulation, skills development and population. Agents optimise their behaviour. Their choices are taken subject to their preferences, production possibilities, resource availability and the structure of the economic system taking into account all interdependencies with the other agents. Changes in productivity are not for free and emerge due to spending on R&D, economies of scale, externalities, sector composition changes, adoption of cost-saving production methods. Multiple qualities (love-of-variety) and imperfect competition allows for the creation and existence of multiple firms that create monopoly rents. Investments in the economy are determined by the savings of the agents. In this sense the system is closed financially. Money supply is fixed and investment projects compete for predetermined levels of financing. Unemployment in capital and labour can be represented only if it is assigned to specific bottom up mechanisms (skills mismatching, minimum wages etc.). Imperfect competition, in a number of markets allows individual firms to acquire rents from newly discovered knowledge. Investment in R&D is determined by the expected returns.	Energy is considered an essential production factor part of the KLEM production functions but also is a resource and an economic activity that generates revenues. The impact on growth depends on the substitutability between energy and other inputs (mainly capital) The economics of exhaustible resources explores three mechanisms to compensate the depletion of exhaustible resources: substitution with reproducible capital, resource-enhancing technological change, and the resort to an alternative technology. Four hypotheses on energy-growth relationship have been empirically tested and confirmed in different studies: the growth, conservation, feedback and neutrality hypotheses.

Paradigm	School of economic thought	Key theory elements	Energy-growth relationship
Non-equilibrium	(Post-) Keynesian	Demand-led economy, which is inherently unstable and subject to shocks Risk and uncertainty play a key role Keynesian tradition fits better in examining short-term economic issues rather than long-term, such as economic growth. Aggregate demand is considered the driving force of economic growth. To endogenize technical change it is linked to capital accumulation.	Initially, the energy-growth relationship was hardly considered within this school of thought. The environmental equilibrium (EE) constraint into the standard IS-LM model recently integrates environmental considerations into the Keynesian macroeconomic framework. Recently, post-Keynesian research started looking at the effects of rising GHG levels on output and employment. Post-Keynesian theory has influenced the 'ecological macroeconomics' field, with commonalities such as the stresses on the non-substitutability of production inputs, the rejection of the utility maximization assumption, the importance attributed to the role of institutions, the fundamental uncertainty, and the existence of path-dependency.
Non-equilibrium	(Post-) Schumpeterian	Demand-led economy, which operates in a non-optimal way and changes perpetually in a dynamic way. Entrepreneurial ideas aim at improving a firm's productivity or lowering its production costs, securing temporary monopoly rents. Profit is what motivates both the entrepreneurs and the financial institutions that fund their innovative ideas. Innovation brings diversity of products, methods, and industrial organization among competing firms generates heterogeneous profit rates and productivity. Uncertainty and bounded rationality play a key role. Emphasises the role of institutions in macroeconomic growth. The quality of interactions between actors, networks and institutions determines whether innovative ideas will be brought into the market.	Energy did not play a role in the early Schumpeterian theory. Energy considerations were introduced by post-Schumpeterian schools, such as Evolutionary Economics, Innovation Systems perspective, and Technology Transition approach. Energy related research within the above-mentioned post-Schumpeterian schools involves analysis of energy systems, energy innovation, and energy transition policies.

The neoclassical school constitutes the mainstream school of thought. It is concerned with the optimization of the allocation of scarce resources among actors with the view to maximize their utility or profit. A central premise of the neoclassical school is that when prices are left to fully adjust and are not distorted, a given economic system will reach a state of general equilibrium where supply and demand is equal in all markets.

Keynes had a radically different view on how the economy operates, rejecting its rapidly self-equilibrating neoclassical property. He conceptualized the economy as inherently unstable and subject to shocks.

Schumpeter, as Keynes, also treated economics as a dynamic and organic process, where the "creative destruction" is the main driving force of progress and economic growth. Schumpeterian theory puts forward the role of entrepreneurs and their innovative ventures as the driving forces of economic development. In the neoclassical framework, the driving force of economic growth is also technical change. However, in the Keynesian tradition economic growth is driven by aggregate demand.

Technical change was introduced in the neoclassical framework as a factor that determines economic growth by the Solow-Swan model. In the neoclassical endogenous growth theory, technical change is explained as a result of "learning-by-doing" or as a result of investment in research. As discussed below, technical change and innovation are central in the Schumpeterian theory. In Keynesian theory, technical change is introduced through Kaldor's technical change function, which measures technical change as the rate of growth of labour productivity.

The neoclassical school has the longest history on studying economic issues related to energy and the environment, compared to the other two schools. This usually involves the study of optimization of the use of exhaustible resources and the empirical investigation of the growth-energy use nexus. In post-Keynesian theory, energy and environment have been generally overlooked. Only recently post-Keynesian economists have start looking at the effect of environment and resources on the macroeconomy and at questions of energy use and climate change within the context of economic growth. The post-Schumpeterian school, on the other, hand, has been on the forefront of studying the implications of energy transition on the economy, using a multitude of approaches, including Evolutionary economics, Innovation Systems, and Technology Transitions theory.

1.1.1. Traditional and modern neoclassical school of thought

The neoclassical theory is considered the mainstream economic school of thought. A key element in the founding Walrasian theory was how to allocate efficiently the scarce resources of an economic system, where the maximization of individuals' utility and minimization of firms' production costs results in a state where demand and supply is equal in all markets once prices are left to fully adjust and there are no frictions in the system.

The classical theory assumes that economic agents maximize their utility (households) or profit (firms) while taking rational decisions, have perfect knowledge of prices, with stable expectations, in markets that are perfectly competitive, with prices at a level that all markets are cleared and resources are fully employed. According to classical economic thinking, economies can deviate from their output and employment equilibrium, but this is only a temporary disturbance, which will be restored by the optimising power of market forces.

In the classical school, real output is given by a production function with labour and capital as inputs. Here, labour market ensures full employment, and involuntary unemployment is attributed to artificial restrictions. Also, in the classical macroeconomic framework, ‘supply creates its own demand’ as interest rates ensure the aggregate spending in the economy will always be sufficient to meet the full employment level of output. Finally, changes in the money supply cannot influence output and employment (Snowdon and Vane, 2005).

The classical economic framework did not account for **technical change** and related productivity gains. Technical change was eventually recognised for its role in economic development by the neoclassical school with the Solow-Swan model (Solow, 1956; Swan, 1956; Solow, 1957).

In this supply-driven model, optimal levels of labour and capital, with their predetermined productivity, lead to a certain level of supply. With decreasing returns to scale, long-term growth is only possible with technical change, which increases economic efficiency as measured by the total factor productivity (TFP). TFP is exogenous and thus, although the Solow-Swan model incorporates innovation, it cannot explain it. The part of growth that cannot be explained by measures of capital accumulation and increased labour inputs is accounted for by the productivity increase, which is also referred to as the Solow residual. Besides innovation, TFP might account for an increased use of environmental resources, which are not considered as explicit inputs in the model.

The literature on the “**endogenous growth models**”, introduced by Romer (1987), tries to explain changes in the TFP, incorporating technical change, economies of scale, externalities, changes in the composition of an economy’s sectors, and adoption of cost-saving production methods. There are two categories of endogenous growth models in relation to how they treat technical change. The one explains technical change as a result of experience in production - “learning-by-doing”, where firms cannot internalize innovation gains - and the second as a result of investment in research -“Research and Development”, where firms can internalize innovation acquired through research (Romer, 1986, Lucas, 1988; Romer, 1987).

The role of technical change in the process of economic development can be described as follows (EC, 2016a):

1. Firms produce by fully utilizing their resources, including labour, to meet their intermediate and final demand for their products, given the finite set of production factors, technology options, and households.
2. To finance their investment, firms seek funds in the capital markets.
3. Households receive payments for their labour, shares (if the hold any), rents (if they own property), and subsidies, and they choose how to allocate their total income between consumption and savings.
4. Savings are used to finance firms investments, and investment accumulation determines the capital stock used in production, including physical production stock (renewal of machinery, buildings, etc.) and knowledge stock (e.g. technical progress, R&D, etc.).
5. The increased amount of capital, labour and productivity expands the production frontier and allows for greater production.

Originally, production functions in neoclassical theories did not include **energy** as a distinct factor, highlighting labour and capital inputs as the fundamental inputs and considering materials and energy as intermediate inputs. Extraction activities, such as mining for materials and drilling for fuels, were value added activities, which are properly accounted for in terms of the capital and labour employed and represented a small share of aggregated output. This position, however, has received some criticism (see Ayres, 2016).

However, the role that the availability and prices of natural resources play in growth motivated a branch of growth theory that incorporates environmental and resource variables[2]. The question of the need for including energy as an input is treated by considering the degree of substitution between energy and other inputs (mainly capital). Low substitutability or even complementarity of the two, especially in the short-term, indicates that energy is essential as an input.

Neoclassical economists have constructed production functions in which energy is included as an explicit factor, recognizing the importance of energy as an essential input for the utilization of the other production factors. Neither labour nor capital can function without energy inputs, for example as fuels for engines, or electricity for light, communication and appliances (Ayers et al., 2013). Hence energy is just as essential for production as capital and labour, which casts doubt on the idea that past GDP growth can be entirely explained by capital or non-specific knowledge accumulation. Economists introduced the KLEM production function, where K refers to capital, L to labour, E to energy, and M to materials (Hudson and Jorgenson, 1974; Jorgenson, 1978 & 1984; Berndt and Wood, 1979). KLEM may provide good means of describing processes of technical change and input substitution through for example CES-type functions such as Cobb-Douglas (Dietz et al., 2013).

Analysts in the **economics of exhaustible resources** have explored three mechanisms through which the depletion of exhaustible resources can be compensated: substitution of reproducible capital for the exhaustible resources, resource-enhancing technological change, and the resort to an alternative technology (backstop technology), which is based on a non-exhaustible resource base (Buenstorf, 2004).

The first mechanism has been examined using elasticities of substitution between the non-renewable resource and reproducible capital. If the elasticity of substitution is greater than one, production can continue without the use of the resource. If the elasticity is below one, the resource is an important component of the production and production will have eventually fall to zero, assuming absence of technical change (Dasgupta and Heal, 1974). If the elasticity of substitution is one, a positive level of consumption can be sustained indefinitely, if the output elasticity of capital exceeds that of the exhaustible resource (Solow, 1974).

The second topic on the effect of technical change on alleviating the dependence on non-renewable resources has been explored in numerous ways. Stiglitz (1974), in his seminal work on this issue, used a Cobb-Douglas framework to show that positive consumption levels can be maintained if the resource-augmenting technological change is at least as high as the rate of the population growth. Finally, the backstop technology ensures that positive consumption can continue indefinitely, although this might be costly (Nordhaus, 1973).

The second key strand of research within the neoclassical school is the **empirical investigation of the relationship between economic growth and energy use**. In particular, the question on the causality between energy and growth is a prevalent topic in the literature. Some empirical studies suggest that energy 'causes' growth and others find evidence that the other way around is true.

[2] For a review see Smulders (2005)

The literature on the causal link of the two could be synthesised into four hypotheses. First, the *growth hypothesis* suggests that there is a unidirectional causal relationship running from energy consumption to growth, implying that energy consumption plays an important role in the production process together with capital and labour and thus it is important for economic growth. This also implies that energy is complementary to labour and capital and a limiting factor to economic growth and energy shocks can negatively impact growth. Second, the *conservation hypothesis* suggests that there is a unidirectional causal relationship running from economic growth to energy consumption, implying that economic growth increase would trigger higher energy consumption. Third, the *feedback hypothesis* suggests that there is a bidirectional causal relationship between growth and energy consumption and may serve as complements to each other. Finally, the *neutrality hypothesis* implies that there is no causality between the two, due to the little effect of energy consumption on economic growth. The findings vary and all four hypotheses have been confirmed by empirical studies. Two comprehensive reviews on this issue have been written by Ozturk (2010) and Payne (2010).

In general, the analysis of the impacts of global warming on growth under the neoclassical tradition follows a supply-side approach. This means that in such models all resources are assumed fully employed, so that total spending on investment and climate mitigation is defined by available saving (Taylor, 2016). Most of these models also assume that mitigation and investment decisions are taken by a ‘representative agent’ who maximizes utility from consumption, discounted over a time horizon (Taylor, 2016). The most representative example of neoclassical macroeconomic climate change models found in the literature is Nordhaus (2010). Many similar models have developed in this literature with different levels of influence in policy and research, however, their review does not fall within the scope of this study.

Within the field of environmental economics, **technological change** has started receiving considerable attention in terms of its role in mitigating environmental problems, including climate change. Environmental issues, and especially climate change, can only be addressed at great cost, given the level of technology development to date, which has obvious implications for economic growth. Therefore, providing incentives to stimulate the development of ‘environmental-friendly’ technologies that can lower the cost of addressing mitigating climate change is key in environmental and energy policy. The costs of energy efficiency and renewable energy technologies have been continuously declining as a result of economies of scale, R&D efforts, and “learning-by-doing”. On the other hand, since in a neoclassical framework the amount of money is given, steering funds towards innovation related to energy and clean production, may crowd out other innovation investments, which might be more productive for the economy. To enhance the understanding of the relationship between technological change and environmental and energy policies as well as the effect that this technical change will have on economic growth, neoclassical economists have developed a multitude of models, usually in a computable general equilibrium setting.

1.1.2. Keynesian and post-Keynesian schools of thought

The conceptualization of the economy by the Keynesian school in the early post-war years can be summarized as follows (Snowdon & Vane, 2005):

1. The economy is inherently unstable and subject to shocks that are attributed primarily to changes in investors’ ‘animal spirits’ (state of business confidence) caused by changes in the marginal efficiency of investments.

2. The economy is characterized by fundamental uncertainty.

3. The economy is not rapidly self-equilibrating, meaning that it can take a long time to return to a state close to full employment if left to its own devices.
4. The aggregate level of output and employment is determined by the aggregate demand. Therefore, authorities can intervene to influence the aggregate 'effective demand' to stimulate a faster return to full employment.
5. Such stabilisation policies should be fiscal as opposed to monetary as the effects of fiscal measures are considered more direct, predictable, and faster than monetary policy in acting on aggregate demand.

The above conceptualization of the economy was expressed in the early IS-LM model,[3] which shows how the goods market interacts with the money market to determine the short-run equilibrium between interest rates and output. The model also shows how fiscal and monetary policy, each with different levels of effectiveness depending on the structural parameters of the model (curve slopes), could be important in stabilizing the economy.

Traditional Keynesian economics does not easily apply to the long-run macroeconomic issue of economic growth, as is the case of the (neo)classical school. However, economic growth has been studied through a Keynesian framework, usually in conjunction with income distribution, where the firm investment is independent from prior saving and is the driving force of the growth process (Hein, 2014). The examination of the determinants of investment and capital accumulation plays a central role in these models. Several post-Keynesian economists have described economic growth and competitiveness using the concept of "cumulative causation", which is associated with knowledge accumulation (Kaldor, 1970, 1972; Arthur, 1989; McCombie and Thirlwall, 2016). The term refers to a virtuous cycle of a path dependent, self-reinforcing process between growth and higher productivity, or a vicious cycle in the opposite direction (EC, 2016a).

Although in many post-Keynesian models **technical change** is exogenous, models that do endogenize technical change do so by linking it with capital accumulation, where the direction of causation runs from technical change to the growth rate of capital stock (Dutt, 2003). Post-Keynesian models that endogenize technical change refer more or less to Kaldor's technical change function (Bellais, 2004). Kaldor's technical change function measures technical change as the rate of growth of labour productivity. To Kaldor (1970, 1972), thus technical change is a function of cumulative investment in the newest technology (EC, 2016a). Moreover, the increase in the stock of knowledge has a direct effect on the productivity of the capital stock, but since the stock of knowledge can only grow through investment, a self-reinforcing and path dependent process is revealed, where (EC, 2016a):

1. Banks create loans for the entrepreneurs that want to invest in their innovative improvements to the existing capital stock;
2. Investment in new capital involves Research and Development (R&D) expenditure in various related technologies, which increases productivity;
3. The productivity improvements reduce production costs, which brings higher real income for entrepreneurs and lower prices for consumers, while reducing imports and increasing exports;
4. Higher income leads to higher effective demand; and

---

[3] 'Investment-Savings' (IS) and 'Liquidity preference-Money supply' (LM), developed by Hicks' (1937) and elaborated upon by Modigliani (1944) and Hansen (1949, 1953).

5. Higher demand and profits incentivise entrepreneurs to reinvest to expand their capital stock, which further expands the stock of knowledge.

The post-Keynesian school has largely ignored concerns with ecological issues and only recently started looking at the effect of **environment and resources** on the macroeconomy (Heyes, 2000) and at questions of **energy use and climate change** within the context of economic growth (Taylor, 2004, 2008; Taylor et al., 2016). Heyes (2000) incorporated environmental considerations into the Keynesian macroeconomic framework, by introducing to the standard IS-LM model the environmental equilibrium (EE) constraint, which represents all interest rate-output combinations for which "the rate at which the economy is using environmental services, is exactly equal to the natural environment's ability to supply them" (Heyes, 2000). Lawn (2003) extended the Heyes' 'IS-LM-EE' model to include the role of technological progress and the necessity of considering 'appropriate institutional arrangements' to act as forces of adjustment to the macro-environmental equilibrium.

In more recent post-Keynesian theory on environment and sustainability (Kemp-Benedict, 2014; Fontana & Sawyer, 2016; Taylor et al., 2016), economic growth is driven by aggregate demand, a key determinant of which is investment. Investment is considered autonomous and is usually modelled as a function of capacity utilization and profit rate, however, other modelling approaches complement that with other factors, such as a parameter reflecting 'animal spirits' (see Fontana & Sawyer, 2016; Hardt & O'Neil, 2017). By including the capacity utilization and profit rate in the investment function, the long-term path of capital accumulation (hence economic growth) is driven by aggregate demand and is influenced by income distribution (Hardt & O'Neil, 2017).

Taylor et al. (2016) construct a post-Keynesian growth model that introduces the accumulation of greenhouse gases (GHG) to study the macroeconomic implications of global warming. More specifically, the model studies the effects of rising GHG levels on output and employment, mitigation offsets, the energy use and labour productivity relationship, income distribution, growth, and the effect of the rebound effect.

Recently, new literature on "ecological macroeconomics" has emerged, as distinct branch in the field of ecological economics, specifically concerned with developing macroeconomic theory and models for the analysis of sustainability challenges. Post-Keynesian theory (see Fontana & Sawyer, 2016) and modelling practice has strongly influenced this new branch, as both fields share many basic assumptions (Hardt & O'Neill, 2017). Such commonalities are the conceptualization of production, which stresses the non-substitutability of inputs, the rejection of the utility maximization assumption, the importance attributed to the role of institutions, the fundamental uncertainty, and the existence of path-dependency (Hardt & O'Neill, 2017). However, a conflicting aspect of post-Keynesians and ecological economists is the attitude towards economic growth, which for the former constitutes a prerequisite for increasing prosperity whereas for the latter continuous growth is neither possible nor desirable.

1.1.3. Schumpeterian and post-Schumpeterian schools of thought

In essence, the theory of Schumpeter (1934) is based on the interplay between the entrepreneur and the financial institutions. An entrepreneurial idea aims at improving the productivity of a firm or lowering firm's production costs, and by inventing "new combinations of economic resources", whether these are labour, capital, knowledge, or material, the entrepreneur seeks to secure temporary monopoly rents. In order to fund the innovative idea, the entrepreneur applies for financing at the financial institutions. Upon the success of this idea, both the entrepreneur and the lender secure a profit, so innovation involves two purely profit-seeking actors.

To Schumpeter (1942) the new combination of economic resources enhances the diversity of products, production methods, product supply, and industrial organization among competing firms, generating strong heterogeneity, in terms of profit rates and productivity. This gives rise to a market selection process, which displaces from the market these firms that are unable to imitate or invent new combinations, a process of “creative destruction”.

To Schumpeter (1939), technically related innovations emerge clustered around certain points in time, which generates important technical expansion and economic development. This is interrupted by periodic eras of unemployment rise and economic instability or depression, due to the inability of all the innovative activity to deliver. Since, in Schumpeter, investment is stimulated by innovation, as innovative activities fail, investment declines, causing economic recession. This process creates economic cycles of various lengths.

Aghion and Howitt (1992) developed an **endogenous growth model** that incorporates key elements of the Schumpeterian theory, such as the creative destruction, to the neoclassical paradigm. In this post-Schumpeterian model, firms engage in R&D with uncertain outcome, when the outcome is successful, the firm makes profit and gains higher market share than the rest that lack the innovation. This firm’s advantage is maintained until the innovation becomes mainstream and the old production method becomes obsolete.

In modern economics, Schumpeterian theory has resurfaced in various forms, particularly in the study of technological development of low-carbon energy technologies. Economists, based on Schumpeter’s ideas, followed new directions of research and developed new theories and approaches, discussed next.

Evolutionary Economics

Evolutionary economics focuses on Schumpeter’s historical approach in economics and the enabling factors and barriers to the “creative destruction” (EC, 2016a). The economy is conceptualized as a complex, hierarchical structure of various levels and subsystems that are linked and interact through feedback mechanisms (Potts, 2000). Selection processes and variations that occur in these subsystems can trigger and affect changes in other subsystems and the total environment. The linear flow model invention-innovation-diffusion gives place to a more dynamic, non-linear approach to innovation.

Innovation and imitation play a key role in the dynamics of evolutionary modelling, while fitness and selection are central drivers of these dynamics. Evolutionary economics researchers described key factors of the historical great surges of innovation evolutions and their consequences as well as the financial dimension of these processes (Freeman & Perez, 1988; Freeman & Louça 2001; Perez, 2001; Nelson & Winter, 1982).

There are six basic concepts that have been prevalent in the evolutionary economic framework (van den Berg et al., 2006; Nelson & Winter, 1982, Jalonen, 2012):

1. **Bounded rationality**: decisions are made within the inherent limitations of individuals and firms to gather and process information. Decision makers are not rational profit maximization agents, but rather take decisions to satisfy their most important criteria while forgoing others.

2. **Diversity**: Bounded rationality implies the heterogeneity in strategies of economic agents. This diversity of economic strategies, agents, structures, and technologies is the primary cause of uncertainty, which in turn is perceived as a necessary condition for innovation and economic growth through competitive selection.
3. **Innovation**: An increase in diversity implies an increase in creative combinations of various factors which is the source of innovation.
4. **Selection**: Diversity is reduced through the process of competitive selection, which refers to the 'survival of the sufficiently adapted' (and not 'survival of the fittest') and the reproduction of successful agents or strategies.
5. **Path dependency and lock-in**: Repeated selection can result in path dependencies. It plays a central role in the analysis of future technical change since the available set of decisions for the development of a new technology is limited by past decisions. Increasing returns to adoption and by extension the path dependent development of a technology could lead to technological lock-in.
6. **Co-evolution**: The concept of co-evolution refers to the interaction and mutual influence between two or more systems, where variations in each system are strongly influenced by the other system(s).

Two separate strands of the evolutionary growth theory highlight different economic levels. The first focuses on the micro-foundations of economic growth. The diversity of production techniques at the firm level is driven by investment rules and the search activities of entities. The model is built from the bottom-up, where simulations of micro data generate patterns consistent with observed macro aggregates. The second strand of research of growth models in evolutionary economics is formulated at the macro level and dynamics are analysed at the sector or industry level. In these models, the aggregate growth rate of output can be driven either by labour productivity increase (Conlinsk, 1989; Silverberg and Lehnert, 1993, Meltcafe et al. 2006) or by a growing variety of the economic system (Saviotti and Pyka, 2004, 2008).

Evolutionary economics has also contributed to climate mitigation policy, in particular as regards innovation in energy technologies. Research within this field is mainly concerned with the analysis through the evolutionary framework of energy systems, energy innovation (van den Berg et al., 2006), energy transition policies (Haelg et al., 2018; Hall et al., 2017), co-evolutionary relationships among systems (Norgaard, 1984, Hannon et al., 2013), and others.

Innovation Systems perspective

The Innovation Systems perspective aims at exploring the microeconomic contents of aggregate production function, focusing on the role of institutions, which results in richer empirical and more qualitative analysis and subsequent policy discussions (Carlsson, 2007). However, the macro economy is not merely the aggregate of micro units, but rather a complex network of micro relationships (Carlsson & Stankiewicz, 1991). The field of innovations systems can be broken down in national, regional, sectoral, and technological Innovation Systems, depending on the analysis boundaries.

The Technology Innovation Systems (TIS) focus on the contextual factors that determine the success or failure of technological systems, having a strong empirical foundation. According to Carlsson & Stankiewicz (1991) a technological system is defined as a network of interrelated and interacting agents in a specific technology area governed by a particular institutional arrangement for the purpose of generating, diffusing, and using technology. Based on this definition, Jacobsson & Bergek (2004), distinguished the three main elements of a TIS: actors (users, firms, suppliers, investors, other), networks (channels of knowledge transfer), and institutions (entities that govern the environment within which actors operate). The quality of the interactions between these agents determines the ability of the TIS to bring innovative ideas into the market and profit to the actors involved. The traction that this approach has gained is reflected in the Global Energy Assessment report (GEA, 2012).

A distinct application of the TIS perspective on innovation in energy technologies is the Energy Technology Innovation Systems (ETIS) approach. ETIS is an integrative approach that covers all the components of energy technology innovation including both supply and end-use energy technologies; all stages of the cycle of energy technology development; and all innovation processes, feedbacks, actors, networks, and institutions (Gallagher et al., 2012).

Technology Transition approach

A relevant but distinct sub-field of studies to the TIS approach is the Technology Transition research. Technology Transition (TT) which also emerged directly from the theoretical foundations of Evolutionary Economics and in particular from Freeman & Perez (1988). This alternative pathway retains a strong qualitative approach, which only recently has advanced its quantitative modelling component. The field of Technology Transitions research is concerned with the understanding and the steering of the structural changes happening in key areas of technology and human activity.

Using a Multi-Level Perspective framework, Geels (2002; 2005) qualitatively described the various societal elements that influence and regulate the evolution of socio-technical regimes. Through this framework, socio-technical regimes, meaning the interplay between people and technology systems, are described by policy and regulation, economics, technology networks and infrastructure, as well as culture, preferences and social influence (EC, 2016a). However, the predictive power of this approach still remains to be demonstrated empirically. Other modelling approaches of the TT research are given by Köhler et al. (2009), Turnheim et al. (2015), Holtz (2011), Holtz et al. (2015). Köhler et al. (2018) provide an assessment of approaches and challenges of modelling sustainability transitions. An interesting recent addition to the TT research is the notion of *positive tipping points,* which are understood as emergent properties derived from complex social-ecological system dynamics that allow rapid deployment of transformative solutions to successfully tackle climate change (Tabara et al., 2018). Tabara et al. (2018) present a framework with which agents' capacities, conditions, and potential policy interventions can be identified, which can lead to the emergence of positive tipping points in various social–ecological systems.

1.2. Main modelling paradigms and relationship to schools of economic thought

There exist a number of approaches and models to describe the macroeconomy. However, all of these approaches can be broadly classified into two main paradigms: the equilibrium (optimisation) and the non-equilibrium (simulation) schools. The two main paradigms presented are based on fundamentally different assumptions and descriptions of the macroeconomic system as detailed in Sub-section 1.1. The neoclassical school of thought gives rise to the equilibrium paradigm, while the Schumpeterian and Keynesian schools belong to the non-equilibrium paradigm. In this section we present these paradigms and also the main associated macroeconomic models which originate from each, with further detail available in EC (2016a). This sub-section also analyses the main methodological differences in macroeconometric and computable general equilibrium models and explains why they lead to different results.

1.2.1. Equilibrium/optimisation modelling paradigm

The early and modern neoclassical school focus on the efficient allocation of scarce resources, which is achieved through price-driven markets where rational and perfectly informed agents operate, who maximize their utility and minimize production costs under preferences, technological constraints and income. The optimisation behaviour of the agents based on rigorous microeconomic theory renders the neoclassical paradigm as a useful tool in evaluating structural change policies (Lucas Critique). In addition, the optimisation framework and resource accounting allows for a consistent ordering and comparability of scenarios as the denominator is common for all scenarios. The neoclassical theory, through the Solow-Swan model and its various extensions, has sought to explain innovation, finance and productivity change. The Walrasian approach that is embedded in the neoclassical theory constitutes the basis of the contemporary optimization methodologies, according to which prices and quantities tend to an equilibrium (i.e. agents produce what is demanded, excess supply in the long run should be driven to zero hence demand equals supply). Due to the theoretical and the methodological underpinnings of this school of economic thought, in this study we will refer to it as the **equilibrium school**. In the equilibrium school, the innovator is an economic agent; a rational, profit maximizing individual who takes fully informed decisions (i.e. undertakes only profit making projects) driven by market price signals and consumer preferences, operating within the institutional and policy framework.

Within the equilibrium school a number of approaches to modelling have been developed:

The **Optimal Growth model** builds on the Solow model by replacing the agent's fixed savings behaviour with one that maximizes lifetime (inter-temporal) consumption. This change has a number of consequences including resulting in knowledge accumulation in the economy production function, allowing for welfare evaluation and tightening the correspondence between equilibria and optima. As mentioned earlier, general equilibrium models are based on the Walrasian macroeconomic representation. In these models supply and demand are equalized across the economy as a whole, although disaggregate analysis of single/specific markets is possible.

Computable General Equilibrium (CGE) models combine the general equilibrium structure with realistic economic data to come up with numerical solutions for levels of supply, demand and price which support equilibrium across a defined set of markets (Wing, 2004). In relation to innovation at a macro-level, CGE models assume endogenous productivity in the sectoral production function. CGE models are helpful to analyse the impact of policies on the economy as they are able to analyse discrete policy changes and trade-offs between efficiency and equity/distribution. Contemporary CGE models have been extended and used in a number of domains including: fiscal sustainability, FDI and endogenous productivity, regional modelling, overlapping generations, price distorting policies, econometric CGE, income distribution and labor market imperfections, monopolistic competition and heterogeneous firms, labor market unemployment, generational policies (Dixon and Jorgenson, 2013) and endogenous technical change (Schwark, 2010).

The **Dynamic Stochastic General Equilibrium** (DSGE) models differs from CGE models in that they highlight dynamic changes in the economy instead of providing a stable view, in order to study the business cycles. For this DSGE models introduce exogenous shocks to the economy in order to study the reaction of the representative agents, also with the possibility to incorporate heterogeneous representative agents.

Partial Equilibrium models allow for analysis simplification as compared to GE models by taking into consideration only a part of the market to attain equilibrium and keeping other parts constant. In other words, market clearance of specific goods is independent from prices and quantities in other markets.

1.2.2. Non-equilibrium/simulation modelling paradigm

Keynesian and Schumpeterian approaches have significant differences between each other in terms of their focus. Scholars following the former approach examine the macroeconomy, the financial sector, and fiscal and monetary policy, while the latter approach is concerned with innovation, transitions, and business management. However, these two schools exhibit many similarities in terms of their assumptions and the conceptualization of the economy, so that they can be seen as two perspectives of the same broad theory (EC, 2016a), a perspective which follows a radically different approach to the equilibrium school. Due to the similarities in their theoretical assumptions and of their methodological approaches, these two approaches together can be categorized as the **non-equilibrium / simulation school**. The non-equilibrium school emphasizes that there is not one preferred equilibrium state for the economy, but rather that it is constantly transformed and affected by the prevailing institutional forces and history.

Entrepreneurs play a central role in the non-equilibrium models by enacting ideas to innovate and improve the existing capital stock. They receive financing to do so from financial institutions and by applying for loans from banks. Improvements in the capital stock translate to increases in productivity that in turn reduces production costs. It eventually also translates into higher incomes for households, which leads to higher effective demand. Part of the profits from this increased demand are re-invested into innovating the capital stock and the cycle continues leading to the expansion of the stock of knowledge.

The models developed to represent these theories are associated with the use of simulation of behaviour models. **Macro-econometric** modelling is based on estimating relationships between different macroeconomic variables through regression analysis and time series. Variables supplied into the models are based on empirical data. In these models the investment behaviour of an agent is derived econometrically. Another approach to simulation of the macroeconomic system is the **systems dynamics** approach. Within this approach the two main model types are **stock flow** and **diffusion** models. The systems dynamics approach uses stocks, flows, internal feedback loops, table functions and time delays for analysis of complex, nonlinear systems. System dynamic models do not necessarily encompass the entire macroeconomy, instead these can be linked to macro-models. Lastly, **agent-based** models are based on autonomous agents in which heterogeneous objects interact with each other and the environment. More recent agent-based modelling attempts to build micro-founded models of long-term economic dynamics from the bottom-up. These models provide a very detailed representation of the innovation process and of the financial condition of firms. They emphasise the heterogeneity among agents (in skills, productivity, capital) and on the role of interactions. This allows in particular to analyse the propagation of technological change through the economy and hence provide useful theoretical insights about the dynamics of technological transitions (see Balint et al. 2017 for a survey and Lamperti et al. 2018 and Hötte 2019 for recent contributions). However, these models do not yet have the level of quantitative accuracy of their CGE counterparts.

1.2.3. Methodological differences in macroeconometric and CGE models leading to differences in results

The two types of models are built on different methodological underpinnings[4] and usually on much different datasets (the former requires long time series to be properly estimated and the second is calibrated on a comprehensive single base year data set). There are three critical differences between the methodological approaches of macroeconometric and CGE models described in the previous section that may cause the two types of models to report opposite results while addressing the same policy question. Opposite results do not necessarily mean that one of the two approaches is flawed but rather indicate that under certain conditions a certain outcome is plausible. The critical differences between the two approaches are:

1. **Capacity utilisation**: CGE models assume full use of capital stock and unemployment in the labour market. Macroeconometric models assume unemployment in labour and, implicitly, in capital (capacity is measured in relation to 'normal output' rather than a measure of the capital stock).
2. **Dynamics of growth,** that is demand driven vs supply driven: GDP growth in CGE models is the result of technical progress, increase in population, capital accumulation, multiplier effect and removal of market imperfections. GDP in macroeconometric models is driven by increases in any or all of final demand components, influenced in turn by technical progress, and constrained by labour supply/population. In CGE models agents optimise their behaviour so as to minimise costs and industries operate to their full potential capacity. In macroeconometric models, agent behaviour is modelled according to the responses derived from time-series econometric estimates with no optimisation assumption.
3. **Money supply and crowding out**: In their default closure CGE models assume that money supply is fixed. Macroeconometric models assume that there is sufficient financing to support any increase in final demand. This means that in CGE models if, for example, a power generation plant needs to move to a more expensive process to produce electricity, it will need to receive more money from the bank (in a form of a loan), leaving less financing resources for the other economic activities – this eventually increases interest rates. In contrast, in macroeconometric models it is assumed that the banking system will expand its balance sheet to supply the required amount of financing to the other companies, without any impact on its capacity. In macroeconometric models the interest rate charged by banks to borrowers is determined by the central bank policy rate, plus a mark-up reflecting macroeconomic conditions (the banks general willingness to

[4] For an exposition of the different schools of economic thought the interested reader can see Elsner et al. (2015) "The Microeconomics of Complex Economies Evolutionary, Institutional, and Complexity Perspectives", while for a hybrid modelling including both neoclassical and Keynesian approaches one can see Naish (1995) "Keynesian real business cycles in a neoclassical framework", Journal of Economic Behavior & Organization, Volume 27, Issue 2.

lend); increased borrowing does not increase interest rates unless one of those channels (exceeding the policy inflation target or increasing uncertainty in financial markets) is affected.

In order to better illustrate how these mechanisms affect the results of both methods a simple example is made below as to how both modelling approaches would represent the case of a company that produces electricity and that want to switch from using fossil fuels to a more expensive (but cleaner) technology.

In the **CGE** approach the first element that has to be considered regards the identification of the driver for this process switch. If the company selected in the reference scenario to produce electricity using fossil fuels, this was because under given fuel prices, technology choices, energy system characteristics, technological learning potential and budget, it was the best available option which maximised its profits. Therefore the driver for the process switch has to have an impact on one or more of these elements. Let us assume that the fossil fuel prices became more expensive, hence making the switch is less unfavourable. In this case the firm needs to finance the additional investment (this can be done either by reducing its own savings or by receiving a loan - in both cases reducing the financing resources that are available for all other economic activities), and engage in a new production process that is characterised by different economic multipliers and productivities / learning effects. To the extent that this switch does not remove any existing market imperfections the switch to the more expensive option will reduce welfare (if the option was beneficial for the economy, agents should have adopted it already in the reference case as they optimised their behaviour).

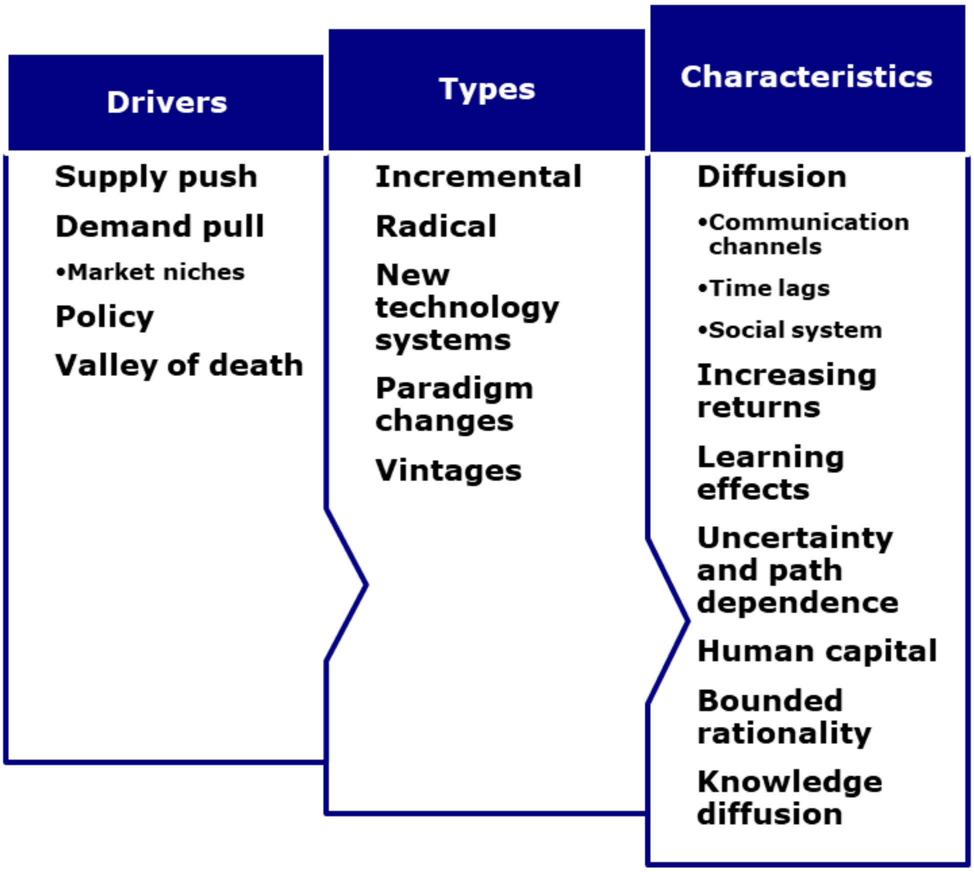
In the **macroeconometric** approach, the switch to the more expensive low-carbon option would, as in the CGE case, be driven by an increase in the price of fossil fuels. What happens next depends, however, upon the impact on demand. If the low-carbon alternative involves more investment it is assumed that banks are willing to create the additional money with no impact on the availability of financing for other economic activities. During the investment phase, the boost to investment increases final demand spending, output and imports, drawing on underutilized resources. If the economy were already operating at full capacity, the impact would be higher generalised inflation and higher interest rates (led by the policy response of the central bank), giving a similar result to the CGE case. During the operation phase, if the low-carbon alternative is more expensive, then this cost is passed onto the price of the firm’s product, raising the price level and curbing household expenditure in real terms. Typically in a decarbonisation scenario, higher investment continues over a considerable period and in any given year this stimulus outweighs the impact of higher prices. But the outcome also depends on the extent to which fossil fuels and investment goods are produced domestically or imported. In the macroeconometric approach, where agents operate under imperfect information and uncertainty, the lack of full information means that the reference case is not necessarily optimal, and thus the alternative outcome following the policy intervention could improve welfare relative to the reference case.

The difference in the two approaches indicates that they are not only relevant for different economic structures and stages of economic development, but also that their complementary use is essential as it allows to highlight the exact conditions under which a policy can be successful in terms of increasing income and generating employment. Using both approaches is also helpful for indicating the range of possible outcomes that arises from our uncertainty about how the economy functions, represented by the two modelling approaches: in decarbonisation scenarios, that uncertainty range can be narrow compared to the growth of the economy over several decades.

1.3. Central aspects of innovation: drivers, types and characteristics

As shown above, the question of technological change is central to the macroeconomic analysis, especially in the context of climate change. Cleaner energy production and energy conservation technologies should be developed and adopted in the short-term, which is a challenging endeavour. Here, the drivers of innovation as well as the types and characteristics of innovation are briefly reviewed, without attempting to organize the concepts in a coherent framework. First the supply and demand drivers of innovation are introduced, followed by the types of innovation and the main concepts used in the various economic schools of thought and innovation theories.

Figure 0-2 Central innovation aspects



1.3.1. Drivers of innovation

Supply push

The idea of the supply-side-driven innovation constitutes the supply (or technology) push argument. For Schumpeter, invention is the first demonstration of an idea, which becomes innovation with its first commercial application in the market. Diffusion of innovation takes place once the emerging technology or process is spread in the market. This invention-innovation-diffusion model is often referred to as the “linear model of innovation”. This continuous flow implies that advances in the underlying scientific base determine the pace and direction of innovation activity. Thus, stimulating innovation requires the increase of new inventions that arise through putting more resources into R&D.

Demand pull

However, the technology-push argument was criticized by scholars for disregarding changes in economic conditions. Economic factors, such as prices, can affect the profitability of an innovation, which inevitably determines the development of a specific technology. Schmookler (1966) focused on patented inventions across different industries and postulated that it is the anticipated market demand that drives technical change.

According to the demand (or market) pull hypothesis, firms perceive profit opportunities in the market and innovate in order to maximize their profit, turning the market, and not the scientific base, into the prime mover of innovation (Chidamer & Kon, 1993). As a result the public policies should favour the creation of market space for new technologies to emerge. Several different drivers may be behind the demand pull for new products and services (social, technical, economic or environmental) as illustrated by the case studies of section **Error! Reference source not found.**.

From the demand pull perspective, market niches play an important role, providing initial demand for maturing products and services that cannot yet compete on costs and/or performance in mainstream markets, but which can be interesting for targeted applications and early adopters.

Public policies constitute an additional driver that reflects underlying socio-economic, technical and environmental considerations. Policy affecting innovation can be implemented through a number of ways, including by the provision of guidance, R&D support, production and demand incentives, provision of infrastructure, promotion of knowledge transfer and diffusion, standardization, and provision of a conducible regulatory environment and market design.

A key criticism to the demand pull perspective is that it can explain incremental technical changes, but fails to account for disruptive innovations (Chidamer & Kon, 1993). The debate, which took place mostly in the 1970s, ended with the conclusion that in practice innovation is a coupling and matching process where interactions are essential. For innovation to be successful the interaction of both “push” and “pull” are required (Tidd, 2006). This conclusion challenges the Schumpeterian linearity of the invention-innovation-diffusion classification of the innovation process.

It is frequently observed that new technologies when progressing from Research towards Diffusion face a “valley of death” in the intermediate stages due to the multiple risks and uncertainties (Murphy and Edwards, 2003; Grubb, 2004). Murphy and Edwards (2003) argue that the Demonstration and Market Formation are expensive processes, and for electricity production technologies, there is a chronic lack of finance, which can create a deadly gap between R&D and Diffusion. According to Grubb (2004), barriers to innovation encountered in both demand pull and supply push approaches can exacerbate the valley of death issue.

1.3.2. Types of innovation

As defined earlier, innovation can be a change in the use of resources, management, and/or finance, so that a firm can secure higher economic returns. However, these changes can involve minor product-level improvements or large technological advancements that have fundamental influence in the economy and society. It is useful to distinguish between different taxonomies of innovation.

The initial categorization of different types of innovation was to distinguish between Incremental and Radical innovation. However, different **types of innovation** have been added in this framework. Moving towards a more system-based perspective of innovation, Freeman and Perez (1988) distinguished between (1) incremental innovation, (2) radical innovation, (3) new technology systems, and (4) changes of techno-economic paradigms. According to them, *incremental innovation* occurs continuously in an industry or service activity not so much as the outcome of deliberate R&D, but as a result of inventions and improvements by producers or users (learning-by-doing and learning-by-using). *Radical innovations* are discrete events, unevenly distributed over sectors and time, and can bring structural change, but their economic impact is not significant until a whole cluster of radical innovations are linked together in the rise of new industries and services. *New technology systems* denotes a far-reaching technical change that affects several branches of the economy and gives rise to entirely new sectors. Such innovations derive from a combination of incremental and radical innovations together with managerial and organisational changes. *Changes of techno-economic paradigms* refer to changes in technology systems whose effects are so far-reaching that they influence the behaviour of the whole economy, leading to a new range of products, services, systems, and industries.

Vintages represent the latest available technology and play an important role within the post-Keynesian schools of thought, particularly with Kaldor. Here, investments in new technology vintages alters the capital stock, leading in this way to technical change through cumulative investment (EC, 2016a). Vintages may be represented as distinct technology levels within macroeconomic models.

1.3.3. Innovation characteristics

Here, the main innovation characteristics as identified in the innovation theories and representation of innovation in modelling paradigms are highlighted.

Diffusion

Schumpeter represented the diffusion process as an *S-shaped curve*, in which an innovative technology or process is taken up slowly and starts with the focus on market positioning, then moves faster as it gathers momentum and achieves rapid diffusion that slows down due to saturation, with the focus shifting to incremental improvements and cost reductions. Rogers (1962) presented a unified theory of innovation diffusion, defining diffusion as “the process by which an innovation is communicated through certain channels over time among the members of a social system”. Building upon this definition, he describes the four elements of diffusion: innovation, communication channels, time, and the social system.

Communication channels are the means by which a message is transferred from one individual to another. Rogers suggests that individuals do not evaluate an innovation on a scientific basis, but rather through the subjective evaluations of near peers. Therefore, both mass media channels, which are effective in creating innovation knowledge, and interpersonal channels, which are effective in forming and changing attitudes towards a new technology, are important in the adoption decision of an individual.

Time lags are present in the diffusion of technologies, in a) the innovation-decision process though which a unit of adoption passes from first knowledge of the innovation to the decision to adopt or reject; b) the relative earliness or lateness with which an innovation is adopted; and c) the rate of adoption of an innovation in a system as this is measured by the number of adopters in a given time period.

The **social system** is a set of interrelated units that are jointly engaged in problem solving in order to accomplish a common goal. The social and communication structure of the system impedes or facilitates the innovation diffusion in the system.

Since then, research in this area has been expanded, with many studies focusing on identifying the reasons behind the “slowness” and variability of the diffusion of different innovations. Such reasons can be traced to the size of sunk costs, the adaptations and improvements that an invention has to undergo after its initial conception, and the inherent slowness of spreading information within and among communication networks (Hall, 2004; Geroski, 2000; Hall, 2004; Allan et al. 2014).

Increasing returns

Research on diffusion revealed that new technologies exhibit ‘increasing returns to adoption’ that became widely accepted in the literature. Adoption refers to the actual implementation of the new technology in the firm or consumer level, while diffusion refers to the spread of this technology across the economy. This means that the more a technology is taken up and used the more likely it is to be further adopted.

Five features of a technology and its social context generate increasing returns. **Economies of scale** arise from the reduction of per unit cost with increases in output since high set-up or fixed costs are spread over more output. When set-up or fixed costs are high, organizations and individuals are incentivised to identify and stick to a single technological option. **Learning effects**, where higher returns from continued use arise as experience is gained in the research, production and application of a given technology. With repetition, individuals learn how to use a technology more efficiently and through their experience small modifications and further innovations are likely to spur. **Adaptive expectations** are produced because the adoption of a certain technology reduces uncertainty and producers and users become more confident about its quality, performance, and longevity. **Network effects** occur when an individual accrue additional benefits from a technology use when other people adopt it. Phones and the internet are good examples of this. Adoption is also affected by the **experience in utilizing the technology** and the skills of the user or firm. For example in the adoption of ICT technologies where the skills of firms may be an important factor (Arthur, 1994; Andrews, 2018).

Learning effects

As shown, a fundamental factor of increasing returns to adoption is the effects of learning. There are four main types of learning typically identified in the literature and described next: learning-by-searching, learning-by-doing, learning-by-using, learning-by-interacting. These learning types can explain channels of incremental innovation, however, they are less relevant for more radical innovations.

There are many endogenous growth models in which **learning-by-searching** driven by the R&D decisions of profit maximizing firms is the factor that determines the rate of technical change in the economy. Usually, these models consider an R&D technology that uses as unique input skilled labour, however, there are also studies that use income instead of labour (see Rivera-Batiz and Romer, 1991; Sala-i-Martin and Barro, 1995; Aghion and Howitt, 1998).

Arrow (1962) introduced **learning-by-doing,** when the productivity of a firm increases with the cumulative growth of the whole industry. The increasing returns are a result of improvements in production efficiency due to the knowledge discovered in the process of production and investment. Due to this effect, as experience in production increases the cost decreases and the quality of the production improves. The learning-by-doing idea has been the central element of a vast array of models (Aghion & Howitt, 1992). Learning-by-doing is often measured in the form of learning curves (see below). It is particularly used in bottom-up models, however, the primary problem with incorporating it into models is the difficulty in identifying the mechanisms behind learning (Popp et al., 2010).

The **learning-by-using** effect was first introduced by Rosenberg (1982) who built on a series of historical case studies. This effect denotes the gains in efficiency that occur due to increased experience generated by the use of technology or product.

The **learning-by-interacting** effect is the learning as a result of producers-consumers interactions. According to Lundvall (1992), this interaction is not only mediated by price mechanisms, but also by closer interactions involving mutually respected modes of behaviour.

There may also be effects decreasing learning or at least making it more difficult to learn. **Knowledge depletion** refers to the concept of the decrease in the stock of knowledge or skills of workers through time and through knowledge obsolescence due to innovation. **Fishing out** on the other hand represents the notion that as the knowledge stock grows and the best ideas are used, it becomes increasingly difficult to innovate as the “low-hanging fruits” are used (Jones, 1995).

Learning curves

The concept of learning curves refers to a combination of different sources of efficiency in the design, manufacturing and use of a product. A typical learning curve estimation regresses costs of production at different points in time as a function of cumulative installed capacity, output, or labour in a log-log fashion (Popp et al., 2009). Through this, the learning rate can be calculated, giving the percentage decrease in costs for each doubling of the cumulative capacity or production, which expresses the learning effect of capacity increase on the cost of technology. Learning curves have been extensively an empirically observed, being applied in the analysis of technical change in various energy technologies.

Learning curves, in general, constitute an important tool for modelling technical change and can be used for informing policy decisions as they can evaluate the cost effectiveness of public policies to support new technologies on different stages of their development.

However, the simplicity of learning curves which provide their analytical advantage can also be a drawback, as they cannot at face-value indicate the underlying determinants of innovation. Nonetheless, learning curves can be detailed by separating factors to some extent, e.g. between learning-by-doing and learning-by-researching, or by changing the capacity or production scope (e.g. global or regional).

Uncertainty and path dependence

Independent of the type of actor, innovation or environment, innovation decisions are inherently uncertain, particularly, in immature technologies. Uncertainty can both create opportunities to engage in emerging technologies and impede entrepreneurs to undertake action (Meijer et al., 2007).

Increasing returns to adoption can have a significant influence over the development of technology also because they can make it “path dependent” and result in technological “lock-in”. Path dependence broadly means that what happened at an earlier point in time affects developments and the future outcome of an event in the long-term. There are competing views on the importance of path dependence and whether it leads to inefficient outcomes. Moreover, path dependence is contingent on the specific context and difficult to prove empirically (Durlauf, 2018).

Human capital

Human capital refers to the stock of an individual’s abilities to perform labour and absorb knowledge to produce economic value. Human capital encompasses social and personality attributes such as social skills, intelligence and creativity.

There are a number of channels through which human capital may impact technical change. Acemoglu and Autor (2012) identify the following: i) talented individuals can use their human capital, if they have access to education, to innovate and contribute to technical change; ii) the effect of the workforce, due to externalities derived from human capital, on technology development; iii) the effect that human capital has on incentivising investment in technology and iv) technology progress due to a mix of skills and human capital in the workforce.

Bounded rationality

The bounded rationality concept highlights the agents’ limited ability to gather and process information and their cognitive limitation, which refrain them from taking perfectly informed decisions. Simon (1955) suggested that actors ‘satisfice’ rather than optimise. He emphasised that the gathering more relevant information to take a more accurate decision is more costly, so there is a trade-off between allocating resources to gathering information and taking a decision based on the current information.

Nelson and Winter (1982) named ‘routine’ any regular and predictable procedural, organizational, or strategic process undertaken by a firm, such as a production activity, a hiring process, or R&D activity. Routines are persistent features of firms that determine their behaviour, are passed on over time, and are selectable (Foxon, 2006). Routines change gradually when they do not satisfice according to certain criteria through increased investment in R&D.

Knowledge diffusion

Knowledge diffusion characterizes the spread of knowledge within a group of innovators and imitators (Karl, 2010), occurring in a **purposeful or non-purposeful manner**. Purposeful knowledge transfer within a network can occur in a number of ways, including through patent licensing, company acquisitions or within multi-industry corporations. This knowledge transfer network can cross multiple boundaries, e.g. international or intersectoral and involve a number of different actors. On the other hand, knowledge diffusion occurs through other less-purposeful ways, for example through worker and researcher mobility, or scientific publications.

Related to unintentional knowledge diffusion is the concept of **spillovers:** positive externalities due to knowledge being a (partial) non-excludable good which therefore is transferred from innovative firms and individuals to others. Spillovers can take place within or between different industries (including upstream and downstream industries), regions/countries and across time, as well as concern core or peripheral technologies for a certain industry.

Traditionally, the concept of technology spillovers indicate investments in technology development bring about positive externalities by increasing publicly available knowledge base and thus represent a public good (Arrow, 1962). Based on this, the incentive for private companies to invest in R&D is diminished. This has been contested by scholars that point out that R&D investments can increase the “absorptive capacity” of an entity since R&D plays an important role in learning (Cohen and Levinthal, 1989).

2. Energy as a factor of economic growth

The objective of this section is to present the main channels through which energy can drive economic growth, addressing both conventional and unconventional channels presented in the theory reviewed in Section 1, with a focus on energy. This section starts with the description of the role of energy as an economic activity in the EU, followed by a subsection that describes energy as an input in the production process, and finishes with a review of how energy affects other key determinants of economic growth. The analysis of this section is focused predominantly on the unconventional ways energy affects economic growth, and thus attention has been particularly paid to sub-section 2.3, while sub-section 2.1 and 2.2 rely on a previous study that examined the macroeconomic impacts of energy (see EC, 2016b).

2.1. Energy as an economic activity

This sub-section discusses the role of energy as an economic sector, by presenting the development of key figures over time. First the value added of the energy sector in the EU economy is presented. [5] Then, the global investments in the energy sector from 2003 to 2017 are explored (oil & gas and electricity). Finally, the growth of different renewable energy technologies as well as the changes on employment over time are reviewed.

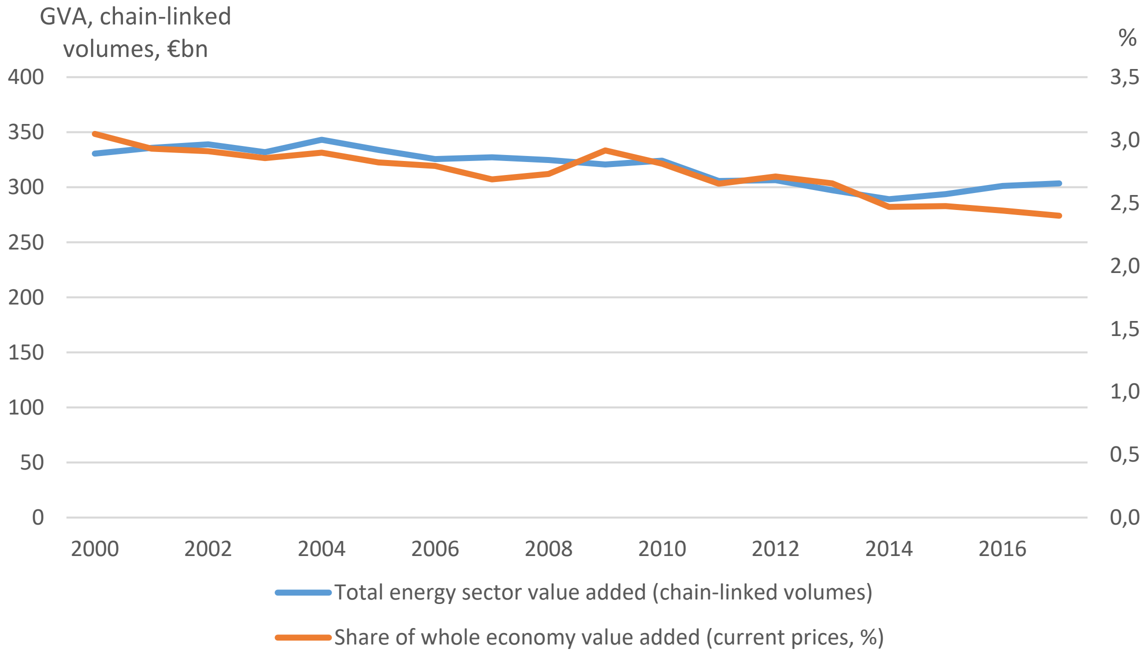
Value added of the energy sector

The EU energy sector has been in decline over the past decade both in absolute terms as in the share of gross value added. As can be seen in

[5] Considered as mining of coal and lignite, extraction of crude petroleum and natural gas, manufacture of coke and refined petroleum products and electricity, gas, steam and air conditioning supply.

Figure 0-3 below, the value added of the energy sector has fallen by around 13% in real terms between 2000 and 2014, while the EU economy grew by almost 20%. This is consistent with the fall in the energy intensity of the EU economy (EC, 2016b). Furthermore, the figure shows that the share of energy value added in the overall EU value added in 2014 was estimated at around 2,5%.

Figure 0-3 Value added of the EU energy sector



Source: Eurostat National Accounts and Structural Business Statistics.

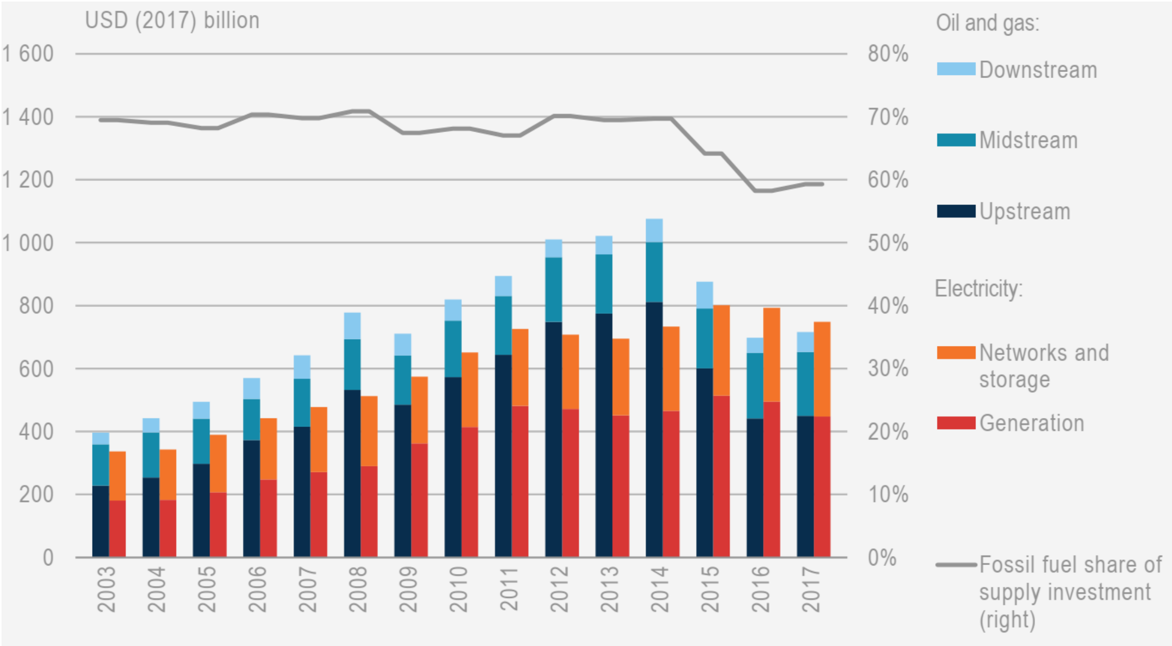
Investments in the energy sector

The global investment in oil and gas and electricity supply from 2003 to 2017 is presented in Figure 0-4. The investment in oil and gas and electricity together has almost doubled during this period. In 2003, downstream, midstream, and upstream oil and gas investments were estimated at USD 400 billion, while investments in electricity network and storage and generation were close to USD 350 billion. In 2017, the former was estimated above USD 700 billion, whereas the latter at around USD 750 billion.

The increase of investment in electricity was more or less steady during this period, decreasing only slightly in periods 2011-2013 and 2015-2017, however, investment in oil and gas increased steadily until 2014, when it reached more than USD one trillion, and fell sharply next year to around USD 850 billion, a decline of almost 20%, due to reduced greenfield exploration. The oil & gas share of supply investment was steady at 70% of total investment until 2014, when it rapidly fell to 60% following closely the drop in oil and gas supply investment.

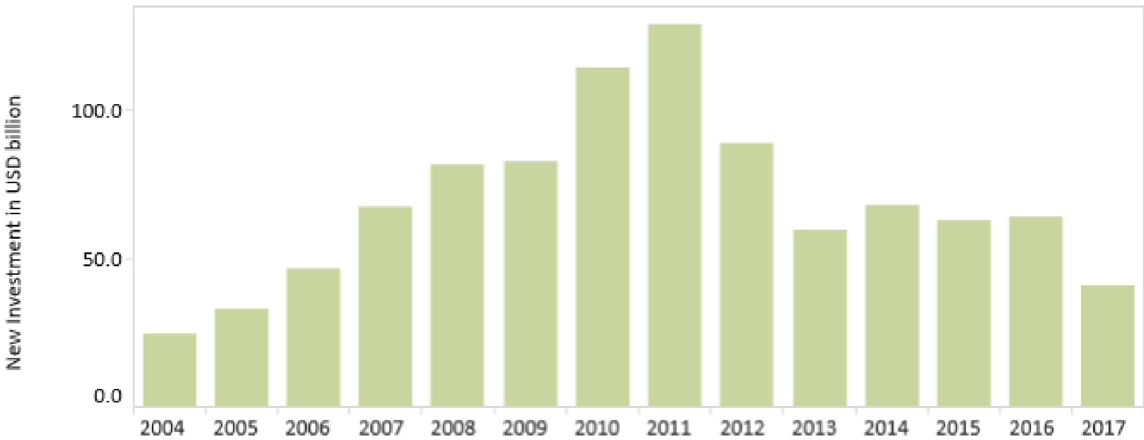
Figure 0-5 shows new investments in renewable energy in Europe between 2004 and 2017. A spike in investments occurred in 2010 and 2011. Table 0-2 below shows 2018 investments in fossil fuels, different power generation sources, renewable transport and heat, electricity networks, total energy supply, and energy efficiency in the EU, other key countries, and in the world. In 2018 the EU invested USD 14 billion in the upstream oil and gas sector and USD 33 billion in downstream activities and infrastructure. Investments in power generation from coal, gas and oil, nuclear and renewables taken together equalled USD 61 billion.

Figure 0-4 Global investment in oil & gas and electricity supply



Source: IEA, 2018. World Energy Investment Outlook 2018.

Figure 0-5 Investments in renewable energy in Europe



Source: IRENA based on data from Frankfurt-School-UNEP Centre/BNEF. 2018 Global Trends in Renewable Energy Investments 2018. Investment volume adjusted for re-invested equity. Total values include estimates for undisclosed deals.

Table 0-2 Energy investments by energy sector and region (billion USD_{2017})

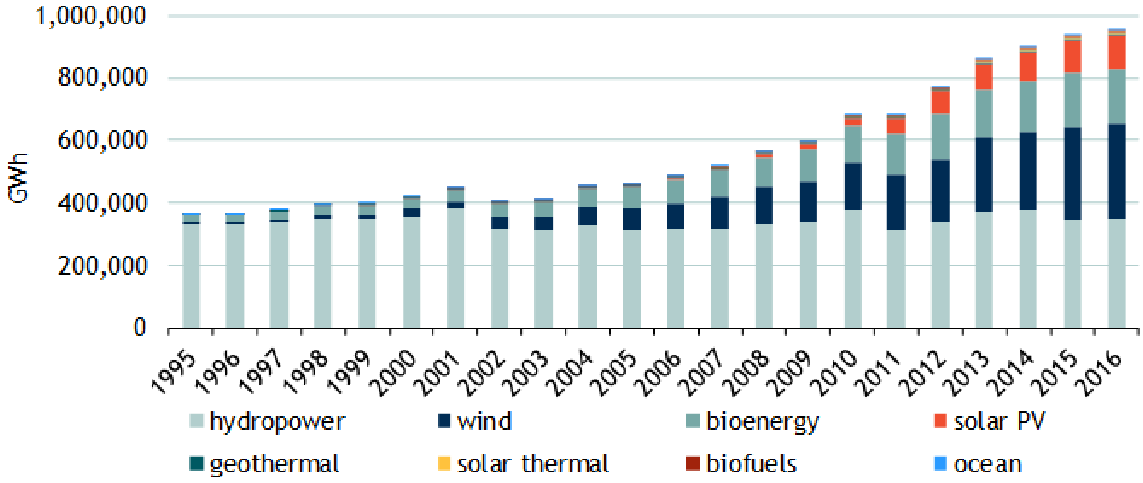
	Oil and gas		Coal	Power Generation						
	Upstream	Downstream /Infrastructure	Mining and infrastructure	Coal, gas and oil	Nuclear	Renewables	Renewable transport and heat	Electricity networks	Total energy supply	Energy efficiency
EU	14	33	2	6	0	55	2	36	148	NA
US	70	49	2	14	4	41	1	65	245	42
Japan	1	3	0	2	0	18	0	8	33	9
Russia	58	16	6	6	0	1	0	10	97	4
China	31	27	44	22	8	98	12	80	322	65
India	3	9	7	16	0	19	0	20	74	8
Brazil	23	3	0	1	0	14	1	7	49	2
World	450	266	79	132	17	298	20	303	1566	236

Source: IEA, 2018. World Energy Investment Outlook 2018.

2.1.1. Renewable energy industry

Figure 0-6 shows the evolution of electricity generation from renewable energy technologies between 1995 and 2016. Between 1995 to 2003 electricity generation from RES was more or less stagnant at approximately 400 000 GWh. However, from 2004 onwards a steady increase in electricity generation from RE technologies can be observed.

Figure 0-6 Electricity generation from RE technologies in the EU

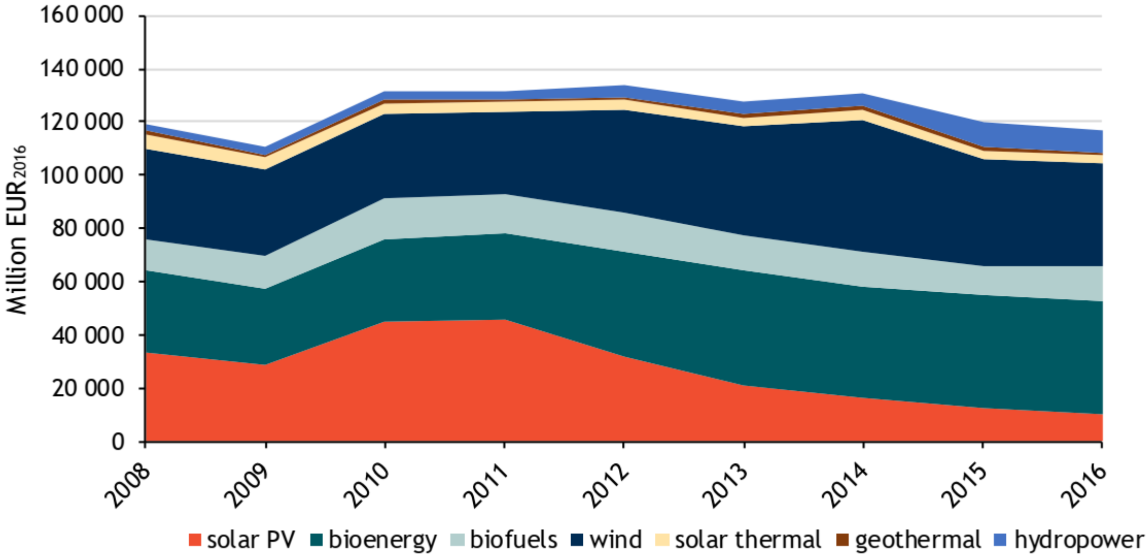


Note: The study considers biofuels as a separate category from biomass.

Source: Trinomics (2019). Study on impacts of EU actions supporting the development of renewable energy technologies.

The turnover of the renewable energy industries in the EU between 2008 and 2016 is shown in Figure 0-7. The total turnover of the industry remains more or less at the same level for the whole period at just below € 120 billion. The solar PV industry has seen the greatest turnover reduction – from above € 40 billion in 2010 to below € 10 billion in 2016. A short discussion on the reasons for this turnover reduction is presented in section 7.5 on the case study on solar PV. Among the variables contributing to this decline we identify competition from China due to overall lower manufacturing costs and a tightening of finance available in the EU to fund expansion following the 2008 financial crisis. During this period, the bioenergy and wind energy industries had the highest growth, with biofuels and hydropower following at a lower level.

Figure 0-7 Turnover of EU renewable energy industries

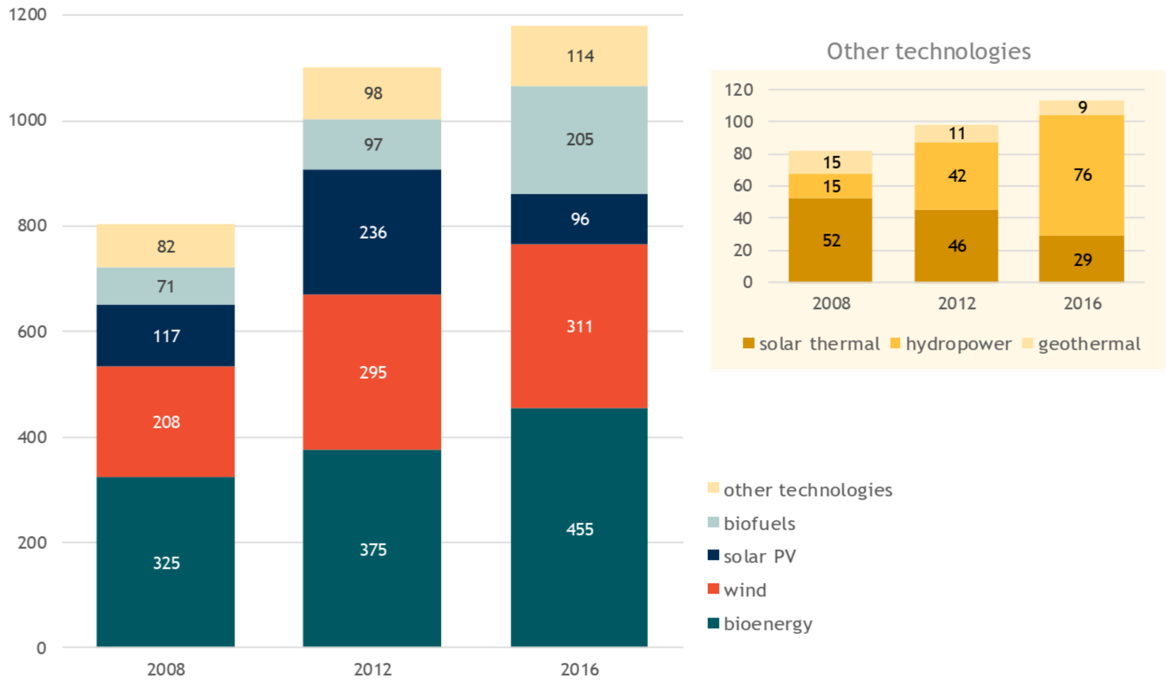


Note: The study considers biofuels as a separate category from biomass.

Source: Trinomics (2019). Study on impacts of EU actions supporting the development of renewable energy technologies.

As can be seen in Figure 0-8, overall, jobs in the EU grew from 803 000 to 1 180 000 in the eight renewable energy sectors together. Bioenergy remains the sector with the highest share of jobs in the renewable energy industry followed by wind energy and biofuels. All these three sectors experienced a significant increase in jobs over the period 2008-2016. The solar PV sector saw a dramatic decline in jobs between 2012 and 2016 after a strong increase between 2008 to 2012. This is a result of the declining local market and the low competitiveness of the local manufacturers against their Chinese counterparts (Trinomics, 2019).

Figure 0-8 Number of jobs per technology sector (in thousands)



Source: Trinomics (2019). Study on impacts of EU actions supporting the development of renewable energy technologies.

2.2. Energy as an input

Energy is an essential input to production as it affects the utilization of the rest of the production factors. In the neoclassical tradition, the importance of energy is often recognized in the production function in which energy is included as an explicit factor. This does not mean that that all neoclassical production functions include energy as a distinct factor, in fact most represent value added as a function of labour and capital inputs, excluding intermediate inputs, such as materials and energy. In general, the production functions express the contribution of each economic factor to growth, reflecting both the size of the change in this factor and the value share of this factor in the production costs. Since the value share of energy is small, its estimated contribution to growth is also small. The question of necessity of energy as an input is treated by considering the degree of substitution between energy and other inputs (mainly capital). Low substitutability or even complementarity of the two, especially in the short-term, indicates that energy is essential as an input.

Initially, production functions used to include only capital and labour, however, they were later extended to incorporate energy inputs and natural resources. The Solow (1956) model, as described in Section 1, was developed including only capital and labour as factors of production. As a direct extension of the Solow model, the neoclassical approaches to economic growth assume that GDP growth is driven by technical change and capital investment, including knowledge investment (Romer, 1994; Aghion and Howitt 1998; Barro and Sala-i-Martin 2003). The role that the availability and prices of natural resources play in growth motivated a branch of growth theory that incorporates environmental and resource variables,[6] however, it has not yet affected the core of the growth theory.

The importance of energy in the production process and consequently in the economy is shown in the dependence of the rest of the production factors on energy. Neither labour nor capital can function without energy inputs, for example as fuels for engines, or electricity for light, communication and appliances (Ayers et al., 2013). Hence energy is just as essential for production as capital and labour, which casts doubt on the idea that past GDP growth can be entirely explained by capital or non-specific knowledge accumulation. The first attempts to include energy as an explicit production factor[7] followed the energy crises in the 1970s-80s, when oil prices triggered deep recessions. As a response to this revealed relationship, economists introduced the KLEM production function, where K refers to capital, L to labour, E to energy, and M to materials (Hudson and Jorgenson, 1974; Jorgenson, 1978 & 1984; Berndt and Wood, 1979).

The introduction of material and energy variables poses issues regarding their measurement and finiteness and exhaustibility of resources that render the notion of indefinite economic growth problematic (Stern, 2011). The discussion of limits to economic growth due to resource constraints has been empirically examined through the spectrum of substitutability between resources and capital. The substitution of these two critical factors indicates how much one of the two has to be increased when the use of the other is decreased to maintain the same level of production. Many ecological economists have argued that although the substitution between energy carriers has played a central role in driving economic growth in the past, it has now reached its limits (Stern, 2011). There is an increasing amount of empirical research on the topic, arguing that energy is

[6] For a review see Smulders (2005)

[7] See Hudson and Jorgenson (1974), Allen and et al. (1976), and Jorgenson (1978)

subject to limited substitutability. Econometric analysis of aggregate production functions shows that OECD countries exhibit complementarity or weak substitutability between capital and energy (Berndt and Wood 1979; Koetse et al., 2008; Fiorito and van den Bergh, 2011; EC, 2016).

According to Apostolakis' (1990) review, most time series studies, due to the reflection of short-term relationships, find that energy and capital as complements, whereas most studies that approach this question through pooled cross-section of countries or regions classify them as substitutes, due to the capture of more long-term effects. While most growth models with resource variables exclude realistic considerations on the capital-resource substitutability, D'Arge and Kogiku (1973), Kümmel (1982), Gross and Veendorp (1990), van den Bergh and Nijkamp (1994), Kümmel et al. (2002), and Lindenberger and Kümmel (2011) do include them.

Another related strand of literature is concerned with the drivers of energy usage in households. Energy price is a driver of energy consumption, although in Europe income does not affect consumption in a clear way, but is different in different income percentiles. A wide range of other drivers has also been suggested in the literature. There are technological factors, which refer to changes in technology that have both positive (larger, more energy-consuming televisions) and negative (energy efficient technologies in refrigerators) relationship with energy consumption. Policy-related drivers refer to the existing regulation that affects household energy consumption, such as the Energy Performance of Buildings Directive of the EU that has stimulated energy saving material and practices in old and new buildings. Other factors include consumer behaviours, such as choosing products with lower energy use, or sociocultural effects, such as the age, education, nationality, etc. In the EU, household energy consumption increased from 2000 to 2012 following the increasing numbers of dwellings and their use of household appliances, thus a trend which persisted during and after the economic crisis (EC, 2016b).

Energy is a primary input of production in the energy-intensive industry, which implies that energy has a direct impact on the competitiveness of this industry. There is an increasing body of literature that examines the competitiveness of the energy-intensive industry. The identified factors that influence competitiveness include energy efficiency, openness to trade, relative production costs, and relative environmental regulation. However, assessing the influence of energy costs on the competitiveness of an industry, and in particular an energy-intensive industry, is challenging. This is because energy-intensive industries are highly capital intensive and the prices for their products are set in global markets. Since energy price changes might not trigger changes in the level of output, a true assessment of the competitiveness of an industry in a country or region can be revealed in those rare occasions that a decision is taken on whether to invest to renew or replace an existing plant (EC, 2016b). However, even then the importance of energy prices might not be able to be distinguished from the rest of the decision factors.

In the EU, the energy prices increased between 1995 and 2007 affecting the competitiveness of manufacturing sectors. Although manufacturing firms had invested in more energy efficient technologies during this period, which decreased the energy intensity of the sector, the energy prices growth led to higher energy costs (as a share of the overall production costs) (EC, 2014). According to EC (2014), there is a negative relationship between energy intensity and exports and between energy cost shares and exports. This means that higher energy prices in the EU affect negatively export competitiveness, which is not being fully offset by energy efficiency improvements.

The effect of environmental regulation on the economy has been discussed in the literature extensively, however, no clear consensus has been reached. It is quite clear, though, that environmental regulation can influence the competitiveness of energy-intensive sectors. Jaffe et al. (1995) examined how environmental regulation affects three variables (1) export growth; (2) shifts of production of ‘pollution-intensive’ goods in countries with lower level of environmental regulation; and (3) changes in investment in countries with more stringent regulation. Their results do not support the hypothesis that environmental regulation has large adverse effects on competitiveness.

2.2.1. Energy Efficiency

In discussing energy as a factor of economic growth the consideration of energy efficiency has become increasingly important in recent years. Energy efficiency is seen as a way to reduce the environmental footprint of energy use while maintaining the corresponding outputs that energy services provide (Howarth, 1997). Many studies have shown that energy efficiency offers the most cost-effective option for meeting emission reduction targets (McKinsey, 2010; IEA, 2012). In Europe, energy efficiency is seen not only as a tool to reduce GHG emissions but also as an important factor in the strategy to increase the security of energy supply. Energy efficiency measures are attractive as they can be applied to many segments of the economy, including buildings, industry, transport and the energy sector itself, such as in energy transport. Energy efficiency is a key pillar of all recent EU energy legislation, and has been stated in the form of the Energy Efficiency First principle of the Energy Union.

As described in section 2.2, the relationship between energy consumption and economic growth (the energy-growth nexus) is an important one and has been extensively discussed in the scientific literature (e.g. Menegaki et al., 2018). Whereas the relationship between energy and economic growth is multi-dimensional and each may (or not) cause the other, **energy productivity** has a more specific relationship to economic growth. Energy productivity is defined as economic output (measured e.g. in gross domestic product, GDP) per unit of energy used: thus increases in the economic output for the same unit of energy input indicate higher energy productivity. This is related to the concept of **energy efficiency** of the EU Energy Efficiency Directive, defined as the ratio of output of performance, service, goods or energy, to input of energy. **Energy intensity** is another closely related and widely used term. Energy intensity and energy productivity are inversely related. The higher the energy intensity the lower the energy productivity.

Increasing energy productivity characterizes the **decoupling** of economic growth from energy demand. Empirically, evidence of such decoupling has also taken place in the EU. The European Environmental Agency (EEA) reported that the EU's final energy intensity decreased by 18.6 % between 2005 and 2017, at a rate of 1.7 % per year. During this time, the final energy consumption decreased at a rate of 0.5 % per year, while gross domestic product grew by 1.2 % annually over the same period (EEA, 2019).

The relationship between economic growth and energy productivity described in the literature mostly focuses on the following two main strands which are opposite in the direction of causation:

Energy productivity may lead to reduced production costs, which in turn may boost the overall factor productivity and economic growth; and

An increase in the share of less energy-intensive sectors, such as the service sector, may lead to overall economic growth, while simultaneously increasing the energy productivity in the economy (Vivideconomics, 2013).

Regarding the first strand, early research on the relation between energy and economic growth from a production function perspective was published by Dale Jorgenson (1984). Jorgenson observed a decline over time in the use of energy as an input per unit of output. He attributed this to technological change and concluded that technological change can be an important driver of growth by affecting energy productivity. More recent work on the topic has argued that high quality forms of energy input and increased efficiency have contributed to past rates of economic growth (Ayres and Warr, 2009, Stern, 2011, Warr and Ayres 2012). Based on a virtuous economic cycle, energy conversion efficiency results in declining prices and increased demand for products or services. This in turn incentivises new investment, further economies of scale, R&D and leaning-by-doing (Ayres, 2012).

On the other hand, Liu et al. (2019) note that progress in energy productivity might simply alter the flows of energy inputs and prices and result in the reallocation of energy and non-energy resources throughout the economy. The implication is that gains in energy productivity might not lead to net gains in economic growth. More fundamentally, the assertion that increased energy efficiency entails reduced energy consumption has been questioned (Khazzoom, 1980). In 1992 Harry Saunders described what eventually became known as the **rebound effect**, namely the hypothesis that energy efficiency might paradoxically lead to increased energy consumption. Saunders (1992) went on to show that this is true in neoclassical economic theory over a range of assumptions, which other academics confirmed. Thus, energy efficiency gains generally result in less-than-proportional reductions in energy consumption.

Different authors have identified and described different types of rebound effects, which can generally be classified in two types: direct and indirect. Direct rebound refers to the impact that a given energy service or product has on the use of that same energy service or product. An illustrative example could be a car buyer that drives an efficient car more frequently then she/he would an inefficient one. Indirect rebound reflect the impact of re-spending the money saved from improved energy efficiency (Nadel, 2012).

Gillingham et al. (2015) make a point of distinguishing between different types of rebound effects based on costless exogenous energy efficiency improvements on the one hand and typically costly policy-induced improvements on the other hand. They conclude that unless the rebound effect has serious external costs, it will still result in overall benefits, rather than costs, of energy efficiency policies (Gillingham et al., 2015). Empirically, research on household energy consumption found that almost half of the EU countries, including Norway, exhibit a rebound effect of above 50% and that in six Member States this effect is greater than 100%. Thus, rather than decreasing overall household energy consumption the net effect of energy efficiency measures results in an increase of energy use (Galvin, 2014).

The second strand of research looks at the structure of the economy and how it effects the overall energy demand. Since different sectors differ significantly in their energy use, a shift in the overall economic structure towards less energy-intensive economic sectors (such as services, finance) should entail reduced energy demand. A number of studies have reported convergence in energy use and productivity between countries and within manufacturing sectors (Miketa et al, 2015; Mulder et al, 2007).

Besides these two main strands, in the context of analysing the decoupling of energy consumption from economic growth, the degree of substitutability between energy and other factors in the aggregate production function needs to be considered. Early research on this topic reported mixed findings on whether capital and energy are complements of substitutes (Howarth, 1997). In a paper published in 1987 Solow argued that the contradictory findings may be the result of inadequate underlying assumptions of the aggregate production function approach (Solow, 1987). More recent work by, for example Stern (2010), reports that empirical findings in the literature attribute the observed decoupling to both technological change and **substitution** within a category of similar production inputs, for example, a shift to higher quality fuels (more energy dense). The substitution of energy for other production inputs plays a smaller role in the observed decoupling. Stern concludes that the elasticity of substitution between energy and capital is likely to be low. These observations are in line with research by ecological economists that draws attention to the limits of substitution between different production input categories and in particular the substitution of resources (including energy) by manufactured capital (Constanza and Daley, 1992).

2.3. Energy influence on other determinants of growth

The previous subsections indicate that as a factor of economic production and as an industrial sector of the economy, energy has a significant effect on a number of determinants of a country's economic growth. This sub-section is concerned with the review of the other channels through which energy affects economic growth. To that end, the analysis is focused on the relationship of energy with several factors highlighted in the literature as the most important determinants of growth.

The factors that determine economic growth have over the last decades attracted increasing attention in theoretical and applied economic research. Seminal empirical work in this field include the work of Kormendi and Meguire (1985), Grier and Tullock (1989), Barro (1991; 1996). The literature concerned with the identification of determinants of growth focuses on fitting the appropriate variables in linear growth regressions. The list of growth determinants has grown enormously in the cross-country regression literature, resulting in a total of more than 140 variables to date (Moral-Benito, 2012). From an empirical point of view, the problem of the ever-expanding list of determinants is due to model uncertainty, which arises because the non-unified growth theory does not provide enough guidance to the construction of empirical models (Moral-Benito, 2012).

In this subsection, the centre of interest of our analysis is the underlying factors of economic growth that have been widely recognised in the relevant literature and at the same time can be linked to energy. The determinants considered are 1) Technical change/R&D, 2) Human capital, 3) Climate change mitigation, 4) Openness to trade and foreign direct investment (FDI), 5) Public infrastructure, and 6) Energy quality. Other factors related to the institutional framework (e.g. regulatory institutions, macroeconomic stabilization institutions, property rights, etc.), political factors, sociocultural factors (e.g. trust, ethnic composition, cultural diversity, etc.), geographic factors (e.g. latitude, distance from coast, temperature, etc.), and demographic factors are not considered in our analysis.

Figure 0-9 Summary of energy influence on determinants of growth

		Theory	Examples
Growth determinants	*Technical change*	▪ High energy prices **enhance** technical change / innovation ▪ Energy policies can **enhance** low-carbon innovation	▪ Climate and energy policies in transport drove the demand pull behind the recent large cost reductions in lithium-ion batteries
	Human capital	▪ Energy access **enhance** the quality of human capital	▪ The benefits of household lighting to entertainment, time savings, education, and home productivity are estimated at USD 20–30 per month
	Climate change	▪ **Net negative effect** on growth, mixed results on impact of (renewable) energy consumption	▪ Impact on economy due to climate damages (e.g. from extreme events, global warming) and costs of adaptation and mitigation
	Openness to trade	▪ **Positive** relationship between energy consumption and international trade	▪ Estimates by the European Parliament indicate benefits for an internal energy market, of around 250 billion €/year
	Infrastructure	▪ Infrastructure is required for supply of certain energy carriers ▪ Indirect relationship by affecting other determinants	▪ Energy infrastructure (e.g. smart grids) is changing the role of the energy market actors, the functioning of the energy system, and business models.
	Energy quality	▪ **Positive** relationship between energy quality and growth ▪ **Energy ladder**: The shift to higher quality of energy accompanying development stages	▪ Use of electricity in farming, particularly irrigation, can increase productivity and thus economic growth

2.3.1. Technical change

Innovation and technical change has long been recognized as an important, or even the most important, factor of economic growth (see Section 1). Through several channels, energy can be a determinant of innovation itself which can increase productivity and trigger further economic growth. Apart from the intuitive notion that the availability of adequate energy supplies is a precondition for scientific knowledge development and for an effective R&D sector, energy prices are crucial as innovation instigator as well.

The underlying concept that relates energy prices and innovation is a modern manifestation of the “induced innovation” idea first proposed by Hicks (1932). It originally states that changes in the relative price of the factors of production induce innovation directed to economizing the use of the factor that has become relatively more expensive. In a similar fashion, the increasing price of energy is itself a spur to inventions that are less energy-intensive, meaning that the inducement mechanism would lead firms to introduce goods and industrial equipment that deliver higher utility and economic output, respectively, per unit of energy consumed.

The link between energy prices and technical change is supported by empirical research. Earlier research on induced environmental innovation include Lanjouw & Mody (1996) and Jaffe & Palmer (1997), however, the first to empirically show the link between energy prices in particular and induced innovation were Newel et al. (1999) and Popp (2002). Newel et al. (1999) conceptualized capital goods as products and their resourceconsuming properties as product characteristics and showed that innovation can respond to changes in energy prices by becoming more energy-efficient. Popp (2002), provides a more systematic evidence on the energy-saving innovations following an energy price increase. He looked at how energy prices impacted patents for energy-saving innovations using data from 1970 to 1994. Through this, he documented that there is a strong positive impact of high energy prices on the development of new technologies which reduce the cost of pollution control in the future. Moreover, Cheon and Urpelained (2012) found evidence that increasing international oil prices reinforce innovation and public R&D in renewables.

Other determinants of energy-related innovation are primarily environmental policies. There is a large body of literature aiming at measuring the effect of environmental policies on environment-friendly or energy-efficiency innovation. Usually these studies use patents to estimate how their number is affected by the policies (along with other factors) by means of panel data across countries. Relevant examples of empirical studies of such kind are Popp (2010) , Johnstone et al. (2010), Nesta et al. (2014), Calel and Dechezleprêtre (2016). Popp (2010) found that subsidies for climate-friendly R&D will increase energy R&D, but will have little impact on green innovation. Johnstone et al. (2010) found that different types of public policy instruments are effective for different types of renewable energy innovation. Nesta et al. (2014) liberalized energy markets can enhance the effectiveness of energy policies aiming to foster green innovation. Calel and Dechezleprêtre (2016) found that EU ETS has increased low-carbon innovation, while not crowding out patenting for other technologies.

However, these studies focus their analysis only on specific energy and environmental technologies, while other studies have a broader set of energy innovations. Recent such studies are Dasgupta et al. (2016), Fabrizi et al. (2018), and Sterlacchini (2019). Dasgupta et al. (2016) found that market-based incentives result in dynamic efficiency gains and that political economy factors are important for stimulating energy-related innovation. Similarly, Fabrizi et al. (2018) found that market-based regulation policies have a great contribution to green innovation and that participation in research networks can have the same effect. Finally, Sterlacchini (2019) concluded that environmental policy stringency has exerted more significant impact on "green" innovation than oil prices, and the policy stringency at the OECD aggregate level is more significant than individual country measures. This conclusion is also supported by Peters et al.(2012), Dechezleprêtre and Glachant (2014), and Costantini et al. (2017).

The infrastructure subsection discusses the diverse impacts that smart grid technologies have on the energy system and the economy. Especially, the development of smart grid technologies foster renewable energy technologies, distributed generation, electric vehicles and demand-side management. This illustrates the role of energy technologies as drivers of innovation within the energy sector and vice versa.

The case studies of section **Error! Reference source not found.** illustrate the interaction o f innovation and energy technologies. For example, while both lithium-ion batteries and fuel cell technology were developed initially for other applications such as aerospace, since the 2000s electric vehicles became their major market, driving R&D efforts and learning-by-doing which has drastically reduced the costs, especially of batteries. Fuel cell technology is also intrinsically related to hydrogen production and use throughout the economy. Climate policies driving decarbonization have recently revived the interest in hydrogen, which can play an important role in the decarbonization of hard-to-electrify applications. These include especially industrial processes such as steel making and production of chemicals as well as to provide heat to the poorly-insulated, old building stock (Trinomics, 2018).

2.3.2. Human capital

Access to energy services is fundamental to fulfilling basic human needs as well as to fuelling economic growth and social development. There is ample evidence that energy services can affect productivity, health, education, the water sector and communication services. Through these factors, access to and improvements in energy services can enhance human capital, which can be a driving force of economic growth. Indeed, there is an extensive literature that supports the positive relationship between human capital and economic growth, including (Lucas, 1988; Barro, 1991; Mankiw, et al., 1992; Barro and Sala-i-Marin, 1995; Aghion and Howitt, 2009).

Energy services can increase the availability of educational services as well as their quality (IEA, 2010). Modern, cleaner and affordable energy can contribute to reducing the dropout rates and increase the likelihood that children will attend and complete schools (GEA, 2012). Moreover, electricity can facilitate access to educational media and tools in schools and use of more sophisticated teaching equipment. In addition, communications at home can increase learning through various channels, from social interactions to distance-learning modules.

Energy is also crucial for the general improvement of the health of a population. Maintaining sanitary conditions, allowing access to advanced medical equipment, vaccination, and medication are only some of the different channels that energy services can enhance health. All the above can induce tremendous improvements in the quality of a country’s human capital.

In addition, there is a negative relationship between high quality human capital and energy use. Pablo-Romero and Sánchez-Braza (2015) have found that a more qualified work force uses more efficiently of the physical capital, which decreases the need for energy use.

Fang (2017) analyses the role of human capital within the energy-growth nexus for 56 countries, finding that human capital enhances the positive effect of energy as a factor input on growth. The study notes however that the literature on the topic is not consensual, with energy and human capital also having been indicated as substitutes rather than complements such as in Pablo-Romero (2015).

GEA (2012) indicates that energy services improve the quality and availability of educational services, which also impacts the chances of children completing school education. This occurs also through indirect ways, for example by creating a more children-friendly environment, e.g. with clean water, sanitation, lighting, space heating/cooling and cooking energy. Energy access also increases the retention of teachers in rural areas and electricity allows for equipment such as computers and printers. Clean energy and energy efficiency also reduces school buildings energy demand and thus educational costs, improves children’s health (for example by reducing pollution from biomass combustion), and frees up time for education by reducing the time spent e.g. collecting fuel or water. Furthermore, these aspects foster gender equality as many of the negative factors hindering education affect girls disproportionately. As an example, the World Bank ranges the benefits of household lighting to entertainment, time savings, education, and home productivity at USD 20–30 per month (GEA, 2012).

2.3.3. Climate change

Climate change will have a profound effect on economic growth. Sea-level rise, weather-related extremes (e.g. floods, heatwaves, and storms) and water scarcity are only some climate change effects that are already reducing the availability of commodities essential for growth. At the same time, climate change will have differing effects on the world, with the poorest countries (and households) being disproportionately affected by it, mainly due to having fewer financial resources to cope with it. Many studies have tried to estimate the impact of climate change on growth, with most of them measuring sectoral impacts of global warming individually and then adding them up to find the total impact. The first studies on the welfare effects of climate change were produced by Nordhaus (1991, 1994), Cline (1992), Fankhauser (1995) and Tol (1995). In general, most of these studies and more recent ones that are concerned with the estimation of the impact of temperature rise on GDP find that the effect will be negative, reducing global GDP as much as 4.8%, depending on the assumption of temperature rise. However, there are other studies that point out to initial benefits of a modest temperature increase, followed by negative effects once the temperature passes a certain threshold. For a review of these studies, please refer to Tol (2009). IPCC (2014) has estimated that the global annual economic losses for a temperature increase around 2.5ºC above preindustrial levels will be between 0.2 of 2.0% of income.

Reducing emissions to mitigate climate change entails some costs, such as costs of developing and deploying low-emission and high-efficiency technologies and consumer costs of shifting spending to low-emission goods and services. According to IPCC (2014a), mitigation scenarios that are *likely* to limit global warming to lower than 2ºC through the 21st century compared to preindustrial levels entail losses in global consumption of 1 to 4% by 2030, 2 to 6% by 2050, and 3 to 11% by 2100, relative to consumption of the baseline scenario, which increases anywhere from 300% to more than 900% over the century. Furthermore, delaying mitigation action increases mitigation costs in the medium- and long-term (IPCC, 2014a).

The same applies to adaptation planning and implementation, which will be required even in a 1.5ºC temperature increase relative to pre-industrial levels. There is currently very little quantified evidence on the cost of adapting to this level of climate change. Economics tells us that the optimal level of adaptation is the point where the marginal cost of adaptation is equal to its marginal benefit (IPCC, 2014b). However, the more mitigation efforts delay the more expensive adaptation to ever increasing temperatures will be, as more intense phenomena will need to be addressed. Since the assessment of adaptation costs and benefits is a rather difficult exercise, its impact on economic growth cannot be clearly defined, nevertheless, further work on this is urgently needed to build the evidence base for a more informed and cost-effective, adaptation policy.

The demand for energy will be also affected by climate change. According to IPCC (2014b), climate change will likely increase the energy demand in most regions of the world. These temperature-induced changes in energy demand can cause a change in the global GDP between -3 to +1.2%. Energy supply will also be impacted through temperature- and non-temperature-induced factors, however, non-temperature-induced effects have not fully been studied and thus the full cost estimates of climate change on energy supply is underestimated. Energy-related economic impact is expected to be negative in developing and positive in developed countries (IPCC, 2014b). Adaptation within the energy sector is necessary in order for the cost of climate change to be reduced, but much research is still needed to identify the implications of extreme weather on the energy sector.

Climate change and its mitigation have been clearly linked to anthropogenic activity. A large body of literature has established a significant relationship between renewable energy consumption and economic growth. The renewable energy consumption-economic growth nexus has been described following four different hypotheses, similarly to the energy-growth causality relationship described above (see Section 2.2). The *growth hypothesis* implies that renewable energy as a primary source of input has an impact on growth with causality running from energy consumption to economic growth. In the *conservation hypothesis,* the unidirectional causality is running from economic growth to renewable energy consumption, assuming that an increase in economic output increases energy use. The *feedback hypothesis* assumes a bi-directional causality between renewable energy consumption and economic growth, which are jointly determined and affected at the same time. The *neutrality* hypothesis suggests that economic growth and renewable energy consumption are independent and completely unaffected from each other.

Sadorsky (2009) used data from 18 emerging economies and empirically established a causation between economic growth and renewable energy consumption, confirming the conservation hypothesis in the long-term. In the short-term the study finds no feedback in either direction between renewable energy consumption and growth (the neutrality hypothesis).

Bowden and Payne (2010) analysed the causal relationship between both non-renewable and renewable energy use and economic growth in the U.S., finding no causality between commercial and industrial renewable energy consumption and economic growth. However, they found evidence for a positive causal relationship running from residential use of renewable energy to economic growth, supporting the growth hypothesis.

Menegaki (2011) does not confirm any kind of causality direction between renewable energy and economic growth in the short- and long-term in the EU-27, supporting the neutrality hypothesis and concluding that the low levels of renewable energy consumption for 1997-2007 cannot play an important role in enhancing economic growth.

In a series of empirical investigations, Apergis and Payne (2010a, 2010b, 2011a, 2011b, 2011c, 2012) studied the causal relationship between renewable energy use and growth for many groups of countries including both developed and developing ones. In the majority of the cases, the results show that there are cointegration relationships and bidirectional causality for the long- and short-term, supporting the feedback hypothesis.

Moreover, Apergis et al. (2010) found that there is a short-term bidirectional causality between low-carbon energy use and economic growth, suggesting the feedback hypothesis, and the long-term analysis revealed an unidirectional causality running from consumption of nuclear and renewable energy to economic growth, validating the growth hypothesis.

Apart from renewable energy, mitigation efforts include energy efficiency measures as well. Coupled with measures of transition to a low-carbon energy production, energy efficiency projects in key sectors (energy supply, transport, industry, building) can lower the demand for energy and are considered by many scholars as a precondition to reach a carbon neutral future. Energy efficiency measures in the transmission and distribution of energy has a great potential to contribute substantially to the mitigation of the impact of the energy sector on climate change. Losses as a fraction of power generated tend to be lower in developed countries, with developing countries reaching up to 20% in 2010, while developed countries had losses around 6.5% in 2000 (IPCC, 2014c). Energy efficiency measures in the transport sector include efficiency improvements (e.g. in engines, vehicle design, appliances, materials), modal shifts (e.g. from privately owned vehicles to public transport), and improved logistics, etc. Energy efficiency in buildings involve efficiency improvements in devices (e.g. heating/cooling systems, cooking, lighting, etc.), systemic efficiency (e.g. integrated building design, district heating/cooling, smart grid, etc.), and behavioural changes. Industry energy efficiency include improvements in motors, boilers, recycling, etc. as well as effective reduction of demand for goods, and improved durability and reparability of products. Although a substantial body of literature is dedicated to the energy efficiency measures mentioned above, their contribution to lowering the total energy demand cannot be precisely estimated. All the more so because the rebound effect has the ability to significantly lower the potential gains of such measures.

2.3.4. Openness to trade and foreign direct investment

Openness to trade has long been associated with the increase of economic growth of a country. The relationship between exports and economic output is one of the most exhaustively researched area in international economics (Giles and Williams, 2000). However, the link between energy and international trade is an important yet understudied topic. The study of this relationship is important for several reasons. If, for example, energy consumption is found to be associated with trade, policies to reduce energy use can be harmful for international trade, impeding economic growth. Moreover, as Rahman and Mamun (2016) pointed out that "an absence of international trade variable (export plus import) in a growth model may underestimate or overestimate the effect of energy consumption on macroeconomic growth."

There are empirical studies investigating in particular the relationship between energy consumption and trade. Generally, most papers find a positive relationship between energy consumption and international trade, with the direction of causality varying significantly among different papers. From the papers reviewed here, three have found unidirectional causality running from energy consumption to trade, three found evidence of the opposite unidirectional causality, five found a bidirectional causality, and two no relationship at all.

Cole (2006) examined the trade liberalization-energy consumption relationship, finding that trade liberalization enhances economic growth, which is what boosts energy demand. In addition, trade liberalization stimulates capitalization, which also affects energy use. For a panel of six Middle Eastern countries, Narayan and Smyth (2009) found evidence of causality running from electricity to real GDP and from real GDP to exports in the short-term and in the long-term evidence of causality running from electricity use and exports to real income and real income to electricity consumption. In two papers, Lean and Smyth (2010a; 2010b) found evidence for causality running from electricity generation to exports in their first paper and no evidence for causality between these two factors in their second.

Sadorsky (2011) did not focus only on electricity, instead he looked at energy consumption in general. He found causality running from exports to energy consumption in the short-term and a feedback relationship between imports and energy use. In a similar paper for a panel of seven South American countries, Sadorsky (2012) showed a bi-directional causality between energy consumption and exports, output and exports, and output and imports in the short-term and an unidirectional short-term relationship from energy use to imports. For the long-term, his result showed a causal relationship between trade and energy consumption.

Ghani (2012) examined the relationship between trade liberalization and energy demand, indicating that trade liberalization has an insignificant impact on energy use, but only until a certain level of capital per labour is reached after which it affects energy consumption. Dedeoğlu and Kaya (2013) looked at the relationship between exports and imports and energy consumption by integrating economic growth as an additional factor of trade openness and energy use. Their results showed a cointegration among all variables and a positive impact of economic growth, exports, and imports on energy consumption. Moreover, the causality of the relationship between energy consumption and exports (imports) is bidirectional. Nasreen and Anwar (2014) explored the same relationship between growth, trade and energy consumption. Their results revealed a positive relationship between energy use and income growth and between energy use and trade openness, while an inverse relationship is observed between energy consumption and energy prices. The analysis of their estimations confirms a feedback causality between economic growth and energy use and between trade openness and energy use.

Ben Aissa et al. (2014) focused on renewable energy consumption and trade. Their results indicate that no causal relationship between renewable energy use and economic growth exists nor does exist between renewable energy use and trade in the short- and long-term alike.

Energy can have an effect on international trade through other channels than energy consumption, however these channels have not been examined in depth in the literature. For instance, renewable energy can enhance the integration of developing and developed countries in international trade, while openness to trade can be a driving force for renewable energy technology transfer (Amri, 2017). On the other hand, Inglesi-Lotz (2018) indicated that energy conservation policies targeted at decreasing greenhouse gas emissions may lead to a reduction in international trade, when the trading leads to significant emissions as in the case of oil-intensive fuels (e.g. road transport of bulk cargo). Moreover, the effects of cross-border energy infrastructure development, which has been a widespread practice particularly in the EU, on the trade relationships of the two (or more) involved states has not received attention in the relevant literature.

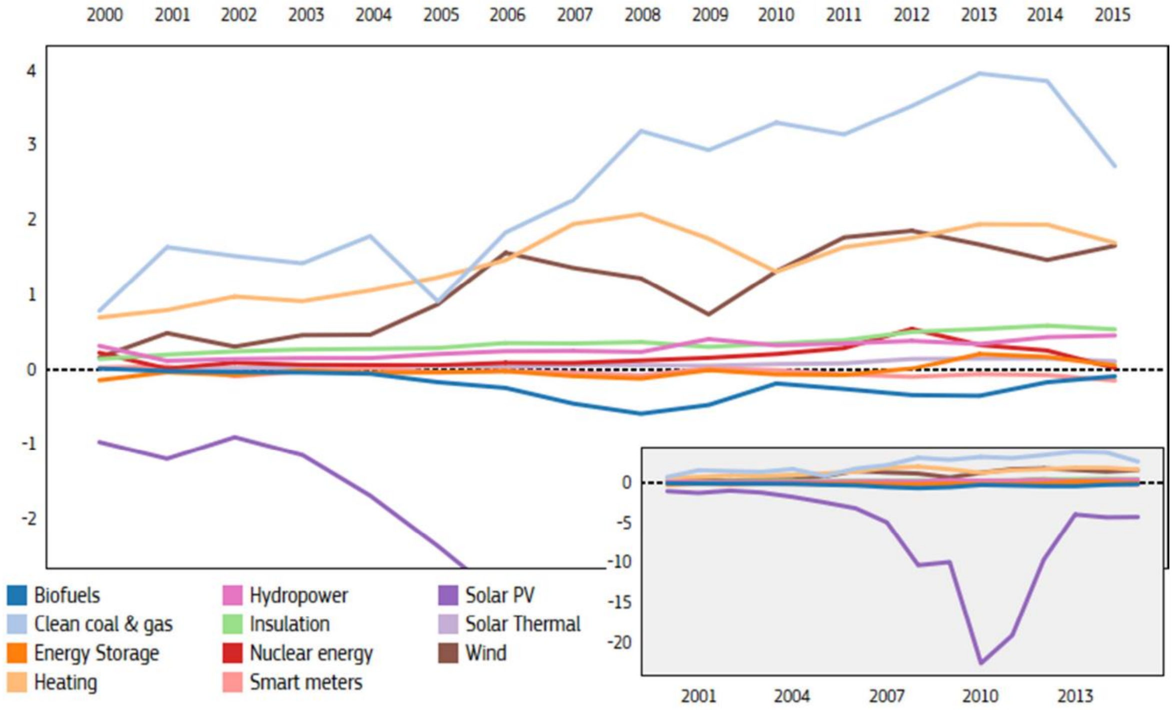
Reviewing studies assessing the benefits of energy markets integration, a DG Energy study (Booz&Co., 2013) found there is little research on the topic for gas markets, where nonetheless increased security of supply and reduced energy prices arise as the most important benefits. The literature review of the study then shows that integration of electricity markets on its turn may lead to improvements between 1 to 10% of electricity system costs (which should lead to a much smaller macroeconomic impact), with an important part coming from the integration of renewable energy sources when applicable. The study’s own quantification of the price-reduction benefit of an European internal gas market sets it at 30 billion €/year, with additional unquantified benefits to security of supply and retail competition. The assessment of the benefits of an European internal electricity market indicates market coupling will lead to benefits of up to 4 billion €/year (Booz&Co., 2013). However, a truly integrated electricity market going beyond market coupling could provide up to 40 billion €/year of benefits. Estimates by the European Parliament indicate even higher benefits for an internal energy market, of around 250 billion €/year (EP, 2015).

The trade in energy technologies of EU Member States with each other surpasses the value of the EU28 with non-EU countries. From 2000 to 2015 European trade flows increased, with the export surplus of the EU28 growing especially for coal & gas[8] (to over 2 billion €), heating and wind (each over 15 billion €). This while solar PV and biofuels constantly exhibited an export deficit, with solar PV accounting on average for half the EU energy sector technology imports (Figure 0-10). Furthermore, this export deficit was concentrated in a few Member States: Belgium, Germany, Spain, Italy and the

[8] Comprises the following products: ‘Condensers for Steam or Other Vapour Power Units’, ‘Other Gas Turbines of a Power Not Exceeding 5,000kw’, ‘Other Gas Turbines of a Power Exceeding 5,000kw’, and ‘Parts of Other Gas Turbines’.

Netherlands. The Chinese share in imports of energy technologies increased from 3% to 15%, while for the US it changed from 51% to 23%, accompanying a general shift of imports to Asia. On the other hand, in 2015 the main EU partners for export were the US, Switzerland and Russia.[9]

Figure 0-10 EU trade balance with extra-EU (billion €)



Source: JRC (2017) EU energy technology trade

The International Energy Charter of 2015 and the Energy Charter Treaty of 1994 aim to promote international investments enabling the energy transition and energy access, guarantee investors' rights in international disputes, and serve as a benchmark for the regulatory reform of energy markets worldwide. As such, the Treaty is a particular example of international trade agreement by addressing private investment dispute resolution, which lately has come under scrutiny, with Italy and Russia withdrawing from the Treaty recently. Nonetheless, the 2015 and 1994 initiatives supported international trade and investments in energy.[10] Within this context of increased multilateral agreements for international energy trade and investment, the World Energy Council developed rules on energy trade. It highlights the conflict in national policies which aim to foster the deployment of renewable energy source and at the same time apply import tariffs in renewable energy technology, affecting the economies of scale, ultimate market size and the incentives for innovation. The Council lists several initiatives to reduce trade tariffs in

---

[9] JRC (2017) EU energy technology trade

[10] Bonafé (2017) The New International Energy Charter: Sustainable Energy Transition, Investment Dispute Resolution and Market Regulation

environmentally-friendly technologies, including within the G8 and the Asia Pacific Economic Partnership. A product list covering energy efficiency, renewable energy, natural gas, CCS and nuclear is proposed to be addressed in an environmental goods international trade agreement.[11]

2.3.5. Infrastructure

The different infrastructure classes include transportation (passenger and freight), ICT, energy (electricity, heat and fuels and petrol, especially gas), water and waste (solid and sewage). The link between infrastructure and economic growth is relatively well established in the literature, however *how much* it matters remains a debatable topic. Estache (2012) does find that infrastructure investment requirements vary significantly across regions, but nonetheless the need for energy infrastructure is the highest, accounting for 40-60% of the total. Also, while Estache (2014) highlights the importance of infrastructure to growth, it notes until recently that infrastructure was mostly left unaddressed in mainstream macroeconomic models and in country development strategies, in the case of sub-Saharan Africa. Hence, there are few theoretical studies addressing the nexus of *energy* infrastructures specifically and the determinants of growth. This despite World Bank projects between 1964 and 2003 showing a social rate of return of 18.4% for energy and mining, and with energy being the single most efficient infrastructure investment for growth (Estache, 2012, 2014).

First, infrastructure in general and energy infrastructure in particular can impact several of the determinants of growth reviewed in this sub-section. Clearly, infrastructure can reduce the price of energy goods used in intermediate and final consumption, but also lead to growth through more unconventional channels.[12] First, energy infrastructure can enable innovation diffusion in different markets. Investments in smart grid technologies are the fastest-growing investment class in electricity networks. The broad range of smart grids technologies generally provide data gathering, analysis and control capabilities which are already changing the role of the energy market actors, the functioning of the energy system and facilitating new business models. Smart grids improve the reliability of the energy system, allow to develop renewable energy sources, distributed generation (including behind-the-meter), electric vehicles and demand-side management, among others.

Second, infrastructure reduces transaction costs, improving domestic and international trade. Moreover, while historically international energy infrastructures have been developed primarily for security of supply, in the last decades they have enabled the integration of energy markets worldwide, with the EU being a prime example as discussed in the openness to trade subsection (subsection 2.3.4).

Third, energy infrastructure development leads to significant investments, with the IEA (2018) estimating that global investments in electricity networks alone in 2017 amounted to 300 billion USD, with EU investments amounting to 35 billion USD, in line with the figures reported by Ecofys (2014). Investment in infrastructures can furthermore constitute a counter-cyclical, fiscal policy. Besides promoting trade, energy and other sectors,

[11] World Energy Council (2015) World Energy Perspective – Catalysing the Low-carbon Economy

[12] The following channels are based on Srinivasu (2013) and Carlsson (2013).

infrastructure allows for the clustering of economic activity, leading to economies of scale and specialization. Also, energy infrastructure allows for automation, freeing up time for individuals to spend in more productive activities and allowing for further specialization of work.

Fourth, energy infrastructure promotes human capital, especially through increased energy access in developing countries. As discussed in the specific subsection, the impact manifests itself through better education, health and improved services from other infrastructures such as water and communication.

However, infrastructure development alone does not automatically lead to growth. Weak institutions, low competition in the economy and poor infrastructure regulation all limit the socio-economic payoff of infrastructure. Moreover, infrastructure payoffs are slow to manifest themselves, as the long-lived, lumpy and capital-intensive investments provide returns only in the long-term (Estache, 2012). Furthermore, disruptions in energy supply due to infrastructure issues can lead to important economic impacts due to the dependence of the economy on energy inputs, such as electricity, natural gas or oil products. This is attested by the high reliability standards that drive infrastructure development and result in the higher infrastructure capacities in order to guarantee security of supply.

2.3.6. Energy quality and developmental stages

In economics, energy quality refers to the relative economic usefulness of different fuels and electricity per heat equivalent (Stern, 2011). There is a wide range of physical characteristics that affects a fuel's relative quality. These include a fuel's energy density (heat unit per fuel unit), power density (energy density per time), cost of conversion, ease of distribution, ease of storage, physical scarcity, controllability, safety, and environmental impact (Cleveland et al., 2000; Stern, 2011). In addition, some fuels can be used for more valuable activities than others. Some energy resources are more productive than others and offer a higher utility in output production. In other words, the shift to a higher quality fuels, such as electricity, has an impact on the amount of energy required to produce a given economic output, which clearly affects economic growth. There have been many ways to measure energy quality a comprehensive review of which is presented by Stern (2010).

There are very few studies that have incorporated energy quality considerations in their examination of the energy-GDP cointegration/causality. Stern (2000) used a quality weighted energy index in his cointegration analysis, showing that energy is significant in explaining GDP and finding evidence of cointegration among GDP, capital labour, and energy. Oh and Lee (2004) followed Stern's approach and arrived at similar conclusion. Warr and Ayres (2010) replicated Stern's model and used their own measure of exergy (i.e. the energy available for useful work) instead of Stern's energy quality index. They found both short- and long-term unidirectional causality running from their energy quality measure to GDP. Finally, Liddle (2012) applied panel cointegration estimations to OECD panel data disaggregating among five most energy intensive manufacturing sectors, adjusting energy consumption for quality of the energy sources, which confirmed the importance of energy quality in these energy-intensive manufacturing sectors. In general, the results of these studies, showed that there is a positive relationship between energy quality and GDP.

Related to the quality of energy use is the concept of energy ladder. As the economies move through different stages of development, it has been observed that the relationship between energy and economic activity, as well as the energy mix, change significantly. This phenomenon was first described by Barnes and Floor (1996) as the energy ladder. At the lowest level of income and social development, energy comes predominantly from harvested biological sources (such as wood and dung), sun, and human effort. At the intermediate stages of development, other sources of energy, including processed biofuels (e.g. charcoal), animal effort, and some fossil fuel energy sources become more prominent. At the highest level of development, when industrialization has occurred, commercial fossil fuels become predominant together with electricity. To this it could be added that highly-developed economies aim to replace fossil fuels by renewable energy sources.

In general, the continuous process of development provides the means to avoid the use of traditional fossil fuels and as incomes increase, households consume higher quality energy carriers like electricity (Hosier, 2004). As a general trend, at the national level, as income per capita increases, there is a shift to higher share of electricity in final energy use (Burke, 2013; Burke and Csereklyei, 2016; Csereklyei et al., 2016). However, as Barnes and Floor (1996) and others have recognized the ladder does not imply a monotonic transition through different types of energy. Energy resources typically associated with different types of development can be used concurrently at any stage of income and social development (Toman and Jemelkova, 2003). Moving up and down the ladder for different energy-related services can be a result of changes in relative opportunity costs and household incomes. Nevertheless, as a general trend at the national level, as income per capita increases, there is a shift to a higher share of electricity in final energy consumption.

As an example, GEA (2012) illustrates how energy access can affect development in rural areas through several channels. As irrigation is a central factor in developing agriculture, mechanized water pumps increase crop yields, facilitates switching from single- to multi-cropping, and increases the willingness of farmers to invest in fertilizers, improved seeds and other technologies which reduce their risks and improves productivity. Moreover, reliable and affordable energy enables value-adding activities and post-harvest processes, also allowing households to develop off-farm activities.

3. Case studies in (energy) technology transitions

3.1. Introduction

This section presents case studies on energy technology transitions. The objective is to define which of the innovation aspects discussed and which of the impacts of energy on growth covered in previous sections can be observed in the technology transitions. This provides evidence of the relevance of the aspects identified in the theoretical review, which provides a prioritization of the aspects which are most important to be represented in the models and scenarios reviewed in section **Error! Reference source not found.**.

As a complementary objective, the case studies present data on the value chain, market, patenting and academic publications in the technologies, according to availability. This provides further data for the representation of the technology transitions in macroeconomic models.

The six case studies are presented in Annex A. Section 3.2 compares the results of the case studies according to the innovation aspects discussed in section 1 and the impact of energy on growth as analysed in section 2.

The case studies have been selected according to their importance to central energy technology and industrial priorities of the EU:

- The key strategic value chains chosen by the Strategic Forum for Important Projects of Common European Interest (Council, 2019)
- The most relevant energy technologies in the 2050 Long-Term Strategy (EC, 2018a)
- Eligible areas for financing and investment operations in the InvestEU programme (EC, 2018b)
- Project categories mentioned in the proposal for the update of the EU Innovation Fund (EC, 2019)

Using expert knowledge of the project team on the importance of each of these priorities and considering the availability of data for the case studies, the six technologies presented in Table 0-3 were scored in the ranking and selected. The case studies cover a number of value chains, focus on current energy technology transitions, but include also a historical energy technology transition (combined cycle gas turbines) and a case study only partly related to energy (autonomous vehicles). The focus has been on technologies which have reached a certain maturity (although not necessarily large-scale commercial deployment).

The final list of case studies is:

- Case study 1: Combined cycle gas turbine
- Case study 2: Lithium-ion batteries
- Case study 3: Hydrogen fuel cells
- Case study 4: Carbon capture and storage
- Case study 5: Solar PV
- Case study 6: Autonomous road vehicles

Table 0-3 EU energy technology and industrial priorities ranking

Category	Technology	Score
Low-carbon energy technologies	Hydrogen technologies and systems	1.5
	Batteries (Li-Ion)	1.5
	Low-carbon industrial processes and carbon capture and valorisation technologies	1.3
	Solar PV	1.0
	Wind (bottom-founded offshore, floating offshore, onshore)	1.0
	Heat pumps	1.0
	Low-carbon steel-making	1.0
	Demand-side management	0.9
	Net zero energy building construction and renovation	0.9
	Electric mobility for vehicles	0.9
	Biofuels (2nd generation)	0.8
	Geothermal	0.5
	Synthetic methane gas	0.5
	Methanol	0.5
	Ocean energy	0.5
	HVDC transmission	0.4
	Concentrated solar power	0.4
	Nuclear fusion	0.4
	Nuclear fission	0.4
	Hydropower	0.4
Other technology innovation	Connected and autonomous mobility for vehicles	0.9
	Circular economy processes	0.8
	Industrial internet of things	0.6
	Cybersecurity	0.6
	Smart Health: Medical devices and personalized medicine & analytics	0.5
	Microelectronics	0.5
	High-performance computing	0.5
	Power gas-fired turbines	0.3
	Internal combustion engines	0.3
	Wired and wireless networks	0.1
	Additive manufacturing	0.0
	Bio-based materials	0.0

The case studies have all been organized according to the following structure:

- Technology and market overview
    - Short description
    - Cost reductions
    - Market status (with a summary table)
- Development of the technology
    - Summary of the development (with table)
    - Main historical phases in the development
    - Future growth and sectoral interactions

3.2. Comparative analysis of the technology transitions

This section compares the technology transitions from two perspectives using evidence collected in the case studies:

The innovation aspects most relevant as identified in the case studies, building on the aspects identified in section 1.

The impact of energy technology transitions on growth, building on the analysis of energy as a factor of economic growth of section 2.

One aspect to consider is that the case studies cover **two outcomes for historical energy transitions**. In the first, successful innovations have been able to establish a significant market in the (recent) past, such as in the case of combined cycle gas turbines, solar PV and lithium-ion batteries. However, a second outcome is possible where such an established market does not exist (yet). Hence, while fuel cells have been applied since the 1960s, the total global market is still limited. Likewise, CCS has a long history of research (albeit shorter than fuel cells) but has NOT moved to large-scale commercialization, and highly or fully autonomous vehicles are yet to be commercialized. However, this outcome conceals the fact that the market prospects for these technologies differ significantly, with fuel cells and autonomous vehicles poised for significant growth in the coming years already.

Although the case studies highlight a number of innovation aspects, the **limitations of the methodology** must be considered before the analysis of the results. First, 5 of the case studies focus on energy technologies are conducted, and therefore the results discussed relate only to the energy sector and may not apply to other innovations, e.g. regarding digital technologies which may fundamentally transform the economy and lifestyles and thus for example provide further evidence for paradigm changes. This is partly addressed by the analysis of autonomous road vehicles, which already can be characterized as new technology systems with higher interaction with other technologies.

Moreover, although the case studies include 3 technologies which are not yet deployed in large-scale, the focus is on (potentially) successful energy technology innovation and their impact on growth, with the risk of positive bias. Hence, some of the innovation aspects for which there is no evidence of importance may still play a role in blocking innovations.

Finally, some innovation aspects are more difficult to be observed and measured, such as government policies for knowledge diffusion or international academic/private cooperation. Nonetheless, given the complexity of technology transitions, some of these are extremely relevant, although here the case studies address this potential pitfall by conducting an extensive qualitative analysis of the technology development.

Table 0-4 Summary of the case studies in technology transitions (I)

	Lead countries			Innovation aspects			Market		
	Past	Present	Future	Past	Present	Future	Past	Present	Future
Combined cycle gas turbines	Leadership of **US** with **DE, JP** gaining modest market shares			**Knowledge diffusion** within industrial conglomerates **Spillovers** from aerospace **Supply push** by R&D from conglomerates driving **learning-by-searching** Competition driving clear **vintage** efficiency leaps			Sustained growth to late 2000s **60-80 GW/y**	Moderate, developing markets **50 GW/y**	Uncertain with mixed regional drivers **60 GW/y**
Lithium-ion batteries	Begin in **US**, **JP** taking lead with shift to portable devices	**CN, KR** accompanying shift to new markets, **JP** 3rd	**Asia** maintains lead**, US** (and **EU**) catching up	**Supply push** by R&D from industry and academia **Knowledge diffusion** within national innovation system			Start with niches Growth due to portable devices **20 GWh** in 2010	Strong growth due to EVs, especially China	
				Policy by R&D support	**Policy** by varied instruments **Increasing returns** due to Asia supply chain			**100 GWh** in 2016	**1200-1600 GWh** in 2030
Hydrogen fuel cells	**US, JP** for multiple variants **KR, CN, DE** for specific variants	**US, KR, JP** for technology **CN** for manufacturing and demand	Determined by **CN** developing technology, and **EU** manufacturing	**Policy** by R&D support **Supply push** by private R&D			Niche applications **96 MW** in 2010	Strong growth due to EVs, but competition with lithium-ion batteries	
				Policy by public demand pull	(inter)national **knowledge diffusion** **Policy** by varied support, including strong demand pull			**500 MW** in 2016	**400 GW** in 2020-2030
CCS	**US, CAN, NO**	**US, CAN, NO, NL, BR, JP, AU, SA, UAE**	**US, CAN, NO, NL, BR, JP, AU, SA, UAE**	**Spillovers:** from geology sector, steel and iron, cement, chemical and fertilizers, to electricity Demand pull: from steel and iron, cement, chemical and fertilizers **Spillovers**: to Carbon Capture and Utilization (CCU), hydrogen from fossil fuels			**18 large-scale** facilities in operation worldwide (0.4 to 1 million tons CO_2/y)		At least **27 large-scale facilities** in development or construction

	Lead countries			Innovation aspects			Market		
	Past	Present	Future	Past	Present	Future	Past	Present	Future
				Policy: CO_2 emissions tax (NO) R&D **Knowledge diffusion:** from oil industry and geology sectors **Supply-push:** Research programs e.g. MIT's **Demand-pull:** Additional recovery of oil	**Policy:** ▪ Carbon pricing, e.g. ETS ▪ R&D support (investment, production support) ▪ Guidance to mitigate **uncertainty and path dependence** **Social systems:** increased public acceptance due to awareness on climate change				worldwide
Solar PV	**US, JP, DE, EU**	**EU, DE, JP, CN**	**CN,JP**	**Policy**: ▪ Public R&D investment ▪ Long-term policies to reduce uncertainty ▪ Subsidies and tax cuts **Supply push** by academia R&D **Knowledge diffusion** from academia to industry **Demand pull** from niche markets **Spillovers**: electronics (electronic connectors, chip-making industry, lithography, microprocessors and LCD)		**Increasing returns** due to economies of scale **Social systems** based on increased climate change awareness and public acceptance To a lesser extent **policy** **Demand pull** from emerging markets such as IT, AI, distributed power-generation	Global capacity of less than **50 GW** in 2008	Global capacity of over **400 GW** in 2017	Up to **8500** GW of installed capacity by 2050
Autonomous road vehicles	**US, DE, JP, EU** with R&D	**US, DE, JP** with traditional car manufacturers and disruptors **CN** with disruptors		**Knowledge diffusion**: Industry-academia partnerships with researcher mobility **Supply push**: Academia, increasingly disruptors (digital, mobility services, EVs), car manufacturers **Spillovers** e.g. audio/safety **Policy** through e.g. R&D, guidance	Varied **policy**, including regulation **Spillovers** e.g. digital/platform techs, connected vehicles **New technology systems:** Mobility services with connected and autonomous vehicles		No significant market up to 2019		Growth with US, CN and EU being major markets **60-77 billion USD** by 2030

Table 0-5 Summary of the case studies in technology transitions (II)

Case	Cost reductions		Competitiveness	Sectoral interactions	
	Past	Future	Present[13]	Past	Future
Combined cycle gas turbines	**Strong reduction at start** (above 20% in 1980-2000) **Moderate reduction later** (10% in 2008-2018)	**Limited reduction** (4% in 2020-2030)	**Competitive**	Spillovers from **aerospace and oil & gas** Security of supply and primary supply to **electricity sector**	Mixed interaction with **renewables and combined heat-and-power** Potential for **electricity supply from low-carbon gases** Positive driver from **coal phase-out** Sustained spillovers with **aerospace and oil & gas**
Lithium-ion batteries	**Strong reduction** EV: More than 70% from 2010 to 2017 Stationary: 25% from 2010 to 2015	**Strong reduction** EV: 50% from 2017 to 2030 Stationary: 80% from 2017 to 2030	**Mobility:** +48% compared to ICE vehicle **Stationary power supply:** competitive for short-duration discharges	Demand pull from **electronics, mobility and power supply**	Enabler of **renewable power and EV** development Enabler of **renewable isolated power systems** Enabler of **digitization**
Hydrogen fuel cells	**Strong reduction** PEMFC: over 80% from 1995 to 2006	**Strong reduction** PEMFC: 75% from 2015 to 2030 AFC: 50% from 2015 to 2030	**Mobility:** +0.25 USD/km compared to BEV **Stationary power supply:** 80%+ to CCGT LCoE	Niche demand pull (**aerospace, marine, military**)	Strong interaction with the hydrogen economy: ▪ Hydrogen supply ▪ Secondary transport infrastructure (**refuelling stations**) ▪ Transport decarbonization (**EVs but also rail, maritime**) ▪ Industry decarbonization (power and feedstocks) **Energy system integration and flexibility** (electricity and gas) Cheap electricity supply from **renewable power**

[13] For lithium-ion batteries: BNEF, 2017. Lithium-ion battery costs and market; Schmidt, O., Melchior, S., Hawkes, A., Staffell, I., 2019. Projecting the Future Levelized Cost of Electricity Storage Technologies. Joule 3.

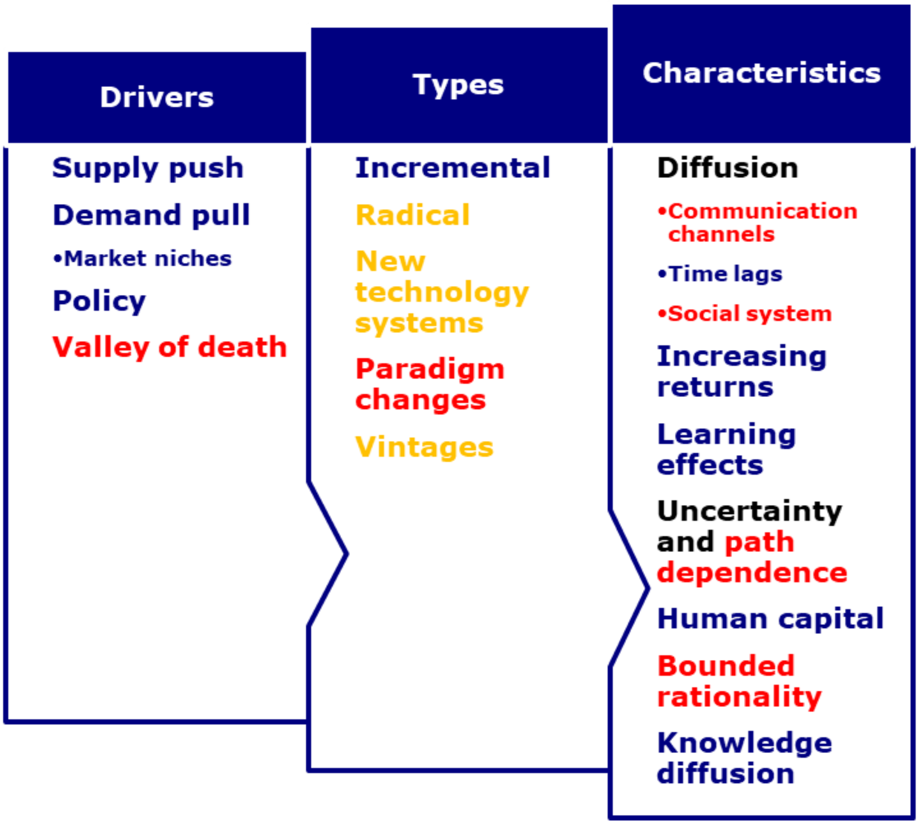
For hydrogen fuel cells: Morrison, G., Stevens, J., Joseck, F., 2018. Relative economic competitiveness of light-duty battery electric and fuel cell electric vehicles. Transportation Research C 87; Lazard, 2018. Levelized Cost of Energy 2018

Case	Cost reductions		Competitiveness	Sectoral interactions	
	Past	Future	Present[13]	Past	Future
CCS	**Costs still highest barrier and vary significantly** No comparable cost reduction available due to maturity. Available costs of CO_2 avoided: ▪ USD 21.5/t for gas processing and bio-ethanol production ▪ USD 78/t for coal-fired power ▪ USD 89/t for gas-fired power ▪ USD 124/t for cement production	**Moderate reduction** Decrease of first-of-a-kind to nth-of-a-kind range between -5% to -28%	**Power generation:** First-of-a-kind plant plants between+2%(natural gas) and +70% (PC super-critical)	**Spillovers** from the geology sector Important application for the **steel and iron, cement, chemical and fertilizers industries and power-generation** to mitigate GHG emissions Can be used to **produce carbon-neutral hydrogen** from steam reforming Capture and transport technologies can be used for **Carbon Capture and Utilization** (CCU)	
Solar PV	**Strong reduction** LCOE from more than 50 €ct/kWh to less than 10 €ct/kWh	**Further reductions** Predicted: 2 €ct/kWh by 2050	**Competitive**	**Spillovers:** ▪ Electronic connectors ▪ Chip-making industry ▪ Lithography ▪ Microprocessors and LCD	Will depend on **storage** technologies to solve the issue of intermittency
Autonomous road vehicles	No past cost data available for level 3-5 autonomy	**Strong reduction** Level 3: 60% from 2015 to 2035 Level 4: 38% from 2015 to 2035	**Personal vehicles:** +20% per km	**Spillovers** from digital technology **Air/space/marine** automated vehicles **Spillovers** from vehicle safety & comfort within car manufacturers	Growth synergy with **platform and digital sectors, connected electric vehicles**

3.2.1. Innovation aspects in technology transitions

Figure 0-11 highlights the most relevant innovation aspects identified in the case studies. These are discussed in detail next, according to the categories of drivers, types and characteristics of innovation.

Figure 0-11 Relevant innovation aspects identified in the case studies



Relevance of innovation aspects in case studies on technology transitions:

Relevant **Partially relevant** **No relevance observed**

Drivers of innovation

The influence of supply push and demand pull can be observed throughout the case studies. Specific supply push can be observed in the innovation aspects, while the analysis of markets lists the influence of different applications in the technology phases. The analysis shows that a combination of supply push and demand pull is a requirement for all successful innovations, which comprise CCGTs, lithium-ion batteries and solar PV.

However, the relative importance of supply push and demand pull differs per case. CCS technology for climate mitigation has been almost exclusively driven by supply-side incentives, while the recent Chinese leadership in solar PV is mostly due to emphasis on demand-side policies. Fuel cells markets did not take off yet due to a lack of technology competitiveness, despite significant R&D efforts indicating a lack of demand pull (which is changing due to climate policies).

Hence, supply push is a determinant aspect of innovation in all case studies, with development efforts necessary for all technologies. In the case studies R&D efforts are conducted both by academia and industry, at different intensities per technology and phase. Moreover, the lead private actors conducting the R&D efforts differ per case, e.g. in CCGTs R&D has been led especially by industrial conglomerates, while for autonomous vehicles disruptors such as electric car manufacturers (e.g. Tesla) and mobility service companies (Uber, Lyft) are pivotal, including in new markets such as China. Moreover, industry is present also in the early phases for all technologies, due to the scope of the case studies which do not analyse the invention/basic research phase.

Likewise, although demand pull is a required aspect for the success of technology transitions, the drivers behind demand pull are varied and their relative importance accompanies changes in the environment in which the technologies are applied. Economic drivers are central to enable significant market growth and consequently economic impact through the various channels. Energy technologies are faced with competition from alternative options for the supply of energy and related products and services such as mobility, and hence competitiveness is relative to the alternatives and possible synergies. Hence, solar PV for off-grid applications benefited in the beginning from high oil prices, which also constitute a driver for CCS.

Other drivers can complement economic considerations when the economic driver is not enough to create sufficient demand pull, such as for CCS and fuel cells. Technical drivers such as security of energy supply for CCGTs or constraints in extreme applications (such as in space for fuel cells, batteries and solar PV) may play an important role not only in the initial development phases but throughout the technology phase.

Climate change action is the first major environmental driver on the most recent technologies analysed here, as even autonomous vehicles show an important interaction with low-carbon transport options such as fuel cells and electric vehicles. Pollution is the second central environmental driver, being observed both in the historical technology transition of the CCGT and for recent ones addressing pollution from electricity generation (solar PV, fuel cells) and transport (lithium-ion batteries, fuel cells, autonomous vehicles).

Social drivers for demand pull of new energy technologies are in contrast the ones less observed in the case studies, arising in the case of autonomous road vehicles. However, the focus of the study on the later phases of innovation may not reveal the importance of subjective drivers for early adoption of new technologies and the impact of this provision of demand pull.

Policy is a central driver of innovation in all case studies, acting to provide both supply push and demand pull (through the social, economic, environmental and technical drivers). Hence, public R&D support was central in the start phase of in most cases, with the exception of CCGTs and CCS. Moreover, policy increased demand pull in the form of investment, production or consumption support, as well as direct demand from government branches. Here, it must be noted the difference between supply push in the form of R&D support and demand pull through investment or production support to the supply chain, which act on technologies with different readiness levels.

The impact of policy is apparent from the development pattern which arises from the case studies, where usually early public R&D support complemented by direct demand for niche applications in the military and aerospace. In later phases R&D efforts by the private sector can take the lead and apply the technology to new markets with larger potential growth, such as for back-up and primary power supply, or transportation.

Types of innovation

Section 1.3.2 lists four types of innovation: incremental, radical, new technology systems and paradigm changes. All successful technologies transitions analysed (solar PV, lithium-ion batteries, CCGTs) took a long time to become established. Moreover, autonomous vehicles, CCS and fuel cells will require similar long transitions if they are successful. Therefore, even radical innovations take time to establish themselves, as discussed before.

Of the technologies analysed, highly autonomous vehicles are the clearest case of radical innovation, for two reasons. First, they are likely to transform transport in the coming decades, while they are not even commercially available at the moment. Moreover, autonomous vehicles arose mainly from purposeful R&D and interact with a number of radical innovations for their success (especially connected and electric vehicle technologies).

Nonetheless, the most often encountered in the case studies is incremental innovation, which arises in all case studies. As radical innovations take a long time to become established and require developments in several complementary technologies, incremental innovation plays an important role even in this case. New technology systems can possibly be observed in the case of autonomous vehicles, when the larger context of the interaction of connected and autonomous electric vehicles with the development of mobility services provision is considered, which may radically transform the transport sector, including the automotive industry. Paradigm changes could not be observed in the case studies selected, although the technologies reviewed do make use of important far-reaching innovations in the digital, communication and chemical fields.

The importance of vintages in the case studies is directly related to the incremental innovations observed. For fuel cells, CCS, solar PV and lithium-ion batteries, the performance and cost improvements are rather continuous. While CCGTs also saw continuous improvements, the model waves released from the 1980s on required important R&D efforts incorporating novel technologies, with manufacturers racing each other to bring leaps in efficiencies (often with accompanying reliability issues). The levels of vehicle automation also allow to identify a clearer separation between vehicle technology, but in reality improvements in automation will be driven by incremental changes making the categorization of automation levels less clear-cut.

Hence, clear-cut vintages with step changes in performance and/or cost can be observed for CCGTs, but not the other technologies analysed.

Main characteristics of innovation

Concerning the diffusion of the technology, given the long time required in technology transitions, there are clearly time lags to adoption in all case studies even when technologies are successfully upscaled and adopted. This is even more apparent when taking a longer perspective starting from the initial R&D efforts (i.e. from the invention phase) rather than from the market introduction of the technology (i.e. the deployment phase).

Knowledge diffusion is a central characteristic of the technology transitions studied, either in the form of purposeful knowledge transfer or as spillovers. Cooperation establishing purposeful knowledge transfer is observed in many forms, being between private, public and academic actors and reaching across sectors and international boundaries. Private-public-academic and intersectoral cooperation is often observed within a country and play a central role such as for lithium-ion batteries in Japan and later South Korea. However, international knowledge diffusion is less commonly observed, although it does occur as in the case of purposeful cooperation of Japan actors with North-American ones in the case of fuel cells.

The most important observed channels through which knowledge diffusion occurred comprise cooperation in innovation networks (often national and sponsored by governments), private partnerships, licensing or acquisition of technology, company mergers and acquisitions, foreign direct investments as well as intra-conglomerate knowledge transfer. These vary in importance not only per technology, but also per country and phase. Additionally, there is no clear dominance of a certain channel for international knowledge diffusion, as e.g. company acquisitions and technology licensing are apparent in CCGTs, technology acquisitions and JP-US partnerships in fuel cells or foreign direct investments in China for batteries and solar PV.

Technology spillovers can be observed in most case studies, whether enabling innovation in the technologies studied or supporting development in other sectors. However, the separation between purposeful (and thus resource-demanding) knowledge transfer across technologies and unintended spillovers is not clear cut, as either plays a role in the diffusion of knowledge across sectors. However, where it occurred, knowledge diffusion played a central role in the development of e.g. CCGTs using aerospace technology or of solar PV with electronics technology. Moreover, often multiple sectors provided key technologies for the case studies, as in the case of CCS, solar PV or autonomous road vehicles.

Learning effects in the form of learning-by-doing or learning-by-searching are apparent in all technologies, albeit the importance of purposeful R&D varies. Hence, all development phases of CCGTs and fuel cells were marked by important R&D efforts, in the former case by US, Japan and Germany industrial conglomerates. Other technologies saw important learning-by-doing in the more mature phases of strong deployment, such as for solar PV or lithium-ion batteries. Determining the relative importance of each in the case studies is not straightforward, especially when considering the influence of increasing returns, which are most apparent in the form of economies of scale. The evidence that there is some distinction between learning-by-doing and economies of scale is most apparent in the cases where China managed to develop a majority share in the production of a certain technology while not being able to become a leader in technology development as evidenced by the quantity and quality of patents and publications (for example in batteries). Nonetheless, both factors are at play in the important cost reductions observed for some technologies such as batteries or solar PV.

Human capital is a relevant characteristic in all case studies, with specific evidence that it can manifest itself in many forms. Examples include the importance of worker mobility in the case of autonomous vehicles following the DARPA Challenges in the US, the high company specialization in the CCGT market, and the importance of quality national innovation systems which result in countries such as US, Canada, Japan, South Korea and Germany regularly leading in the case studies selected. Moreover, the impact of human capital on the ability of these countries to absorb technology from abroad is apparent in cases such as fuel cell development in Japan.

Less relevant innovation aspects in the technology transitions reviewed

While many innovation aspects were identified as highly relevant in the case studies, this section discusses those which do not appear as so. In contrast to knowledge diffusion, technology communication channels among users was not apparent in many case studies, except in the case of CCGT acceptance by power utilities by spreading the familiarity with models with improved reliability. Linked to this, the importance of social systems in the case studies was limited, being observed e.g. for the market diffusion of solar PV or increased public acceptance of CCS, although the actual impact of the latter is not apparent. Social system aspects could be important in the future for the diffusion of autonomous and electric vehicles, but given the status of the market for autonomous vehicles this remains to be observed. Furthermore, it will be necessary to separate the social aspects influencing the diffusion of electric and automated vehicles.

The learning effects of learning-by-using and learning-by interacting are not frequently observed in the case studies either.

Path dependence also does not appear as a major factor across the case studies. On the contrary, the frequent leadership of specific countries in North America, Asia and Europe across the case studies points to other more important factors influencing innovation, such as national knowledge diffusion and cooperation, human capital, policy and demand pull drivers. Hence, developments may have been shaped by specific events (e.g. the DARPA Challenges for autonomous vehicles) and the lack of certain elements such as adequate human capital, effective public policy or infrastructure (for CCS, fuel cells or autonomous vehicles) affects innovation in the energy technologies and may create a development lock-in. However, there is no strong evidence that the technology transitions observed were strongly shaped by discrete historical developments and would have been fundamentally different otherwise, thus indicating the need to separate path dependence and development lock-in aspects.

Likewise, bounded rationality and the use of routines by firms in their processes is not apparent in the technology transitions. Routine selection may certainly play a role in innovation through learning-by-doing. Furthermore, choices of actors influencing the energy system may be limited by information availability or the cognitive ability. The analysis applied is not able to highlight the decision making process of public and private actors and the impact on the technology transitions. However, this may also be affected by selection bias given the technologies analysed are either successful or still have market potential. Additionally, it is not straightforward to prove that choices of actors are suboptimal from their perspective, although it may deviate from the socially optimal choices.

3.2.2. Technology transitions, energy and growth

The case studies clearly highlight the importance of the conventional and unconventional roles of energy discussed in section 2. The case studies reveal clear impact on energy conventional roles as an economic activity, and to a more limited extent as an input. Of the unconventional roles, the impact on technical change, climate change, infrastructure and energy quality and development stages is most apparent. Human capital and openness to trade impact could be observed only to a limited extent.

Starting with **energy as an economic activity**. While CCGTs constitute a case of historical technology transition, they should still keep a relevant impact on the economy, although the potential for growth is uncertain given mixed influence of environmental (climate change) and technical (power system flexibility) drivers. In contrast, the low-carbon energy technologies all have significant potential for growth, although the uncertainty around this is higher for fuel cells and especially CCS.

At the country level, the impact of innovation and manufacturing on growth must be separated. Indeed, the example of China for lithium-ion batteries provides evidence that it is possible to leverage low-carbon technology manufacturing to achieve economic growth while having more limited impact on innovation, at least in the early stages of supply chain development. This indicates also a link between energy as an economic activity influencing technical change, at least at the national level.

The influence of **energy as an input** is less evident in the case studies. On one hand, although some low-carbon technologies have been able to reach a significant deployment level and have seen important cost reductions, such as solar PV, they have not (yet) been able to significantly driver energy prices down globally. They were thus not able to promote growth through this channel, while the case studies have not focused on the impact of public support costs on energy prices. On the other hand, as a mature technology with significant deployment, CCGTs were able to promote economic growth through cheaper electricity supply (pending on gas prices and competition with alternatives, especially coal).

However, the focus of this study is on the **influence of energy on the other determinants of growth**. This interaction of energy and **technical change** is first apparent in the analysis of the demand pull drivers. In cases such as CCS, CCGT, fuel cells or lithium-ion batteries, competition with and between fossil energy sources for electricity supply and transport were major determinants of the strength of the economic driver in fostering innovation. The technical driver also makes apparent the importance in quality between the case study technologies and the alternatives, which were unable to meet the technical requirements, allowing the development of e.g. fuel cells, solar PV or CCGTs. Moreover, competition between the case studies is apparent also, as between lithium-ion batteries and fuel cell vehicles (an example of economic demand pull) or between CCS and solar PV as a form to provide low-carbon electricity (an example of environmental demand pull). This economic, technical and environmental competition (and synergy) between technologies has been a central determinant of the (potential) success of solar PV, CCGTs, lithium-ion batteries and autonomous vehicles.

Once sufficiently mature, these can then directly impact growth, representing an important economic sector but also through sectoral interactions. Hence, the case studies highlight the interactions of autonomous vehicles with connected and electric vehicles as well as mobility service providers which may result in a market of almost a trillion USD. Similarly, fuel cells are a central piece in the future hydrogen economy, which may enable the supply of low-carbon energy and feedstocks for all economic sectors. This may be further compounded if CCS technology develops sufficiently in order to supply low-carbon hydrogen from fossil fuels, providing an alternative to water electrolysis. Given the importance of knowledge diffusion posited in section 2.3 and confirmed in the case studies, energy technologies may further promote growth by maturing national research networks, providing new more form of spillovers to other sectors.

The impact of the selected technologies on **human capital** manifests itself only to a limited extent, for example by increasing energy access in isolated systems (for solar PV and lithium-ion batteries). **Climate change** on the other hand is a major demand pull driver through the ability of the technologies to support mitigation by directly and indirectly decarbonizing the economy, and to support adaptation by increasing the resilience of the energy system and energy access. However, immediate consequences of climate change such as global warming or increased extreme events have not been observed in the case studies.

Concerning **openness to trade,** the case studies highlight a number of trade and foreign direct investments in energy technologies. These include e.g. company acquisitions or technology purchasing and licensing by Canada and China for fuel cells or Japan for CCGTs, as well as direct foreign investments in China due to the potential market and economies of scale in solar PV and batteries. Hence, energy technology trade and investments may lead or support bilateral and multilateral trade openness.

Infrastructure often affects the viability of certain of the analysed technologies (e.g. hydrogen refuelling or connection of solar PV), and conversely the case studies had some limited impact on **infrastructures.** The evidence encountered includes for example gas turbines enabling more efficient transport of oil & gas, off-grid solar PV reducing the dependence on electricity networks, fuel cell technology spillovers driving the development of electrolysers for power-to-gas applications and batteries increasing the flexibility of the electricity system both through stationary and EV storage. As section **Error! Reference source not found.** indicates infrastructure affects the other d eterminants of growth such as trade or human capital, by changing the performance and more fundamentally the function of modern energy infrastructures the case studies impact growth through a highly indirect channel.

Finally, the impact of the cases studies on **energy quality and the development stages** is evidenced by the importance of technical drivers of demand pull, such as the need for increased security of supply in developing economies satisfied by the deployment of CCGTs and the off-grid supply of electricity by solar PV. Environmental drivers are also apparent in the different national development stages, especially the deployment of solar PV and low-carbon mobility (fuel cells and battery EVs) in China and South Korea to reduce pollution from electricity supply and transport.

4. Models and scenarios for the energy-innovation-growth nexus

The first objective of this section is to compare in section 4.1 a select number of models representing different modelling paradigms as described in section 1 with a focus on the macroeconomic ones, and to review how these models represent the energy system and endogenous technical change. In addition, the purpose of this review is to understand the impact of these aspects on economic growth, as discussed in section 2.

Furthermore, a number of select energy transition scenarios are compared in section 4.2. The scenarios chosen are based on select models discussed in the section and aim to illustrate the effect of different ways of modelling innovation and endogenous technical change on the modelling outcomes.

4.1. Representation of the energy system and endogenous innovation in select models

This section encompasses the comparison of six macroeconomic models and three integrated assessment models, and their approach to describing the energy system, representing aspects of innovation and analysing the impact on growth. It also contains a discussion section that compares and contrasts the different approaches.

In total, there are nine models reviewed:

- One agent-based macroeconomic model (Eurace@Unibi)
- Two (hybrid) computable general equilibrium (CGE) models (GEM-E3-FIT and IMACLIM-R)
- One Input/Output simulation model (GINFORS)
- Two macro-econometric models (E3ME and NEMESIS)
- Three integrated assessment models (IAM – IMAGE, REMIND and WITCH)

The models were selected to cover variate approaches to modelling innovation and the energy system. Maquette models are included in the scope of this task, of which Eurace@Unibi was selected.

The detailed model analysis is presented in Annex B. After a brief description, the analysis of each model addresses three aspects:

- Representation of the energy system
- Representation of innovation aspects
- Relationship between the energy system and growth[14]

[14] For GEM-E3 and E3ME this is extensively discussed in chapter 1.

4.1.1. Comparison of the selected models

Table 0-6 summarizes the key information of the reviewed models regarding how these models represent the energy system, innovation and what is the impact on growth. Here the models are first analysed from the perspective of the representation of the energy system, and then the interaction of the energy system with the economy is discussed.

As innovation (and particularly in energy technologies) is an important factor influencing this interaction, the endogenous representation of innovation is analysed at the end.

Representation of the energy system

The representation of the energy system varies significantly among models:

- Eurace@Unibi does not represent the energy system. An extension of the Eurace model (which led to Eurace@Unibi) does model, in a simplified manner, the electricity sector, which consists of a fossil-fuel and a renewable power producers.
- The E3ME uses a bottom-up approach (Future Technology Transformations models) for some sectors and a top-down for others, and disaggregates energy consumption by fuel types so that the associated emissions can be easily estimated.
- The NEMESIS model uses an energy production function represented by a nested constant elasticity substitution (CES) function that combines electricity and a Solid fuel, Liquid fuel, Gas (SLG) bundle, while the power generation sector is modelled with a more detailed CES function. A feature of NEMESIS is that it includes electricity transmission and distribution losses.
- The two CGE models have also considerable differences between them on how they model the energy system, with GEM-E3-FIT including a rather detailed representation of the whole energy system, while IMACLIM emphasises in particular the transport sector.
- The three IAMs follow radically different representations of the energy system. IMAGE incorporates an energy demand and supply model, called TIMER, as the energy module, whereas REMIND includes energy as an explicit factor in the production function, disaggregating it into energy for buildings, industry, and transport (and their detailed energy inputs). It then used an energy system module to define energy supply costs. In the WHITCH model the energy system is fully integrated into the rest of the economy.
- GINFORS's energy module represents the energy system as a conversion of primary energy to secondary in the electricity, gas and water supply, and coke and refined petroleum sectors.

Overall, the representation of the energy system in the models differs both in which model level the energy system is represented, which specific energy sectors are represented and with what level of detail. Following the overall trend towards combinations of models and the quest to a more detailed representation of the energy system, most models analysed make use of a hybrid approach, incorporating an energy systems submodule of some kind. At the main model level, generally macroeconomic models succeed in a higher representation of the energy sector, while IAMs naturally have a greater difficulty in representing economic sectors in general. Nonetheless, following its focus, REMIND achieves a representation of energy as a production factor much more detailed than the capital or labour factors of production.

Table 0-6 Summary of reviewed models

Models	Type	Energy system representation	Endogenous representation of innovation[15]
Eurace *@Unibi*	Agent-based macroeconomic	▪ Does not contain a representation of the energy system.	▪ There is **no endogenous technical change** for either renewable or conventional electricity generation. ▪ Capital good **vintages improve the technological frontier** driven by R&D investments. ▪ Quality differentiation of consumption goods. ▪ Human capital (general and job-specific). ▪ **Learning-by-doing** for job-specific skills.
GEM-E3-FIT	Computable general equilibrium	▪ Bottom-up representation of power generation, including renewables, nuclear and CCS (fully calibrated to PRIMES and PROMETHEUS). ▪ **Endogenous specification of energy-efficiency improvements**; ▪ Transport electrification. ▪ Household energy use divided into (i) heating and cooking and (ii) electric appliances. ▪ Biomass modelling. ▪ Depletable energy sources module. ▪ Energy taxes and subsidies.	▪ **Endogenous technical change deriving from R&D spending** is expressed as productivity improvement by the production factor and/or as total factor productivity in certain sectors. ▪ **Productivity improvements based on learning curves**. ▪ **Regional total factor productivity** determined by accumulated production, R&D stock, and knowledge stock in other regions due to technical transfers and spillovers. ▪ **Endogenous households' decision on education,** which affects labour productivity; patent generation; patent replication; the shares of each skill type labour to total labour force; and the capacity to absorb knowledge spillovers.
IMACLIM-R	Hybrid computable general equilibrium	▪ Energy demand is modelled for: residential, commercial, industrial, transport and other sectors. ▪ The energy supply dynamic modules comprise primary energy and energy transformation (13 electricity generation technologies).	▪ **Learning-by-doing** for electricity and liquid fuels. ▪ **Price-induced energy efficiency improvements.** ▪ **Capital vintages and constraints to vintage adoption**.

[15] **Bold items** refer to endogenous representation of innovation in energy technology

Models	Type	Energy system representation	Endogenous representation of innovation[15]
GINFORS	Dynamic Input/Output simulation	▪ Primary energy is converted into secondary in the electricity, gas and water supply, and coke and refined petroleum sector. ▪ Final demand of a sector is estimated by determining the energy intensity of a sector and the shares for the energy carriers, for each industry and use. ▪ Final demand of households is divided in heating, mobility, and household appliances. Demand for each purpose is defined by specific parameters and the shares of each energy carriers are determined from their relative prices. ▪ Competition between electricity generation technologies	▪ **One- or two-factor learning curves** for global and cost components. ▪ **National cost component** for system integration, grid connection and macroeconomic factors.
E3ME	Macro-econometric	▪ Includes the **bottom-up Future Technology Transformations** (FTT) energy sub-models of power generation, steel, road transport, and household heating. ▪ For other sectors, top-down econometric equations of energy demand. ▪ For all sectors, energy consumption is disaggregated by fuel type.	▪ Investors' **decisions on electrical installed capacity**: o Technology diffusion follows 'Lotka-Volterra' or 'replicator dynamics' equations. o **Learning-by-doing** and **increasing returns to adoption** affect decisions and result in **path-dependent** technology scenarios. ▪ Through the non-energy sectors, which feature sets of technology indices made based on **accumulated capital and R&D stock**.
NEMESIS	Macro-econometric	▪ Energy production factor uses a nested CES function combining electricity and a SLG bundle. ▪ The power generation sector is modelled with a more complex nested CES function. ▪ Transmission and distribution losses are also taken into account.	▪ Through representing the **stock of knowledge and its impact on innovation and economic performance**: o Each sector has a knowledge stock, which 1)increases by sectoral R&D expenditures and spillovers, and 2) decreases due to aging of knowledge. o This leads to process and product innovation. ▪ Through embodying **endogenous technical change in production functions**: o It models asset vintages, each with different productivity levels using CES production functions. o Includes national, foreign and public R&D spillovers, with lag. ▪ By expanding the latter approach with the inclusion of investments in ICT and other intangibles: o Innovation depends also on sector's absorptive capacity.

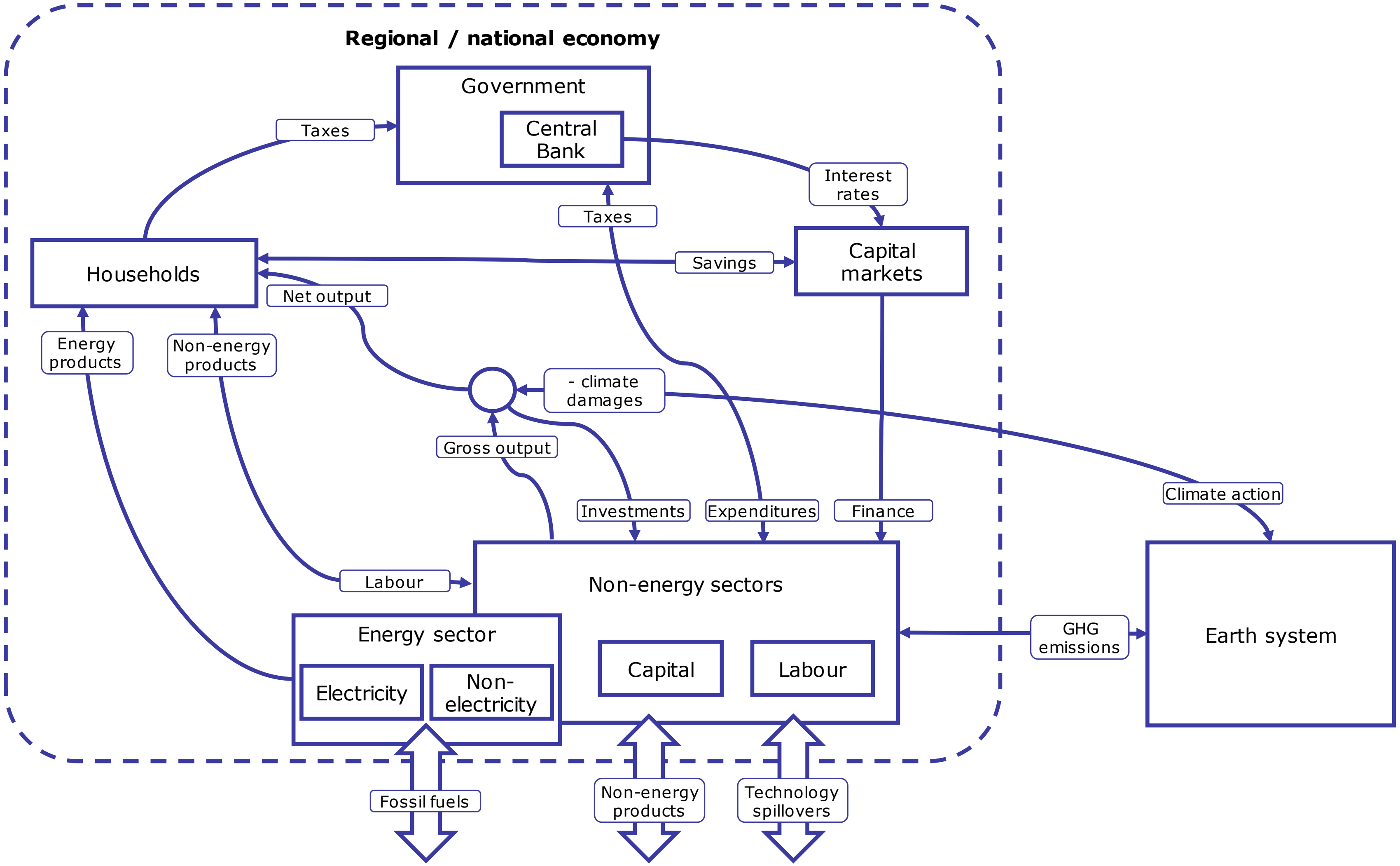
Models	Type	Energy system representation	Endogenous representation of innovation[15]
IMAGE	Integrated assessment model	▪ 12 primary energy carriers with three basic components: energy demand, conversion and supply. ▪ Energy demand is represented by residential, heavy industry and transport. ▪ Energy conversion to electricity and hydrogen is more detailed than other carriers. It includes wind, solar, nuclear and 20 types of fossil and bioenergy power plants, plus 11 types of hydrogen production technologies. ▪ Energy supply highlights the dynamics of resource depletion, trade and technical change.	▪ **Learning curves for the capital output ratio** of coal, oil and gas supply and for the investment cost of wind, solar PV, bioenergy, nuclear and hydrogen technologies, as well as for the rate of decline for the energy conservation cost curves. ▪ **Learning-by-doing** for fossil fuels, renewables, nuclear, hydrogen and energy conservation cost curves ▪ **Technology adoption for specific sectors'** energy demand.
REMIND	Integrated assessment model	▪ Energy is the only disaggregated production factor. Various final energy types in the three sectors industry, buildings, and transport are aggregated in a nested CES function. ▪ Technology choice in the energy system is modelled via linear substitution between competing technologies for secondary energy production, with supply curves for exhaustible resources as well as renewables. ▪ Energy system module optimizes energy supply for all final energy types.	▪ Energy system module includes **learning rates of investment costs for specific technologies** (learning-by-doing). ▪ **Cost mark-ups (decreasing returns)** for fast growing technologies are implemented to provide a more realistic rate of deployment.
WITCH	Integrated assessment model	▪ CES production function with 1st level separation of electricity and other energy carriers. ▪ Input factor costs determined by utilisation factors, fuel efficiencies, investment and operation & maintenance costs, and capital depreciation. ▪ Power system integration aspects (flexibility and capacity constraints, grid investments)	▪ Increasing returns: learning curves based on knowledge stock and installed capacity ▪ Learning-by-researching: knowledge stock accruing from R&D investments ▪ Decreasing returns: Fast deployment cost mark-ups ▪ Knowledge diffusion: R&D spillovers ▪ Human capital: absorptive capacity

Interaction of the energy system and growth

The interaction between the energy system and economic growth depends of course on the representation of the energy system, but also on how the general economy is represented in each model. As discussed in Chapter 1, each modelling paradigm entails certain assumptions regarding the behaviour of the economy, although recent macroeconomic models have made significant advances in addressing identified modelling shortcomings. Moreover, innovation is an important factor contributing to economy growth, with the specific representation of endogenous innovation analysed in the following section.

Error! Reference source not found. presents a schematized representation of the main e lements of a regional or national economy in the models reviewed. However, no model includes all the elements indicated – for example, the central bank or climate damages are include in a few models only. Moreover, as discussed, the energy system may be represented as part of the general economy, or modelled separately.

Figure 0-12 Schematic interaction of the energy sector and the economy



Bearing in mind no model represents all the interaction mechanisms between the energy system and growth, the main possible ones (as summarized in Table 0-7) are:

- **Substitution between production inputs**, which is, in most models a central mechanism allowing for structural change in the economy. However, for each of the following possible substitutes, elasticities may vary significantly in the models:
    - Energy and non-energy inputs (capital and labour)
    - Energy inputs and energy efficiency
    - Between energy inputs (especially electricity and non-electricity inputs)
- **Endogenous innovation in energy technologies**, both within the energy sector of a national economy as well as due to cross-sectoral and cross-regional spillovers. These mechanisms are extensively discussed below;
- **Available productive slack in the economy** due to the utilization level of energy assets and/or capital assets for their manufacturing, with each modelling approach allowing or not for under-utilization of assets. In the case of energy assets, utilization may be further restricted depending on the level of detail in representing energy demand and supply, that is in the temporal and geographical resolution of the models capturing, for example, the availability profile of intermittent renewable energy technologies;
- **Costs of climate action and net climate damages**, which impose a double burden on the productive capacity of the economy. Optimization modelling approaches with endogenous climate action decisions will minimize the combined cost of climate actions and climate damages. Climate action includes both mitigation and adaptation costs, and in specific circumstances may have positive impact on growth, such as when increased investment in renewable energy technologies is enhanced by the circular flow of income or endogenous innovation in certain models. Likewise, climate change and especially global warming can have positive impact in specific economies e.g. increased agricultural productivity. Nonetheless, no model indicates a net benefit from climate impacts;
- **Changes in household preferences**, leading to new behaviours and consumption patterns for energy products and related services, such as mobility. This mechanism of interaction is not addressed extensively in most models analysed;
- **Changes in wages and cross-sectoral effects** may significantly alter the competitiveness of energy, energy-intensive and other sectors and result in the structural change of the economy. As the representation of labour markets is a common feature of macroeconomic models in general, this factor is well-captured although not specific to the energy system;
- **Investment in energy technologies** (both R&I and capital assets), due to public policies or induced by prices. Public policy includes economic support (such as for renewable energy technologies), regulation (e.g. of renewable energy targets, coal phase-out) or carbon pricing. Such investments may have a positive or negative effect on the economy depending on combined impact of the circular flow of income (positive) mentioned above and crowing-out of investments in other sectors (negative). Whether crowding-out due to increased cost of capital will occur depends on the endogenous representation of interest rates and capital markets, possibly influenced by a central bank. In the presence of labour markets, increased activity in the energy sectors may furthermore drive wages up, as mentioned.

Table 0-7 Main energy-growth interaction mechanisms in the selected models

Models	Energy-growth interaction mechanisms
Eurace @Unibi	▪ Optimal feed-in tariffs lead to higher growth through the deployment of renewable energy without disproportionately affects household consumption and investments by the consumer goods sector, with a slight net positive impact on total employment for high feed-in tariffs. ▪ No significant crowding-out of investments in the consumer goods sector due to renewable energy investments, despite the hike in the central bank's interest rate. ▪ No under-utilization of electricity production assets, except in a case where renewable energy penetration would become so large to supply the entire electricity demand. ▪ Feed-in tariffs affect the government budget through feed-in tariff expenditures and changes in the government revenues due to changes in growth. At moderate feed-in tariff levels the effect is positive (reducing deficit). ▪ No decoupling of energy consumption and growth, but there is decoupling of growth and emissions through reduced fossil fuel consumption.
IMACLIM-R	▪ Decoupling of growth and energy demand possible due to structural changes in the demand for energy carriers caused by consumer preferences and production capacity investment choices of non-energy sectors, in response to the relative prices of the energy carriers and technologies. These are affected by innovation due to learning-by-doing in energy supply technologies and vehicles, and in price-induced energy efficiency. ▪ There is crowding out of investments between the energy and non-energy sectors, given saving rates and thus available finance is exogenous. ▪ First mover advantages and disadvantages in energy efficiency represented. The speed of diffusion of energy efficiency improvements affects growth. ▪ Increased investment needs in electricity generation technologies due to the detailed representation of the sector and rigidity in their installed capacity affects growth negatively.
GINFORS	▪ The energy sector impact on changes in the economy and emissions are determined exogenously by energy and climate policies ▪ Investments triggers economic growth through the circular flow of income, partially compensated by increases in capital costs which reduce growth (partial crowding-out). ▪ Reduced material use due to dematerialization policies increases the productivity of firms at the end of the supply chain, while reducing economic activity in sectors upstream. Globally, the net effect of this dematerialisation depends on the geographical extent: when dematerialisation occurs globally, other more material-intensive regions benefit, negatively impacting the EU economy. The positive investment effect predominates in the short-term, while the negative dematerialisation effect is strongest in the long-term.
NEMESIS	▪ Decoupling of energy and growth possible first through the increased use of capital, given the high substitutability with other factors, and second by public and private R&D investments in non-energy production factors which might be enhanced by international or intersectoral spillovers. ▪ The ability of regions to gain a competitive advantage through private and public investments depends on the strength of spillovers. ▪ Electricity and the bundle of coal, oil and gas have high elasticity of substitution, but the substitutability between renewables, nuclear and fossil sources is more limited. ▪ There is no possible crowding-out of sectoral investments due to higher capital costs as interest rates are determined exogenously.
IMAGE	▪ GDP per capita is set exogenously, and thus growth impacts the energy system, rather than the other way around. ▪ Potential decoupling between energy consumption and economic growth is possible due to price-induced energy efficiency and structural change in the energy supply, while substitution of fossil energy sources with renewable ones may further contribute to decoupling. ▪ Capital supply does not affect the deployment of different energy technologies, and thus there is no crowding-out. Nonetheless, high-marginal cost assets such as combined cycle gas turbines or plants with CCS technology may be underutilized.

Models	Energy-growth interaction mechanisms
REMIND	▪ Only partial decoupling of the economy from energy consumption possible ▪ Decoupling from emissions more readily achievable, through energy efficiency (exogenous) and technological learning for renewable electricity sources, electric vehicles and electricity storage. ▪ Benefits of lower investment costs for renewable energy partially affected by lower capacity factors as deployment increases. ▪ Effect of interregional spillovers is limited, so economies benefit most from their own cost reductions driven in energy technologies. ▪ There is no crowding-out possible between different energy technologies as financial markets are not modelled. ▪ Underutilization and even decommissioning of energy assets is possible.
WITCH	▪ Economy is supply-driven, with consumption defined by the gross output, adjusted for the climate impacts and energy-related and climate action costs. ▪ Substitution between energy services with capital and labour is limited. The energy efficiency stock does reduce energy input needs. ▪ Regional economies may develop a lead in energy efficiency, although international spillovers occur. ▪ Regions may increase output by production and trade in fossil fuels, but emissions from their consumption affect gross output due to both the impacts of global warming and the costs for climate action. ▪ Crowding-out will occur between the necessary investments and other costs of energy supply technologies, energy efficiency R&D, fossil fuel extraction and climate action.

Endogenous representation of innovation

As regards the innovation representation, in all of the models reviewed, technical change is endogenous to some degree.

Table 0-8 provides a more detailed overview than that which was conducted for the other models. This includes possible expansions developed in the framework of the MONROE project,[16] which may need to be incorporated in other versions of these models.

Technical change in Eurace@Unibi is endogenously determined by the reinvestment in R&D of part of the capital good producers' revenues, which increases the probability of innovation.

The I/O model GINFORS introduces innovation through its renewable power generation module that models the installed capacity and costs of wind and solar PV. Technology costs, which are determined using learning curves, together with policy measures, energy module variables, and macroeconomic factors determine the installed capacity.

Learning curves that determine the cost of energy technologies are used by many models, including the macro-econometric model E3ME, the CGE model GEM-E3-FIT, and the IAM IMAGE. In the E3ME model, endogenous technical change is modelled in two different ways – through Future Technology Transformation (FTT) models and technology indices of non-energy sectors that are based on the capital and knowledge stock. The other macro-econometric model, NEMESIS, includes up to three ways of innovation representation: through the representation of the knowledge stock on innovation, through embodying endogenous technical change in the production function, and through investments in ICT and intangible spillovers.

The three IA models also include learning effects to represent innovation. IMAGE uses learning curves for the capital output ration of certain coal, oil, and gas supply, and for investment cost of renewables and energy conservation technologies, while REMIND includes learning rates of only investment costs for specific technologies and WITCH uses two-factor learning curves to incorporate learning-by-research and learning-by-doing. The model also uses single-factor learning curves to model the cost evolution of certain renewable energy technologies. The two CGE models follow different approach from each other in representing innovation. IMACLIM includes learning effects for electricity and liquid fuels and price-induced energy efficiency improvements, while in GEM-E3-FIT, technical change derives from R&D spending. In addition, GEM-E3-FIT endogenizes households decision on education, which in turn affects labour productivity, patent generation and replication, and the shares of each skill type labour to total labour force. The Eurace@Unibi and NEMESIS models use also human capital as the factor that determines the absorptive capacity of a firm.

In general, learning effects (mostly learning-by-doing, but also learning-by-searching) are widely employed when modelling innovation representation, since they are included in all of the models reviewed regardless of the economic modelling paradigm followed. Spillover effects have been used by the two macro-econometric models reviewed (E3ME and NEMESIS) and by GEM-E3-FIT. Human capital considerations expressing the capacity of firms and people to absorb knowledge and use new technology were integrated into three of the reviewed models.

[16] See various deliverables of www.monroeproject.eu

Table 0-8 Central aspects of innovation in GEM-E3-FIT and E3ME

<table>
<tr><th>Innovation aspect</th><th>GEM-E3-FIT</th><th>E3ME</th></tr>
<tr><td>Supply push</td><td>▪ Lagged R&D from private actors, dependent on sectoral output and R&D relative prices
▪ Learning-by-searching per sector due to exogenous public R&D for certain energy techs
▪ Endogenous total factor productivity (TFP) determined by learning-by-doing, learning-by-searching, spillovers (intersectoral and interregional), and human capital stock
▪ Exogenous and time-lagged public R&D
▪ Depreciation for public and private R&D (both investments and knowledge stocks)</td><td>▪ R&D from private actors, dependent on sectoral output, R&D relative prices and endogenous investment/labour ratio
▪ Knowledge stock with knowledge depreciation rate
▪ Exogenous consideration of firm concentration</td></tr>
<tr><td>Demand pull</td><td>▪ Energy demand driven by activity, price, R&D (user-specific and global in transport and machinery) and investments</td><td>▪ Energy demand driven by activity, price, R&D (user-specific and global in transport and machinery) and investments, or by technology-specific energy-use characteristics in bottom-up technology sub-models for selected energy users</td></tr>
<tr><td>Policy</td><td colspan="2">▪ Exogenous CO_2 emission policies, public support for R&D on low carbon technologies, targeted energy taxes, regulation standards for energy efficiency / CO2 emissions, subsidies for take-up of low carbon technologies, public spending to renovate public housing</td></tr>
<tr><td>Incremental innovation</td><td colspan="2">Various mechanisms</td></tr>
<tr><td>Radical innovation</td><td>▪ Incipient technologies in bottom-up electricity sector representation</td><td>▪ Incipient electricity technologies included in bottom-up technologies representation (FTT:Power, FTT:Transport, FTT:Heat)</td></tr>
<tr><td>Diffusion</td><td>▪ Lagged private and public R&D investments</td><td>▪ FTT models for electricity supply, road transport and domestic heat</td></tr>
<tr><td>Increasing/ decreasing returns</td><td>▪ Sectoral learning-by-doing affecting TFP</td><td>▪ Technology learning curves in FTT models
▪ Supply curves for renewables, dynamic marginal cost for fossil fuels and nuclear</td></tr>
<tr><td>Learning effects</td><td>▪ Sectoral learning-by-doing
▪ Sectoral learning-by-searching due to public RD</td><td>▪ Technology-specific learning curves for technologies in FTT models</td></tr>
<tr><td>Path dependence</td><td colspan="2">▪ Power sector installed capacities
▪ Capital stock
▪ Absorptive capacities limiting innovation</td></tr>
<tr><td>Human capital</td><td>▪ Affecting labour productivity, R&D and spillovers absorption capacity, with endogenous household schooling decisions</td><td>▪ Affecting total production capacity, with unemployment skills degradation</td></tr>
<tr><td>Knowledge diffusion</td><td>▪ Regional spillovers affected by capacity and bilateral import shares with lags</td><td>▪ Regional and sectoral spillovers from R&D expenditure</td></tr>
</table>

Box 0-1 Micromodels applied to endogenous representation of technical change

With the exception of Eurace@Unibi, all other models reviewed in this chapter aggregate the public and private actors taking the decisions affecting innovation and technology diffusion per sector and region. An alternative approach is possible, and while they are not the focus of this report, there exists a number of micromodels addressing the R&D decisions of discrete public and private actors (including the amount of R&D subsidies). While they do not provide insights into the macroeconomic impacts of R&D, by focusing on the decisions of discrete agents these models are capable of elucidating different aspects of R&D efforts and also providing microeconomic foundations to the modelling of these R&D decisions in macroeconomic models.

Takalo (2013) develops an incomplete information game between a firm conducting an R&D project as well as a public agent subsidizing this R&D and private financing institutions funding it. It shows that higher financing costs increase the optimal level of R&D subsidies directed at the extensive margin but not at the intensive margin. The study also indicates that the additionality of public support (i.e. whether crowding out occurs) is technology-, firm- and even project-specific.

König (2014) develops a model on R&D collaboration networks between competing firms including public R&D subsidies. Results sensibly indicate that firm output increases with collaboration, while it decreases with product rivalry, with the net impact on output depending on the exact levels of technology spillovers and product rivalry. The study then identifies the key firms whose exit causes the biggest impact on welfare, and those who are central to the R&D network. Lastly, optimal homogenous and targeted subsidy levels are identified.

Similarly, Capuano (2018) studies the R&D decisions of two competing firms in a three-stage (cooperation, investment and competition) model. Here, firms cooperate if spillovers are high enough and fixed R&D costs low enough. However, cooperation may not be socially optimal when spillovers are low, thus justifying public subsidies tailored per sector according to the level of spillovers. Finally, while mergers may not eliminate the need for public support, they do increase private incentives for R&D efforts and cooperation.

Without the objective to be exhaustive, these brief examples indicate that micromodels representing the R&D decisions discrete actors can provide relevant insights on the conditions under which these actors undertake R&D and the influence of public support. Given the case studies of section **Error! Reference source not found.** highlight the i mportance of both private and public actors, these micromodels can also support the analysis of the representation of R&D and consequent technical change in macroeconomic models.

Comparison of the endogenous representation of innovation with case studies

The case studies presented in Section 3, which provide a picture of various technology transitions, depict various channels through which the dynamic innovation chain is unrolled. The objective of this sub-section is to compare how different approaches of modelling of the innovation process have captured the actual innovation dynamics in technology transitions.

Various **demand pull drivers** affect innovation in energy technologies, particularly economic (cost-related), technical (performance) and environmental (climate change and pollution). Demand pull drivers have been included e.g. through price-induced innovation in IMACLIM. Moreover, in E3ME innovation is represented also as investors' demand for increased electrical capacity, which are determined by technologies' costs. Technical drivers are also relevant but require hybrid models with detailed energy systems sub-models considering for example security of supply needs. Environmental demand pull drivers are partially considered in the models reviewed, as climate change constraints and resultant climate policies such as carbon pricing drive the deployment of low-carbon technologies which then interact with endogenous innovation mechanisms such as learning curves. On the other hand, air pollution was also identified as an environmental driver for innovation in energy technologies, but is not represented in the models reviewed.

Section **Error! Reference source not found.** highlighted the importance of both **supply p ush and demand pull** for the successful deployment of energy technologies. Supply push drivers are more widespread in the models reviewed. Learning effects are a representation of the effects of supply push driver that is extensively used in all models reviewed. Moreover, R&D expenditures represent supply push drivers themselves and is one of the factors that drive technical change in Eurace@Unibi, E3ME, GEM-E3-FIT, and NEMESIS. However, to capture the combination of both supply push and demand pull a comprehensive approach is needed in simulating R&D, and economic, technical and environmental drivers such as cost reductions of input factors and increased productivity of capital goods.

Furthermore, **market niches** serve to provide demand pull in the initial stages of a technology, especially combined with public policies in sectors such as the aerospace or military. Such demand pull considerations seem to not be particularly picked up by any of the models reviewed in this section, which may arise from the difficulty of representing early-stage technologies.

Three of the models analysed (Eurace@Unibi, IMACLIM and NEMESIS) represent technical change using **vintages**. In the Eurace@Unibi capital good vintages are driven by R&D investments and improve the technological frontier, while IMACLIM places constrains to vintage adoption. The frequent use of vintages to represent changes in technologies contrasts with the observations from the case studies, as in the majority of cases technical change is incremental and technology vintages were only observed in the case of combined cycle gas turbines. However, this involves a discussion of whether vintages need to represent step-changes in energy technologies, or are rather a practical form to represent changes in the capital stock.

While the incremental **innovation type** is present in all technology transition case studies, radical innovations or new technology systems are not as widespread. This indicates that in reality incremental innovation is met more often than radical innovation. As mention in Section 1, learning-by-doing gives rise mostly to incremental innovation. This means that all of the models reviewed in this section have the capacity to capture incremental innovation as all of them include learning effects. As seen in the case studies, radical innovation would require the representation of the whole innovation system with synergies between multiple sectors.

Box 0-2 Modelling radical innovations in macroeconomic models

While the technologies analysed in the previous section mainly represent cases of incremental innovation, this does not mean that radical innovations will not play an important role in the energy transition. Lavrijssen (2017) indicate that technologies and trends such as prosumers, smart meters, behind-the-meter storage, distributed generation, electric vehicles and digitalization in general will fundamentally alter the energy system and the economy, some of which could be classified as radical.

Ciarli (2019) conducts a review of several modelling paradigms and their ability to represent the change of the economic structure. As presented in section 1, radical innovations introduce fundamental changes in the existing technological knowledge, rendering current knowledge obsolete. To Ciarli (2019) radical innovations require changes in large parts of the economy, including consumer behaviour, the production structure and infrastructures. Therefore, the definition of the authors is also related to new technological systems as discussed in section 1.

Surveying the modelling paradigms, Ciarli (2019) finds that structural change and agent-based models are the most suited to address radical innovations. Structural change models may address radical innovations by the introduction of new intermediate sectors. Agent-based models on their turn may model the entrance of actors in the economy leading to the introduction of new technologies, and study its diffusion (successful or unsuccessful).

By differentiating between conventional and green technology types, Eurace@Unibi's eco-technology extension represents this ability of agent-based models to analyse the diffusion and macroeconomic impact of radical innovations. In the model, the lower technical performance and skill level of workers form barriers to the diffusion of the radical innovation. Hence, the model identifies mainly scenarios where either the conventional or the green technology dominates, and where the probability of a transition to the green technology is influenced mainly by the supply-side barrier (lower green capital productivity) and demand-side barriers (lower utilization skills for the green technology). Nonetheless, by representing only two capital goods and one consumer goods sector as well as finding only evidence of slight output improvement for the green technology, the extension does not model a more radical transformation of the economy structure.

The production networks model developed by Gualdi (2018) represents another approach to modelling radical innovation. In the study, to assess the impact of radical innovations firms invest a share of its revenue in R&D leading to a probabilistic development of new technological paradigms. This radical innovation leads to exponential growth, as opposed to the linear growth observed with incremental innovation.

Therefore, although many energy technologies cannot be unambiguously classified as either incremental or radical, models have started addressing their endogenous development, especially agent-based ones. The examples reviewed here adopt a probabilistic approach, which may fit the uncertainty related to radical innovations. Nonetheless, approaches will still vary, e.g. on whether the introduction of radical innovations is a single event or sequential, which influences the final effect on growth. Given this, a central question is how modelling approaches can support policy makers in addressing the uncertainty around radical innovations. For this, their endogenous modelling is a possible avenue, which can be complemented with for example exogenous scenarios.

Increasing returns are regularly observed in the case studies, especially due to economies of scale however, in the case of the models reviewed this characteristic of innovation if often missing. Only the E3ME model explicitly introduces increasing returns to adoption, while benefits of adopting a new technology are often modelled in the form of learning curves (see discussion below). In contrast, often decreasing returns are modelled for fast technological upscaling.

Knowledge diffusion (both purposeful or through spillovers) is pivotal in the case studies, with various channels (company or technology acquisition, partnerships, others) and forms, such as combinations of public/private/academic, (inter)national and intersectoral. The way that new technology is diffused was explicitly taken into account in only two of the models, Eurace@Unibi and IMAGE. In addition, the effects of spillovers on the diffusion of knowledge and technology have been included in E3ME, GEM-E3-FIT, and NEMESIS.

Concerning the representation of learning effects, as discussed, the use of learning curves is a widespread technique to model endogenous innovation. However, one-factor learning curves are most often employed, which bears a parallel with the difficulty in separating learning-by-doing and learning-by-searching in actual historical case studies.

All in all, the models reviewed here seem to capture both supply push and demand pull innovation drivers, but to a limited extent. Furthermore, several of the models included in this section used vintages to represent changes in technologies, although vintages observed in the case studies are not as common and may thus be overutilized in the models. According to the case studies, innovation appears to be mostly incremental, which is consistent with how the models conceptualize innovation. In addition, although increasing returns are frequently observed in the case studies, only one of the models reviewed here explicitly introduces increasing returns to adoption, while many include decreasing returns for the rapid expansion of e.g. renewable energy. Knowledge diffusion, which plays an important role in innovation dynamics, is explicitly considered in only two models, while multiple channels of diffusions were identified in the case studies. Finally, learning effects (learning-by-doing and learning-by-searching) seem to be of great importance in modelling and thus have been used extensively, however, models often use one-factor learning curves which do not differentiate between learning-by-doing and learning-by-searching.

Comparison with the main impacts of energy on growth in the technology transitions

This passage analyses the impact of energy on growth, considering the impacts discussed in section 2 and identified in the technology transitions of section **Error! Reference source not found.**.

The technologies that achieved already a significant deployment worldwide (lithium-ion batteries, solar PV, combined cycle gas turbines) already contribute to growth as an economic activity, with further potential for all reviewed low-carbon technologies (with varying levels of uncertainty). This direct contribution is addressed in the models by those explicitly represent specific energy sectors in the main (macroeconomic) level. Therefore, several models comprise these contributions of energy to growth, including E3ME, GEM-E3-FIT, GINFORS, NEMESIS and IMACLIM.

Similarly to energy as an economic activity, the ability of the models to represent energy as an input depends fundamentally on whether production functions consider energy as an explicit input, and with which level of detail. This occurs in varying degree in all models except Eurace@Unibi.

As discussed, all models represent technical change endogenously, in different ways. Hence, as long as this is the case also for the energy sector, then the impact of technical change in the energy sector on growth is considered (also in varying forms). Hence, only Eurace@Unibi is unable to address this impact. However, representing the impact of energy on technical change is much more challenging. This is done in a few models only, e.g. in NEMESIS and GEM-E3-FIT through intersectoral spillovers and in IMACLIM through price-induced energy efficiency improvements.

Human capital is addressed in some models, usually by representing the sectoral absorptive capacity (dependent on the knowledge stock) such as in Eurace@Unibi (which separates between general and job-specific skills of workers), GEM-E3-FIT and NEMESIS. By adopting an approach such as the knowledge stock, models are able also to represent the impact of energy on human capital. However, the theoretical findings that energy affects human capital by improving health, education, water and communication services remains largely underrepresented in the reviewed models. It must be noted that these theoretical findings were not a marking aspect in the technology transitions reviewed, that which can however be attributed to the review focus rather than to a lack of empirical evidence.

Given the focus of economy-energy-environment models, all models reviewed touch on climate change by assessing the emissions of greenhouse gas emissions of the energy system, except Eurace@Unibi. Nonetheless, unless coupled with an earth systems model, the inability of macroeconomic models to represent the economy-environment interaction is a well-analysed aspect of economy-energy-environment studies. Unsurprisingly then, the integrated assessment models IMAGE and REMIND are better suited to represent the impact of climate change on the economy and energy system.

Albeit the literature indicates energy affects openness to trade in several ways (trade including of technology, foreign direct investments, cross-border infrastructure), the evidence of the impact of the technology transitions on trade openness was rather limited (although of course causing much trade in itself). Eurace@Unibi does not represent the energy system, and thus is the only model not representing trade in energy goods and/or services.

Similar to openness to trade, the impact of energy infrastructure on growth is highlighted in the theory but identified as a relevant aspect only in some of the technology transitions (hydrogen fuel cells, CCS). This is paralleled in the reviewed models, where infrastructure is addressed only in some, e.g. own losses of the electricity sector may be modelled in the production function, or systems integration costs considered in investment costs for electricity sources. However, no model reviewed represents energy networks even in the energy system modules, which can however be addressed by coupling with more detailed energy systems models such as PRIMES. Nonetheless, the representation of more indirect impacts of energy infrastructure on growth such as through openness to trade or improved health, education or water services is far from being achieved, albeit there is little evidence in the case studies of its necessity.

Section **Error! Reference source not found.** highlights that energy quality and d evelopmental stages can be observed in the reviewed technology transitions in the form of demand pull drivers. These include increased security of supply in developing economies, improved energy access through off-grid solar PV, and reduction of local air pollution through solar PV electricity supply and low-carbon transport options (fuel cells and battery

EVs). The energy quality of different energy sources and carriers can be modelled e.g. through limited elasticities of substitution in nested production functions or a more detailed representation of the energy system within energy system sub-modules. However, the representation of future developmental stages poses a more interesting challenge. To our knowledge changes in the utilization of the different energy carriers (e.g. increased electricity consumption in place of biomass) is not a focus of the models and e.g. coefficients of the nested production functions are not updated according to the economy's development stage.

The comparisons above indicate the most important impacts of energy on growth as identified in the technology transitions are represented in some of the models, to a limited extent and in various forms, as there are usually multiple ways to represent an economic phenomena in modelling. Nonetheless, some of the more unconventional impacts appear lacking in the models, as their representation is not straightforward, being hampered both by modelling and data availability challenges. These include pollution-driven technological transition, increased energy quality as economies move in the energy ladder or improved human capital resultant from energy access.

4.2. Energy transition scenarios, innovation aspects and impact on growth

This section compares three different energy transition scenarios meant to provide concrete examples of how the assumptions and representations of technical change and the energy system result in different outputs regarding pathways to decarbonisation, innovation dynamics, the deployment of low-carbon technologies, and growth. The analysis fills in the missing links between case studies and applied modelling, reviewing three scenarios as published in studies which apply some of the selected models:

- **REMIND model:** Complementing carbon prices with technology policies by Bertram (2015)
- **IMACLIM-R model**: Energy efficiency policies and the timing of action by Bibas (2015)
- **Eurace@Unibi model**: Accelerating green technology diffusion by Hötte (2019)

In order to inform on the impact of the representation of endogenous technical change while maintaining a connection to the models reviewed, the scenarios have been chosen according to the following criteria:

- Use of one of the models reviewed in section 4.1
- Focus on low-carbon technology transitions and endogenous technical change
- Availability of data on the impact of endogenous technical change on the technological transition

The detailed analysis of the models and associated scenarios is presented in the Annex C.

4.2.1. Scenarios comparison

As the research questions analysed by each of the scenarios and the scenarios and models themselves vary significantly, the following section focuses on identifying and highlighting innovation aspects, the representation of the energy system and the impacts on growth in each scenario as discussed in previous sections, rather than on comparing the scenarios themselves. Table 0-9 summarizes the key information of the reviewed models, according to the dimensions of:

- Main research questions
- Main findings
- Innovation aspects
- Impact of representation of energy and innovation on growth

The following analysis focuses on the latter two dimensions of the scenarios: the innovation aspects, and the impact of the representation of innovation aspects and the energy system on growth.

Representation of innovation aspects and the energy system, and impact on growth

All scenarios reviewed evaluate the effect of policies on given technology, energy or environmental outcomes, but exogenously. The importance given to policy concurs with the case studies, where in all cases policy has played an important role in technology development and deployment. The “complementing carbon prices with technology policies” scenario evaluates the relative strength of demand pull drivers (price of carbon, support to renewable energy production and moratorium on coal) reflecting environmental considerations. The conclusions suggest that an optimal carbon price policy provides better environmental outcomes then the combined technology policies and sub-optimal carbon price. The “Green Technology Diffusion” scenarios based on the Eurace@Unibi model also explored the effect of different policies on diffusion of green energy technologies. Hence, it examines the effect of different (policy-based) incentives in overcoming path dependence. The study finds that policies should be tailored based on the different barriers (supply- or demand-side) that new technologies have to overcome. Policies based on tax incentives decrees the price for green capital goods homogenously. Policies in the form of green consumption price support benefit firms based to the relative extent to which they use green capital. The study also finds that the supply-side barriers have a stronger association with the transition dynamics than the demand-side ones. In contrast, the “Energy efficiency policies and the timing of action” scenario outcomes emphasize demand pull incentives in the form of price-induced energy efficiency improvements.

In all scenarios analysed learning effects are an important source of endogenous technology innovation. Learning by doing is the most common type of learning effect. This is consistent with the results of the case studies analysed and all models reviewed. This type of learning effect underline the importance of local know-how for technological development, when learning is (partially) dependent on regional capacities. In addition, the “Green Technology Diffusion” include human capital and absorptive capacity as important aspects of innovation.

Directorate-General for Energy
The links between energy transition and economic growth
2022

Table 0-9 Summary of the energy transition scenarios

Scenario Name	Based on model	Main research question(s)	Main findings	Innovation aspects	Impacts of representation of energy and innovation on growth
Complementing carbon prices with technology policies	*REMIND*	*Interaction of different technology policies (renewables support, moratorium on new coal power plants)* *Interaction between these technology policies and suboptimal carbon pricing schemes*	*Sub-optimal carbon pricing results in higher GHG emissions* *Technology policies alleviate cost and emission gap to optimal carbon pricing* *2nd best policies reduce additional costs to 2100 from over 0.4% to 0.2% over optimal baseline*	***Learning effects:*** *learning-by-doing* ***Decreasing returns:*** *diseconomies of scale by fast deployment mark-up costs*	*The energy sector is modelled within a single economic model. It does not contribute to economic activity in itself.* *Energy is an input to the production function of the economy composite good, and thus reductions in the cost of energy supply impact economic growth* *Endogenous learning-by-doing leads to significant differences in capital costs of renewables, batteries and EVs, e.g. up to 6% differences in investment costs for solar PV*

Scenario Name	Based on model	Main research question(s)	Main findings	Innovation aspects	Impacts of representation of energy and innovation on growth
Energy efficiency policies and the timing of action	*IMACLIM-R*	*Energy efficiency policies for climate action*	*Energy efficiency policies translate into up to 2/3s reduction in energy intensity of the economy* *High energy efficiency improvements by the lead region are ineffective if not accompanied by diffusion to regions with worse energy efficiency*	***Learning effects:*** *learning-by-doing for electricity and liquid fuels* ***Demand pull:*** *price-induced energy efficiency improvements* ***Vintages*** *and constraints to vintage adoption*	*Energy is a factor of production in other economic sectors, with energy prices affecting sectoral output* *Endogenous high energy efficiency improvements lead to up to 2.3% reduction in GDP losses due to climate policies, unambiguously when coupled with fast diffusion to follower regions* *High energy efficiency reduce energy expenditures of industry by more than 3 trillion USD in 2100, reducing the share of energy in total production costs by more than 30% and increasing industrial output by 2-8%.*

Scenario Name	Based on model	Main research question(s)	Main findings	Innovation aspects	Impacts of representation of energy and innovation on growth
Green Technology Diffusion	*Eurace@ Unibi*	*Accelerating the diffusion of green technologies* *Determinants of diffusion, learning and the coevolution of innovation and heterogeneous absorptive capacity*	*The endogenous nature of technological innovation seems to be an important factor that governs the process of divergence of the two technological regimes* *The supply-side barrier points to a stronger association with the transition dynamics than the demand-sided barrier* *Symmetric barriers are less inhibiting than asymmetric ones* *Taxes help overcoming disadvantages related to the productivity of the green technologies;* *Subsidies help overcoming barriers related to non-tradable capabilities at the firm level that are needed for the effective utilization of the green technologies*	***Incremental and radical innovations*** ***Learning effects:*** *learning-by-doing and learning-by-searching* ***Path dependence*** ***Human capital*** *and absorptive capacity* ***Diffusion***	*Representation of the energy system is simplified, as there are only producers of conventional and green technologies.* *Conventional and green capital good firms compose an economic sector, thus affecting growth by explicit representation of energy as an economic activity*

Whereas changes in technology are **incremental or radical** in the “Green Technology Diffusion” scenarios, they are represented as **vintages** in the “Energy efficiency policies and the timing of action”, while based on the empirical observations from the case studies, technical change in the form of vintages is seldomly observed. The results from the “Green technology diffusion” study support the idea of the **Schumpeterian creative destruction** associated with radical innovation, where technological regime shifts may lead to the market exit of companies that are unable to adapt to the new competitive environment.

Interestingly, Eurace@Unibi allows for the modelling of different rates and shapes of **knowledge diffusion** depending on the settings used to represent diffusion barriers (e.g. different rates of productivity and skill-related disadvantages). For different scenarios the entry barriers for green technology are set to different lengths, which has an effect on the way and extent to which new knowledge/technology will penetrate the market. The case studies highlight knowledge diffusion as a central characteristic of the technology transitions studied, either in the form of purposeful knowledge transfer or as spillovers.

Another interesting observation regarding the innovation aspects is that in the REMIND model fast technological upscaling is subject to high mark up costs. This has the effect of resulting in **decreasing returns**, which is contrary to the **increasing returns** observed in the case studies for, for example, solar PV.

Endogenous technical change in energy technologies contributes to **economic growth** in the three scenarios reviewed. For example, in the “Complementing carbon prices with technology policies” scenario the long-term costs of a technology policies improve long-term costs of climate action in 0.4% of total consumption in the 2010-2100 period compared to only the application of a carbon tax. These are coupled with reductions in the capital cost of low-carbon technologies by 2100, e.g. 2% for solar PV. In the “energy efficiency policies and the timing of action” scenario, high energy efficiency improvements coupled with technology diffusion lead to reduced GDP losses of 1.7-2.3% at a 4% discount rate. However, high energy efficiency improvements by the lead region are ineffective if not accompanied by diffusion to regions with worse energy efficiency. In the “Diffusion of low-carbon technologies” scenario, there is no relevant change in final output between the cases where the green or the conventional technology clearly dominates, but there is a loss of over 3% output in the cases where there are frequent switches in the dominant technology. This because of the waste of resources in R&D investments and technological skills.

Therefore, endogenous technical change in the scenarios increases economic output, or at least has no negative impact. However, this depends on certain conditions, such as fast technology diffusion or a clear pathway towards a certain technology choice (conventional or low-carbon). Moreover, understanding the impact of the endogenous technical change on growth depends on the availability of information on the models, main inputs and results, which is not always the case. This highlights the importance of model comparison projects such as the AMPERE study.

5. Conclusions and recommendations

Energy and environmental aspects were originally not addressed in the main economic schools of thought, although by now all have made significant progress. This has been accompanied by an increased representation of the energy system as well as consideration of climate change and climate action in macroeconomic models. Concerning innovations, from the beginning they were central to the Schumpeterian school, being later incorporated to various extents in the neo-classical and post-Keynesian schools. Innovation may significantly reduce the costs of the energy transition, and thus the direct and indirect impacts of both incremental and radical innovations need to be better represented in macroeconomic models.

However, the impact of energy & climate policies on the economy and reducing emissions will depend on various aspects, including capacity utilisation, the underlying drivers of growth, the dependence on (energy) imports, and the money supply. This context varies significantly from economy to economy, and macroeconomic models can be important tools to support policy making for the energy transition in a context of significant future uncertainty but also potential for innovation in energy technologies.

The main objective of this report is to review the channels through which energy promotes economic growth. A second objective is to analyse how growth is driven by energy-induced technical change.

This chapter draws on this analysis conducted to provide recommendations on improvements in GEM-E3-FIT and E3ME that will support the Energy Union in attaining its objectives.

5.1. Summary of theoretical and applied chapters

Chapter 1 reviews the key schools of economic thought and the associated modelling paradigms, analysing their main premises and the impact on the model results, as well as the relationship of energy and innovation to growth within each school of economic thought. The three schools of economic thought reviewed in this section are the (post-)Schumpeterian, the (post-)Keynesian, and the neo-classical schools. The main innovation theories are also subsequently examined and especially the innovation aspects which play important role in (some of) the theories. Chapter 2 discusses the different roles of energy in economic growth. This includes both more conventional roles as an activity and an input (including energy efficiency) as well as indirect roles of energy as a factor influencing other variables such as technical change and human capital.

Based on Chapters 1 and 2 a number of points can be highlighted:

- Economic schools of thought have **varying assumptions on the main factors affecting the growth and stability of the economy**, such as the (dis)equilibrium between supply and demand, the possibility of under-utilization of production capacities and of involuntary unemployment, the role of supply or demand in driving growth, the drivers of decisions by households (on consumption and savings) and firms (on investment and production), and the role of finance.
- The **role of energy and exhaustible resources is gaining importance** in all economic schools of thought. Neo-classical economics approaches mainly incorporate energy and materials as an input in the KLEM production function, with varying substitutability with (non-exhaustible) labour and capital playing a major

role on the impact on growth and decoupling. Recently, post-Keynesian approaches have begun to incorporate environmental constraints and the impact of climate change. Given the post-Schumpeterian focus on innovation for the economic cycle, and related theories have made important contributions to the study of innovation in energy technologies.

- All schools of economic thought concur in that **technical change is an important element of economic growth.** In the neo-classical school technical change is an important factor driving Total Factor Productivity. Motivation for R&D comes from the potential profit associated with temporary monopoly. In the (post-)Schumpeterian school of thought, innovation is directly associated with higher productivity and/or lower production costs. Investment in innovation is motivated by profit. In the (post-)Keynesian school technical change, as embodied in capital investment, is the main driver of growth in the long run.
- The many approaches to model the macroeconomy fall under two broad modelling paradigms. The **equilibrium/optimisation paradigm** is closely tied to the neo-classical school where the actions of all economic agents equilibrate the markets for production factors. The **non-equilibrium/simulation paradigm** contrast with this description of the economy and is associated with the (post-)Schumpeterian and (post-)Keynesian schools, where economy is conceptualized as being in a perpetual dynamic change.
- The main differences between macroeconometric and CGE models (associated with the simulation and optimisation paradigms, respectively) are on capacity utilisation, dynamics of growth, and money supply and crowding out. These lead to different outcomes under certain conditions, and thus the **models are not only relevant for different economic structures and stages of economic development, but also complementary for supporting policy making**.
- Among the main drivers of innovation are **supply push** and **demand pull** mechanisms. Policy can affect both supply push and demand pull and thus have a significant impact on driving innovation and technological change. Characteristics of innovation include **diffusion, increasing returns, learning effects, uncertainty and path dependence, human capital, bounded rationality and knowledge diffusion**. The most prevalently observed elements based on the review of the case studies are highlighted in the summary of chapters 3 and 4 below.
- Energy is interconnected with innovation and economic growth. Energy is considered as a sector in the economy, which adds value to the economy, stimulates investments, and creates jobs. Energy can also be seen as an input to production together with the other production factors: capital, labour and materials. Here, **increases in energy productivity** (i.e. decoupling between energy and growth) may be due to energy efficiency actions as well as structural changes in the economy. Substitution of inputs is also possible, with higher elasticity of substitution between different energy inputs than between these and capital.
- Energy also indirectly affects growth and is affected by it through the several interactions with other determinants of growth, such as human capital, trade openness, and infrastructure. Based on this analysis it is possible to conclude that **energy has an influence on economic growth** through a number of direct and indirect channels.

In chapters 3 and 4 the theoretical framework was enriched with an applied analysis based on a number of technology transition case studies, and the review of selected models and of different energy transition scenarios.

The following are the highlights from this applied analysis of Chapters 3 and 4:

- The **case studies chosen illustrate technology development at different stages**. Two distinct outcomes for historical energy transitions can be identified. In the first, successful innovations have been able to establish a significant market in the (recent) past, such as in the case of combined cycle gas turbines, solar PV and lithium-ion batteries. In contrast, technologies like fuel cells or CCS have not yet achieved substantial market penetration despite achieving technological maturity.
- The six case studies of technology transitions highlight some of the theoretical concepts discussed in the two previous chapters. For all cases **policy and a combination of supply push and demand pull drivers have played an important role**. A combination of both types of driver seems to be optimal. Whereas economic drivers are often the underlying basis for technology development, other important drivers identified include technical, environmental and social ones. In particular the case of CCS provides an interesting example of a technology that is primarily driven by climate change action.
- Innovation can arise at different speeds and in different forms with **incremental innovation being the most frequent type observed** in the case studies. Several innovation characteristics are identified in different degrees and forms, such as **increasing returns, learning effects and both purposeful and unintentional knowledge diffusion**.
- From the case studies, **the impact of the energy technologies on the macroeconomy as an economic activity is most visible**, while most technologies in the case studies have not yet been able to systematically reduce the cost of energy (except for CCGTs). Of the unconventional roles, the impact on technical change, climate change, infrastructure and energy quality and development stages are most apparent. Human capital and openness to trade impact could be observed only to a limited extent.
- Following the overall trend towards combinations of models and the quest to a more detailed representation of the energy system, **many of the integrated assessment or macroeconomic models analysed are hybrid**, incorporating an energy systems submodule.
- **Main interaction mechanisms between energy and growth** can be identified, but no model represents them all. Mechanisms include the substitution between production inputs, endogenous innovation in energy technologies, available productive slack in the economy, the costs of climate action and climate damages, changes in household preferences, changes in wages (and their cross-sectoral effects), and investment in energy technologies.
- Which interaction mechanisms between energy and growth are represented (and how) directly influences the possibility for decoupling between growth and energy consumption or GHG emissions. Generally, given the use of limited substitutability between energy with capital and labour, **decoupling from GHG emissions (due to reduced fossil fuel consumption) is more frequently achievable in the models than from overall energy consumption**.

- Generally, **energy efficiency, deployment of renewable energy and structural change of the economy enable the decoupling from fossil energy consumption**, facilitated by the knowledge stocks and spillovers when represented in the models.
- The **models generally represent both supply push and demand pull drivers, incremental innovation and learning effects**, while there is less representation of human capital, radical innovation and increasing returns (on the contrary, decreasing returns are frequently modelled representing resource constraints).

5.2. Central aspects in technology transitions and energy impact on growth

This section identifies the central aspects in technology transitions and economic growth that ideally should be addressed in GEM-E3-FIT and E3ME. It follows the most important aspects as identified in the case studies, which are discussed in section 3.2. First, the aspects related to energy as a factor of growth are discussed, and then the innovation aspects.

Representing the **impacts of energy on growth or the reverse** is a challenge for macroeconomic models in general. While these represent energy as a factor of production as well as the energy sector as an economic activity, not all mechanisms may have the same strength or may conflict with the premises of a certain economic school. Moreover, the unconventional channels discussed in section 2.3 are highly complex. Hence, the main aspects to be considered are:

- The existence and intersectoral influence of labour and capital markets, and the possibility for under-utilization of production capacities. These aspects may be intrinsically connected to a certain modelling paradigm, but can still be implemented in others through various approaches.
- The substitutability between production inputs, which strongly influences decoupling possibilities, and will vary between the different energy inputs, capital, labour, and energy efficiency measures.
- The impact of energy technologies on technical change should be represented in the model, such as how the competition between energy technologies on economic, technical and environmental grounds influences technical change and hence growth. But there are also potential complementarities such as between autonomous and fuel cell or battery electric vehicles, the diverse electricity and gas supply technologies and their positive or negative impact on system flexibility. These interactions are to a large extent technology-specific.
- While climate change is directly impacted by the energy system (and vice versa), in the short-term the feedback of climate change on the energy system (e.g. through global warming, extreme weather or sea level rise) was not observed in the case studies. Some models did represent in a simplified form the impact of climate damages on net output. Nonetheless, clearly private decisions are being currently affected by climate change due to individual considerations and public policy, and the impact of the energy system on climate will feed back to the energy system in the long run.

The energy technology transition case studies additionally identify the following most important innovation aspects:

- **Drivers of innovation**: Supply push can be differentiated by technology as well as public and private R&D efforts and include intersectoral interactions. Demand pull should reflect multiple drivers whose importance varies according to the technology and phase. The important interaction of both supply push and demand pull means that both should be present in the representation of (un)successful energy transitions.
- **Policy** plays a role in all technological transitions and should be reflected in models through supply push and demand pull mechanisms (for example in China for various technologies) but also other factors, such as infrastructure development (as for fuel cell and battery electric vehicles) and knowledge transfer.
- **Increasing returns** are observed in some case studies, arising from economies of scale in the supply chain and learning-by-doing (for example in solar PV or lithium-ion batteries). On the other hand, **decreasing returns** apply due to various constraints. Thus, models should strive for a balanced representation of increasing and decreasing returns reflecting the underlying causes and their regional and sectoral scope.
- **Learning effects** play an important role in innovation, both due to **learning-by-doing** and **learning-by-searching**. E3ME and GEM-E3-FIT should represent and differentiate these learning effects. The models could also consider whether global, regional or sectoral scopes apply.
- **Human capital** at the national level (and its international and intersectoral mobility) is an important factor not only for productivity but also for the success of R&D efforts and effective knowledge diffusion. Models should thus address the impact of human capital considering both general and sectoral skill levels.
- **Knowledge diffusion** (whether purposeful or unintentional) occurs within or across countries or sectors through various channels. Given the complexity, E3ME and GEM-E3-FIT models need to find a compromise in representing the various forms through which knowledge transfer can occur (and the influence of policy).

5.3. Bridging the gap: addressing remaining relevant aspects

Relevant aspects on the relationship of energy and growth

Capacity utilisation and the supply- versus demand-driven dynamics of growth are critical differences in modelling approaches to explaining the results achieved by macroeconomic models, and are, to a large extent, intrinsic to each modelling paradigm (macroeconometric or CGE). Nonetheless, GEM-E3-FIT and/or E3ME are among the most advanced macroeconomic models available, and have made considerable advances in representing the money supply and mitigating the crowding out effect. Further possibilities regarding these issues are discussed below.

Concerning energy as a factor of economic growth, on the one hand, as macroeconomic models both GEM-E3-FIT and E3ME address energy as an economic activity and as an input to a large extent. The impact of technical change on growth is part of the analysis conducted above, and with the MONROE project both models have addressed in much greater detail the impact of human capital on growth. On the other hand, the models have a limited representation of the impacts of energy on energy quality & developmental stages, infrastructures and openness to trade, in line with the other models reviewed.

Many of the central innovation aspects and impacts of energy on growth identified above are also already addressed by GEM-E3-FIT and/or E3ME. The analysis indicates first that specific mechanisms implemented in the models address most of the innovation aspects highlighted in the previous section, as summarized in the section 0. Nonetheless, this representation can be improved, both by drawing from best practices identified in the models reviewed and other novel approaches.

Drawing on best practices from the models reviewed

The following best practices should be considered for GEM-E3-FIT and/or E3ME, taking into account the limitations imposed by the modelling paradigms, data availability and other practical considerations:

- **Costs of climate action and net climate damages:** consider ways of internalizing climate damages. As macroeconomic models, if not coupled to integrated assessment models, GEM-E3-FIT and E3ME do not consider the feedback effect of climate change on the economy. The other macroeconomic models do not take this feedback into account either, but this is a core objective of integrated assessment models.
- **Public support to supply push:** implement synergies produced by coordinated policies that promote R&D, investment, production and adoption of low-carbon technologies; develop endogenous public R&D that considers these policy synergies and defines priorities and allocates resources (e.g. R&D funds) across sectors; model targeted subsidies that increase the levels of private R&D (that is, leveraging);
- **Radical innovations:** represent backstop technologies/sectors and stochastic entrance of these in the economy, including the non-economic demand pull drivers (technical, environmental, social) which lead to increasing development and adoption despite an initial lack of economic competitiveness;
- **Learning effects:** use more sophisticated learning curves, such as multi-factor curves highlighting learning-by-doing, learning-by-researching, and/or intersectoral spillovers, noting their different underlying drivers and implications for European low-carbon industrial strategy. There is also room for separation of the scope of the cumulative capacities used in the learning curves between the global and the regional levels as applicable (including lags);
- **Human capital:** separate human capital stocks into general skills applicable to multiple sectors, and sector-specific skills. This includes considering the representation of the R&D sector, which requires highly-skilled workers with possibly limited skill transferability to and from industry;
- **Knowledge diffusion:** consider the relevant channels of knowledge diffusion (e.g. within industrial conglomerates, technology licensing and company acquisitions) which can vary per sector and which may not be accurately proxied by a single indicator such as bilateral imports or patent citation data. Include also time lags for interregional spillovers.

Improving GEM-E3-FIT and E3ME beyond identified modelling best practices

Although the models reviewed provide important improvement avenues, further advances can be made by novel approaches and drawing from other models not covered in this report:

- **Substitution between production inputs:** Consider the inclusion of endogenous energy efficiency measures, and comparing with other models the parameters determining the substitutability between specific energy inputs, and between energy and capital, labour and materials. The capacity of energy efficiency measures to reduce energy demand and hence substitute energy inputs is already addressed in both GEM-E3-FIT and E3ME;
- **Finance and crowding-out of investments:** Investigate the more detailed representation of financing conditions for specific energy technologies. This is one of the objectives of the 'Representation and implications of the financing challenge' task of the present project. Both GEM-E3-FIT and E3ME are able to represent the creation of money and thus the (partial) mitigation of the crowding out effect;
- **Intersectoral R&D supply push:** Represent investments by industrial conglomerates and cross-sector investments, such as digital technology or oil & gas companies investing in low-carbon technologies. This can be implemented by considering intersectoral variables for determining R&D expenditures, such as activity levels from other sectors;
- **Coordinated national policy:** Implement coordination of national policies in multiple innovation aspects including supply push, demand pull (with support to investment, production and/or consumption), infrastructure and knowledge transfer, and the synergies between them. This could be done through sectoral indexes reflecting policy priorities and influencing public variables across these dimensions.

The recommendations addressed so far concern the development of model capabilities for the endogenous representation of various aspects. However, alternative strategies, leveraging the model inputs (such as through scenarios), can provide important policy insights into the macroeconomic impacts of the energy transition. The use of coherently-designed scenarios applies especially to two challenging topics:

- **Uncertain radical innovations or group of innovations,** impacting multiple sectors through conventional and unconventional channels, for example the development of electric, connected and autonomous vehicles.
- **Coordinated national policy** given the challenges of adequately representing them across the various aspects necessary to innovation and industrial development in a country, such as knowledge transfer initiatives, guidance (e.g. through targets), and support to R&D, investments, production and demand.

Overall, addressing the various recommendations identified is challenging, requiring the selection of the best approach, either endogenously in the models, or exogenously. Nonetheless, the review conducted confirms that to an important extent the models are already capable of providing relevant insights into the macroeconomics of the energy transition, especially when complementary modelling approaches are employed for the same policy question.

6. References

6.1. Chapter 1 references

Acemoglu, D., Autor. D., 2012, What Does Human Capital Do? A Review of Golding and Katz's the Race between Education and Technology. Journal of Economic Literature 50 (2) pp. 426–463.

Aghion, P. & Howitt, P., 1992. A Model of Growth Through Creative Destruction. Econometrica, p.323.

Aghion, P., Howitt, P., 1997. A Schumpeterian perspective on growth and competition. In: Kreps, D.M., Wallis, K.F. (Eds.), Advances in Economics and Econometrics: Theory and Applications, vol. 2. Cambridge University Press, Cambridge, MA, pp. 279–317.

Aghion, P. & Howitt, P., 1998. Capital accumulation and innovation as complementary factors in long-run growth. Journal of Economic Growth, 3(2), pp.111-130.

Aghion, P., Jaravel, X., 2015. Knowledge spillovers, innovation and growth, The Economic Journal, 125 (March), pp. 533-573.

Allan, C., Jaffe, A.B. and Sin, I., 2014. Diffusion of green technology: a survey. Paper presented in the New Zealand Agricultural & Resource Economics Society (NZARES)

Arrow, K. 1962. The economic implications of learning-by-doing, Review of Economic Studies, vol. 29, pp. 155-173.

Arrow, K.J. & Debreu, G., 1954. Existence of an equilibrium for a competitive economy. Econometrica: Journal of the Econometric Society, pp.265–290.

Arthur, W.B., 1989. Competing technologies, increasing returns, and lock-in by historical events. The economic journal, 99(394), pp.116-131.

Arthur, W. B. 1994. Increasing Returns and Path Dependence in the Economy. University of Michigan Press.

Balint, T., Lamperti, F., Mandel, A., Napoletano, M., Roventini, A., & Sapio, A., 2017. Complexity and the economics of climate change: a survey and a look forward. Ecological Economics, 138, 252-265

Barrell, R., & Pain, N., 1997. Foreign direct investment, technical change, and economic growth within Europe. The Economic Journal, 107(445), 1770-1786.

Barro, R.J., Sala i Martin, X., 1997. Technological diffusion, convergence, and growth. Journal of Economic Growth 2 (1), 1–26.

Barro, R.J., Sala i Martin, X., 2004. Economic Growth (second ed.). MIT Press, Cambridge, MA.

Becker, G. S. 1964. Human Capital: A Theoretical and Empirical Analysis with Special Reference to Education. Chicago: University of Chicago Press.

Bellais, R., 2004. Post Keynesian theory, technology policy, and long-term growth. Journal of Post Keynesian Economics, 26(3), pp.419-440.

Binswanger, H., Ruttan, V., 1978. Induced Innovation: Technology Institutions and Development. Johns Hopkins University Press, Baltimore, MD.

Braczyk, H.-J., Cooke, P. and Heidenreich, M. (eds), 1998. Regional Innovation Systems, London: UCL Press.

Buenstorf, G. (2004). The economics of energy and the production process: an evolutionary approach. Edward Elgar Publishing.

Casey, James P., 1976. High Fructose Com Syrup - A Case History of Innovation, Research Management, pp 27-33.

Carlsson & Stankiewicz, 1991. On the nature, function, and composition of technological systems, Journal of Evolutionary Economics, 1, 93-118.

Carlsson, B., 2007. Innovation systems: a survey of the literature from a Schumpeterian perspective, Ch. 53, In Hanusch, H. & Pyka, A. eds. Elgar companion to neo-Schumpeterian economics. Edward Elgar Publishing

Caselli, F., & Wilson, D. J., 2004. Importing technology. Journal of monetary Economics, 51(1), 1-32.

Chiaromonte, F., and G. Dosi, 1993. Heterogeneity, competition and macroeconomic dynamics, Structural change and Economic Dynamics, 4, 36-63.

Chidamber, S. R., & Kon, H. B., 1993. A research retrospective of innovation inception and success: the technology-push demand-pull question.

Ciccone, A., 2002. Agglomeration effects in Europe. European Economic Review, 46(2), 213-227.

Coe, D.T., Helpman, E., 1995. International R&D spillovers, European Economic Review, 39(5) pp. 859-887.

Cohen, W. M.; Levinthal, D. A., 1989. Innovation and Learning: The two faces of R&D, The Economic Journal, 99 (397)

Comin, D., Hobijn, B., 2004(a). Cross-country technological adoption: Making the theories face the facts. Journal of Monetary Economics 39–83.

Comin, D., Hobijn, B., 2004(b). Neoclassical Growth and the Adoption of Technologies. NBER Working Paper, 10733, Cambridge, MA

Comin, D., Hobijn, B., Ravito, E., 2006. Five Facts You Need to Know About Technology Diffusion. NBER Working Paper, 11928, Cambridge, MA

Conlisk, J., 1989. An aggregate model of technical change, Quarterly Journal of Economics, 104, 787–821.

Cooke, P., Uranga, M. and Etxebarria, G, 1997. Regional innovation systems: institutional and organizational dimensions, Research Policy, 26 (4), 475–91.

Dasgupta, P. and Heal, G. (1974) The optimal depletion of exhaustible resources, Review of Economic Studies, Symposium on the Economics of Exhaustible Resources, pp. 3-28

David, P., 1985. Clio and the economics of QWERTY, American Economic Review, 75, 332-337

Davidson, C., & Segerstrom, P., 1998. R&D subsidies and economic growth. The RAND Journal of Economics, 548-577.

Dietz, F. J., van der Straaten, J., & van der Ploeg, F. (Eds.), (2013). Environmental policy and the Economy (Vol. 206). Elsevier.

Dixon, P., Jorgenson, D., 2013. Handbook of Computable General Equilibrium Modeling, vol 1.

Dosi, G., 1988. Sources, procedures, and microeconomic effects of innovation. Journal of economic literature, pp.1120-1171.

Dosi, G., S. Fabiani, R. Aversi and M. Meacci, 1994(b). The dynamics of international differentiation: a multi-country evolutionary model, Industrial and Corporate Change, 3, 225-242.

Durlauf, S., 2018. Path Dependence. The New Palgrave Dictionary of Economics.

Dutt, A. K., 2003. New Growth Theory, Effective Demand, and Post Keynesian Dynamics. In N. Salvadori (ed.), Old and New Growth Theories. Aldershot, UK: Edward Elgar, pp.124-157.

Eaton, J., Kortum, S., 1999. International technology diffusion: Theory and measurement. International Economic Review 40(3), 537–570.

Eaton, J., Kortum, S., 2006. Innovation, Diffusion, and Trade. National Bureau of Economic Research, Cambridge, MA NBER Working Papers Series No. 12385.

EC, 2016a. Policy-induced energy technological innovation and finance for low-carbon economic growth. Deliverable D2 Study on the Macroeconomics of Energy and Climate Policies. Ref. Ares(2016)3442362 - 14/07/2016

Elsner, W. et al., 2015. The Microeconomics of Complex Economies Evolutionary, Institutional, and Complexity Perspectives.

Fagiolo, G., and G. Dosi, 2003. Exploitation, exploration and innovation in a model of endogenous growth with locally interacting agents. Structural Change and Economic Dynamics, 14, 237-273.

Freeman, C., 2018. Innovation. The New Palgrave Dictionary of Economics.

Fontana, G., Sawyer, M., 2016. Towards post-Keynesian ecological macroeconomics. Ecological Economics 121:186–195

Foxon, T., 2006. Bounded rationality and hierarchical complexity: Two paths from Simon to ecological and evolutionary economics. Ecological Complexity, 3, 361-368.

Foxon, T., Gross R., Heptonstall, P., Pearson, P., Anderson, D., 2007. Energy Technology Innovation: A Systems Perspective Report for the Garnaut Climate Change Review

Fragkiadakis, K., Paroussos, L., Karakousis, V., 2018. MONROE H2020 project. D3.4.2: The role of human capital in creating knowledge, absorbing spillovers and the importance of skilled labour migration.

Freeman, C., 1982. The Economics of Industrial Innovation, 2nd edition, MIT press, Cambridge, Massachusetts.

Freeman, C. & Louça, F., 2001. As Time Goes By, Oxford University Press.

Freeman, C. & Perez, C., 1988. Structural Crises of Adjustment, Business Cycles and Investment Behaviour, in G.Dosi et al. eds. Technical Change and Economic Theory, London: Francis Pinter, pp. 38-66

Gallagher, K. S., Grübler, A., Kuhl, L., Nemet, G., & Wilson, C., 2012. The Energy Technology Innovation System. Annual Review of Environment and Resources, 37(1), 137–162.

GEA ed., 2012. Global Energy Assessment, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria.

Geels, F. W., 2002. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Research Policy 31 (8-9), 1257 – 1274.

Geels, F. W., 2005. The dynamics of transitions in socio-technical systems: A multi-level analysis of the transition pathway from horse-drawn carriages to automobiles (1860 - 1930). Technology Analysis & Strategic Management 17 (4), 445–476.

Geroski, P.A., 2000. Models of technology diffusion. Research Policy 29 (4–5), 603–625

Grossman, G.M. & Helpman, E., 1991. Quality ladders in the theory of growth. The Review of Economic Studies, 58(1), pp.43–61.

Grossman, G., Helpman, E., 1993. Innovation and Growth in the Global Economy. MIT Press, New York.

Grossman, G.M. and Helpman, E., 1994. Endogenous innovation in the theory of growth. Journal of Economic Perspectives, 8(1), pp.23-44.

Grubb, M., 2004. Technological Innovation and Climate Change Policy: an overview of issues and options, Keio Economic Studies, vol. 41, no. 2, pp. 103-132.

Grübler, A. & Wilson, C., 2014. Energy Technology Innovation, Cambridge University Press.

Haelg, L., Waelchli, M., Schmidt, T.S., (2018). Supporting energy technology deployment while avoiding unintended technological lock-in: a policy design perspective. Environmental Research Letters 13:10

Hall, B., 2004. Innovation and Diffusion. NBER, Cambridge, MA NBER Working Paper No.10212.

Hall, S., Foxon, T.J., Bolton, R., (2017). Investing in low-carbon transitions: energy finance as an adaptive market. Climate Policy 17:3, pages 280-298.

Hannon, M.J., Foxon, T.J., Gale, W.F., (2013). The co-evolutionary relationship between Energy Service Companies and the UK energy system: Implications for a low-carbon transition. Energy Policy 61, pages 1031-1045.

Hansen, A.H. (1949), Monetary Theory and Fiscal Policy, New York: McGraw-Hill.

Hansen, A.H. (1953), A Guide to Keynes, New York: McGraw-Hill.

Hardt, L., & O'Neill, D. W. (2017). Ecological macroeconomic models: Assessing current developments. Ecological Economics, 134, 198-211.

Hein, E. (2014). Distribution and growth after Keynes: A Post-Keynesian guide. Edward Elgar Publishing.

Hekkert, M. P., Suurs, R. A. A., Negro, S. O., Kuhlmann, S. & Smits, R., 2006. Functions of innovation systems: A new approach for analysing technical change. Technological Forecasting and Social Change, 74, 4, 413-432.

Heyes, A. (2000). A proposal for the greening of textbook macro: 'IS-LM-EE'. Ecological Economics, 32, 1-7.

Hicks, J.R. (1937). Mr. Keynes and the "Classics": A Suggested Interpretation. Econometrica, April.

Holtz, G., 2011. Modelling transitions: An appraisal of experiences and suggestions for research. Environmental Innovation and Societal Transitions, 1(2), pp.167–186.

Holtz, G. et al., 2015. Prospects of modelling societal transitions: position paper of an emerging community. Environmental Innovation and Societal Transitions, 17, pp.41–58.

Hötte, K., 2019. How to accelerate green technology diffusion? An agent-based approach to directed technological change with coevolving absorptive capacity.

Iwai, K., 2000. A contribution to the evolutionary theory of innovation, imitation and growth. Journal of Economic Behaviour and Organisation, 42, 167-198.

Jacobsson & Bergek, 2004. Transforming the energy sector: the evolution of technological systems in renewable energy technology. Industrial and Corporate Change, 13(5), 815–849.

Jaffe, A. B., 1986. Technological opportunity and spillovers of R&D: evidence from firms' patents, profits and market value, NBER Working Paper, No. 1815.

Jalonen, H., 2012. The Uncertainty of Innovation: A Systematic Review of the Literature, Journal of Management Research, Vol. 4, No. 1: E1.

Johnson, A. & Jacobsson, S., 2000, The diffusion of renewable energy technology: an analytical framework and key issues for research, Energy Policy, 28, 625–40.

Jones, C., 1995. R & D-Based Models of Economic Growth. Journal of Political Economy, 103(4).

Kaldor, N., 1970. The Case for Regional Policies*. Scottish journal of political economy, 17(3), pp.337–348.

Kaldor, N., 1972. The irrelevance of equilibrium economics. The Economic Journal, 82(328), pp.1237–1255.

Kamien, M.I., Schwartz, N.L. 1968, Optimal induced technical change, Econometrica 36, 1–17.

Kemp-Benedict, E., 2014a. Shifting to a Green Economy: Lock-In, Path Dependence and Policy Options. Stockholm Environment Institute (Working Paper No. 2014-08.

Kennedy, C. 1964, Induced bias in innovation and the theory of distribution, Economic Journal 74 (295), 541–547.

Keynes, J.M., 1936. The General Theory of Employment, Interest and Money, Palgrave-Macmillan.

Klenow, P. J., & Rodriguez-Clare, A., 2005. Externalities and growth. Handbook of Economic Growth, 1, 817-861.

Köhler, J., Whitmarsh, L., Nykvist, B., Schilperoord, M., Bergman, N. and Haxeltine, A., 2009. A transitions model for sustainable mobility. Ecological economics, 68(12), pp.2985-2995.

Köhler, J., De Haan, F., Holtz, G., Kubeczko, K., Moallemi, E., Papachristos, G. and Chappin, E., 2018. Modelling sustainability transitions: An assessment of approaches and challenges. Journal of Artificial Societies and Social Simulation, 21(1).

Langrish, J., et al, 1972. Wealth from Knowledge, John Wiley & Sons, New York.

Lamperti, F., Dosi, G., Napoletano, M., Roventini, A., & Sapio, A., 2018. Faraway, so close: coupled climate and economic dynamics in an agent-based integrated assessment model. Ecological Economics, 150, 315-339.

Lawn, P. A. (2003). Environmental Macroeconomics: Extending the IS-LM Model to Include an 'Environmental Equilibrium' Curve. Australian Economic Papers, Vol. 42, pp. 118-134

Liebowitz, S. J. & Margolis, S.E., 1990: The Fable of the Keys. Journal of Law & Economics, vol. XXXIII

Liebowitz, S. J. & Margolis, S.E., 1995: Policy and Path Dependence – from QWERTY to Windows 95. Regulation vol. 18, no. 3

Löschel, A., 2002. Technical change in economic models of environmental policy: a survey. Ecological Economics, 43(2), pp.105–126.

Lucas, R., 1988, On the Mechanics of Economic Development, Journal of Monetary Economics 22 (1) pp. 3–42.

Lundvall, B.A., 1988. Innovation as an interactive process: from user-producer interaction to national systems of innovation. Technical change and economic theory.

Lundvall, B.A., 1992. 1992. National systems of innovation: towards a theory of innovation and interactive learning.

Malerba, F. (ed.), 2004. Sectoral Systems of Innovation. Concepts, Issues and Analyses of Six Major Sectors in Europe, Cambridge: Cambridge University Press.

Mankiw, N. G., Romer, D., & Weil, D. N., 1992. A contribution to the empirics of economic growth. The Quarterly Journal of Economics, 107(2), 407-437.

McCombie, J. and Thirlwall, A.P., 2016. Economic growth and the balance-of-payments constraint. Springer.

Meijer, I.S., Hekkert, M.P. and Koppenjan, J.F., 2007. The influence of perceived uncertainty on entrepreneurial action in emerging renewable energy technology; biomass gasification projects in the Netherlands. Energy policy, 35(11), pp.5836-5854.

Merton, R.K., 1973. The Sociology of Science, Chicago: University of Chicago Press,.

Meltcafe, J.S., J. Foster and R. Ramlogan, 2006. Adaptive economic growth. Cambridge Journal of Economics, 30, 7-32.

Meyers, S. and D.G. Marquis, 1969. Successful Industrial Innovation (Washington, DC; National Science Foundation).

Modigliani, F. (1944), 'Liquidity Preference and the Theory of Interest and Money', Econometrica, January

Mokyr, J., 1990. The Lever of Riches: Technological Creativity and Economic Progress (New York: Oxford University Press)

Mowery, D. and Rosenberg, N., 1979. The influence of market demand upon innovation: A critical review of some recent empirical studies. Research Policy 8 pp 102-153.

Murphy, L.M. and Edwards, P.L., 2003. Bridging the valley of death: Transitioning from public to private sector financing. Golden, CO: National Renewable Energy Laboratory.

Naish, H., 1995. Keynesian real business cycles in a neoclassical framework. Journal of Economic Behavior & Organization, Volume 27, Issue 2.

Negro, S. O. & Hekkert, M. P., 2008. Dynamics of Technological Innovation Systems: Empirical Evidence for Functional Patterns.

Nelson, R., 1993. National Innovation Systems: A comparative analysis. Oxford University Press, New York

Nelson, R.R. and Phelps, E.S., 1966. Investment in humans, technological diffusion, and economic growth. The American economic review, 56(1/2), pp.69-75.

Nelson, R., & Winter, S., 1982. An Evolutionary Theory of Economic Change. Harvard University Press, Cambridge, MA

Nordhaus, W. (1973). The Allocation of Energy Reserves. Brookings Papers 3, 529570

Norgaard, R B. (1984). Coevolutionary development potential. Land Economics, 60: 160–173.

OECD, E., 1997. The measurement of scientific and technical activities: Proposed Guidelines for Collecting and Interpreting Technological Innovation Data: Oslo Manual. OECD, Paris

OECD, 2002. Dynamising National Innovation Systems. OECD, Paris.

Papageorgiou, C., 2003. Distinguishing Between the Effects of Primary and Post primary Education on Economic Growth. Review of Development Economics, 7(4), 622-635.

Perez, C., 2001. Technological Revolutions and Financial Capital, Edward Elgar.

Phillips, L., 1966. Patents, Potential Competition and Technical Progress, American Economic Review, 56, pp 301-310.

Potts, J., 2000. The New Evolutionary Microeconomics: Complexity, Competence, and Adaptive Behavior, Cheltenham: Edward Elgar.

Popp , D.; Newell, R. and Jaffe, A., 2009. Energy, the Environment, and Technical change, No 14832, NBER Working Papers, National Bureau of Economic Research, Inc

Popp, D., Newell, R.G. and Jaffe, A.B., 2010. Energy, the environment, and technical change. In Handbook of the Economics of Innovation (Vol. 2, pp. 873-937). North-Holland.

Porter, M. & Stern, S., 2001. National innovative capacity. The Global Competitiveness Report, 2002, 102-118.

Rivera-Batiz, L.A. and Romer, P.M., 1991. Economic integration and endogenous growth. The Quarterly Journal of Economics, 106(2), pp.531-555.

Ryan, B. and Gross, N.C., 1943. The diffusion of hybrid seed corn in two Iowa communities. Rural sociology, 8(1), p.15.

Rogers, E.M., 2010. Diffusion of innovations. Simon and Schuster. 5th Edition

Romer, P.M., 1986. Increasing returns and long-run growth. The journal of political economy, pp.1002–1037.

Romer, P.M., 1987. Growth based on increasing returns due to specialization. American Economic Review, 77(2), pp.56–62.

Romer, P.M., 1990. Endogenous Technical change. journal of Political Economy, 98(5),

Rosenberg, N., 1972. Factors Affecting the Diffusion of Technology, Explorations in Economic History, 10(1), 3-33.

Rosenberg, N. 1982, Inside the Black Box: Technology and Economics Cambridge University Press.

Safarzynska, K. and van den Bergh, J.C., 2008. Evolutionary modelling in economics: a survey of methods and building blocks. Papers on economics and evolution.

Sala-i-Martin, X.X. and Barro, R.J., 1995. Technological diffusion, convergence, and growth (No. 735). Center Discussion Paper.

Saviotti, P.P., and A. Pyka, 2004. Economic development by the creation of new sectors, Journal of Evolutionary Economics, 14, 1-35.

Saviotti, P.P. and A. Pyka, 2008. Micro and macro dynamics: industry life cycles, intersector coordination and aggregate growth. Journal of Evolutionary Economics, 18, 167-182.

Schmookler, J., 1966. Invention and Economic Growth, Cambridge, Mass. Harvard University Press.

Schumpeter, J.A., 1934. The Theory of Economic Development - An inquiry into Profits, Capital, Credit, Interest and the Business Cycle (translated from original 1911 version), Cambridge, USA: Harvard University Press.

Schumpeter, J.A., 1939. Business Cycles, McGraw-Hill.

Schumpeter, J.A., 1942. Capitalism, Socialism and Democracy, Eastford, USA: Martino Publishing.

Schumpeter, J.A., 2014. Treatise on money, Worldbridge

Schwark., F., 2010. Economics of Endogenous Technical Change in CGE Models - The Role of Gains from Specialization. CER-ETH Working Paper No. 10/130.

Silverberg, G., and D. Lehnert, 1993. Long waves and 'evolutionary chaos' in a simple Schumpeterian model of embodied technical change, Structural Change and Economic Dynamics, 4, 9-37.

Silverberg, G., and B. Verspagen, 1994(a). Learning, innovation and economic growth: a long-run model of industrial dynamic, Industrial and Corporate Change, 3, 199-223.

Silverberg, G., and B. Verspagen, 1994(b). Collective learning, innovation and growth in a boundedly rational, evolutionary world, Journal of Evolutionary Economics, 4, 207-226

Silverberg, G., and B. Verspage, 1995. An evolutionary model of long term cyclical variations of catching up and falling behind, Journal of Evolutionary Economics, 5, 209-227.

Simon, H.A., 1955. A behavioral model of rational choice. Quart. J. Econ. 69, 99–118.

Solow, R.M., 1956. A contribution to the theory of economic growth. The quarterly journal of economics, pp.65–94.

Solow, R.M., 1957. Technical change and the aggregate production function. The review of Economics and Statistics, pp.312–320.

Solow, R. M., 1974. Intergenerational Equity and Exhaustible Resources, Review of Economic Studies, Oxford University Press, vol. 41(5), pages 29-45.

Swan, T.W., 1956. Economic growth and capital accumulation. Economic record, 32(2), pp.334–361.

Tàbara, J.D., Frantzeskaki, N., Hölscher, K., Pedde, S., Kok, K., Lamperti, F., Christensen J.H., Jäger J., Berry, P., 2018, Positive tipping points in a rapidly warming world, Current Opinion in Environmental Sustainability, 31, 120-129.

Taylor, Lance, 2004. Reconstructing Macroeconomics: Structuralist Proposals and Critiques of the Mainstream, Cambridge, MA, Harvard University Press

Taylor, Lance, 2008. “Energy Productivity, Labor Productivity, and Global Warming” in Jonathan M. Harris and Neva R. Goodwin (eds.) Twenty-First Century Macroeconomics: Responding to the Climate Challenge, Northhampton MA: Edward Elgar

Taylor, L., Rezai, A., Foley, D., 2016. An integrated approach to climate change, income distribution, employment, and economic growth Ecological Economics, 121, pp. 196-205

Tarr, D., 2013. Putting Services and Foreign Direct Investment with Endogenous Productivity Effects in Computable General Equilibrium Models. Handbook of Computable General Equilibrium Modeling.

Tidd, J., 2006. A review of innovation models. Imperial College London, 16.

Turnheim, B. et al., 2015. Evaluating sustainability transitions pathways: Bridging analytical approaches to address governance challenges. Global Environmental Change, 35, pp.239–253.

Utterback, J., 1974. Innovation in Industry and the diffusion of Technology, Science, Vol 183, February.

Uzawa, H., 1965. Optimum technical change in an aggregative model of economic growth. International Economic Review, 6(1), 18-31.

van den Bergh, J. C., Faber, A., Idenburg, A. M., & Oosterhuis, F. H. (2006). Survival of the greenest: evolutionary economics and policies for energy innovation. Environmental sciences, 3(1), 57-71

Walras, L., 1874. Elements of pure economics, Routledge.

Wing, I.S., 2004. Computable General Equilibrium Models and Their Use in Economy-Wide Policy Analysis

Zhong, L., 2017. Innovation as Determinants of Economic Growth in US Counties. Journal of Applied Business and Economics, 19(4), 107-116.

6.2. Chapter 2 references

Allen, E., L., Cooper, C.L., Edmonds, F.C., Edmonds, J.A, Reister, D.B., Weinberg, A.M., Whittle, C.E., Zelby, L.W., 1976. US energy and economic growth, 1975-2010. Oak Ridge TN: Oak Ridge Associated Universities Institute for Energy Analysis.

Amri, F., 2017. Intercourse across economic growth, trade and renewable energy consumption in developing and developed countries. Renewable and Sustainable Energy Reviews, 69, 527–534.

Andrews, D., Nicoletti, G., Timiliotis, C., 2018. Background paper Going digital: What determines technology diffusion among firms?

Apergis, N., Payne, JE., Menyah, K., Wolde-Rufael, Y., 2010. On the causal dynamics between emissions, nuclear energy, renewable energy and economic growth. Ecological Economics 69 : 2255-60.

Apergis, N. and Payne, JE., 2010a. Renewable energy consumption and economic growth: evidence from a panel of OECD countries. Energy policy; 38 : 656-60.

Apergis, N. and Payne, JE., 2010b. Renewable energy consumption and growth in Eurasia. Energy Economics 32 : 1392-7.

Apergis, N. and Payne, JE., 2011a. The renewable energy consumption-growth nexus in Central America. Applied Energy 88 : 343-7.

Apergis, N. and Payne, JE., 2011b. On the causal dynamics between renewable and non-renewable energy consumption and economic growth in developed and developing countries. Energy System 2 : 299-312.

Apergis, N. and Payne, JE., 2011c. Renewable and non-renewable electricity consumption-growth nexus: evidence from emerging market economies. Applied Energy 88 : 5226-30.

Apergis, N. and Payne, JE., 2012. Renewable and non-renewable energy consumption-growth nexus: evidence from a panel error correction model. Energy Economics 34 : 733-8.

Apostolakis, B.E., 1990. Energy – capital substitutability/complementarity. The dichotomy. Energy Economics, 12(1): 48-58.

Ayres, R. U., B. Warr (2009). The economic growth engine: How energy and work drive material prosperity. Cheltenham, UK and North Hampton MA, US, Edward Elgar.

Ayers, R.U., Van der Bergh, J., Lindenberger, D., Warr, B, 2013. The underestimated contribution of energy to economic growth. INSEAD Faculty and Research Working Paper, Social Innovation Centre.

Barnes, D., Floor, W.M., 1996. Rural energy in developing countries: a challenge for economic development. Annu. Rev. Energy Environ. 21, 497–530.

Barro, R., 1991. Economic Growth in a Cross Section of Countries. Quarterly Journal of

Economics, 106(2), pp. 407-443.

Barro, R., 1996. Determinants of economic growth: A cross-country empirical study. National Bureau of Economic Research (NBER) Working Paper 5698.

Barro and Sala-i-Marin, 1995. Economic Growth, New York, McGraw-Hill.

Barro, R. J., Sala-i-Martin, X., 2003. Economic growth. 2nd Edition. The MIT Press, Cambridge. MA.

Ben Aïssa, M.S., Ben Jebli, M., Ben Youssef, S., 2014. Output, renewable energy consumption and trade in Africa. Energy Policy, 66, 11-18.

Berndt, E.R., Wood, D.O., 1975. Technology, Prices and the Derived Demand for Energy. Review of Economics and Statistics, 57(3): 259-68.

Booz&Co, 2013. Benefits of an Integrated European Energy Market.

Bowden, N. and Payne, JE., 2010. Sectoral analysis of the causal relationship between renewable and non-renewable energy consumption and real output in the US. Energy Sources Part B: Econ. Plan. Policy 5: 400–8.

Burke, P.J., 2013. The National-Level Energy Ladder and Its Carbon Implications. Environment and Development Economics 18(4): 484–503.

Burke, P.J. and Csereklyei, Z., 2016. Understanding the Energy-GDP Elasticity: A Sectoral Approach. Energy Economics 58: 199–210.

Carlsson, R., Otto, A., Hall, J., 2013. The role of infrastructure in macroeconomic growth theories. Civil Engineering and Environmental Systems, 30.

Calel, R., and A. Dechezleprêtre, 2016. Environmental Policy and Directed Technical change: Evidence from the European Carbon Market. Review of Economics and Statistics 98 (1): 173–191.

Cheon, A., and J. Urpelainen, 2012. Oil Prices and Energy Technology Innovation. An Empirical Analysis. Global Environmental Change 22: 407–417.

Cleveland, C. J., R. K. Kaufmann, and D. I. Stern, 2000. Aggregation and the role of energy in the economy. Ecological Economics 32: 301-318.

Cline, W.R., 1992. The Economics of Global Warming. Institute for International Economics, Washington, DC.

Cole, M.A., 2006. Does trade liberalization increase energy use? Eco. Lett. 92, 108–112.

Costanza, R. and H. E. Daly (1992). Natural capital and sustainable development.

Conservation Biology 6: 37-46.

Costantini, V., F. Crespi, and A. Palma, 2017. Characterising the Policy Mix and Its Impact on Eco-Innovation: A Patent Analysis of Energy-Efficient Technologies. Research Policy 46: 799–819

Csereklyei, Z., Rubio, M. and Stern, D.I., 2016. Energy and economic growth: the stylized facts. Energy Journal 37(2): 223–55.

D'Arge, L., Kogiku, K., 1973. Economic growth and the environment. Review of Economic Studies 15(1), 61-77.

Dasgupta, S., E. De Cian, and E. Verdolini, 2016. The Political Economy of Energy Innovation. WIDER Working Paper 2016/17. United Nations University UNU-WIDER.

Dechezleprêtre, A., and M. Glachant, 2014. Does Foreign Environmental Policy Influence Domestic Innovation? Evidence from the Wind Industry. Environmental and Resource Economics 58: 391–413

Dedeoglu, D., and Kaya, H., 2013. Energy use, exports, imports and GDP: new evidence from the OECD countries. Energy Policy 57, 469–476.

Ecofys, 2014. Subsidies and costs of EU energy - Final report.

EEA (2019) Has there been a decoupling of economic growth from final energy consumption in Europe?

European Commission (EC), 2014, European Competitiveness Report 2014, 'Helping Firms Grow'

European Commission (EC), 2016b. EU energy trends and macroeconomic performance. Study on the Macroeconomics of Energy and Climate Policies. Prepared for the European Commission, Directorate-General for Energy, under contract ENER/A4/2015-436/SER/S12.716128

Doytch N. and Narayan, S., 2016. Does FDI influence renewable energy consumption? An analysis of sectoral FDI impact on renewable and non-renewable industrial energy consumption. Energy Economics 54 291–301

Estache, A., Garsous, G., 2012. The impact of infrastructure on growth in developing countries. IFC Economic Notes.

Estache, A., Wodon, Q., 2014. Infrastructure and Poverty in Sub-Saharan Africa

European Parliament, 2015. Mapping the Cost of Non-Europe, 2014-2019.

Fabrizi, A., G. Guarini, and V. Meliciani, 2018. Green Patents, Regulatory Policies and Research Network Policies. Research Policy 47: 1018–1031.

Fang, Z., Yu, J., 2018. The role of human capital in energy-growth nexus: an international evidence. Empirical Economics.

Fankhauser, S., 1994. "The Social Costs of Greenhouse Gas Emissions: An Expected Value Approach." Energy Journal, 15(2): 157–84.

Fiorito, G., van den Bergh, J., M., 2011. Capital-Energy Substitution for Climate and Peak Oil

Galvin, R. (2014). Estimating broad-brush rebound effects for household energy consumption in the EU 28 countries and Norway: some policy implications of Odyssee data. Energy Policy 73:323–332 DOI: 10.1016/j.enpol.2014.02.033

GEA, 2012. Chapter 19 Energy Access for Development. In Global Energy Assessment: Toward a Sustainable Future. Cambridge: Cambridge University Press.

Ghani, G.M., 2012. Does trade liberalization affect energy consumption? Energy Policy 43 (4), 285–290.

Giles, J.A., Williams, C.L., 2000a. Export-led growth: a survey of the empirical literature and some non-causality results: part 1. J. Int. Trade Econ. Dev. 9, 261–337.

Gillingham, K., Rapson, D., Wagner, G. (2015). The Rebound Effect and Energy Efficiency Policy

Grier, K. and Tullock, G., 1989. An empirical analysis of cross-national economic growth, 1951-1980. Journal of Monetary Economics, 24(1), pp. 259-276.

Gross, L., and E. Veendorp, 1990. Growth with exhaustible resources and a materials-balance production function. Natural Resource Modeling 4:77-94

Hudson E.A., Jorgenson D.W, 1974. U.S. Energy Policy and Economic Growth. Bell Journal of Economics, 5, 461- 514.

Hicks, J., 1932. The Theory of Wages. Macmillan, London, UK.

Hosier, R.H., 2004. Energy Ladder in Developing Countries. In Encyclopedia of Energy, edited by Cutler J. Cleveland, 423–35. Elsevier.

Howarth, R., (1997). “Energy Efficiency and Economic Growth”. Contemporary Economic Policy.

IEA, 2010. Energy Poverty – How to Make Modern Energy Access Universal? World Energy Outlook 2010. International Energy Agency (IEA), Paris.

IEA, 2018. World Energy Investment 2018.

IEA (2012). World energy outlook 2012.

IPCC, 2014a. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

IPCC, 2014b. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y .O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P .R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY , USA, 1132 pp.

IPCC, 2014c. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Jaffe, A.B., Peterson, S.R., Portney, P.R. and Stavins, R.N., 1995. Environmental regulation and the competitiveness of US manufacturing: what does the evidence tell us?. Journal of Economic literature, 33(1), pp.132-163.

Jaffe, A.B. & Palmer, K., 1997. Environmental regulation and innovation: a panel data study. Review of economics and statistics, 79(4), pp.610–619.

Johnstone, N., I. Hascic, and D. Popp, 2010. Renewable Energy Policies and Technological Innovation: Evidence Based on Patent Counts. Environmental and Resource Economics 45 (1): 133–155.

Jorgenson, D. W., 1978. The role of energy in the US economy. National Tax Journal, 31, 209-220.

Jorgenson, D. W., 1984. The role of energy in productivity growth. The Energy Journal, 5(3), 11-26.

Khazzoom, D. J. (1980). “Economic Implications of Mandated Efficiency in Standards for Household Appliances,” Energy Journal, 1:4, 21-39.

Koetse, M.J., De Groot, H.L.F., Florax, R., 2008. Capital-energy substitution and shifts in factor demand: A meta-analysis. Energy Economics, 30, 2236–2251.

Kormendi, R. and Meguire, P., 1985. Macroeconomic determinants of growth: cross-country evidence. Journal of Monetary Economics, 16(4), pp. 141-163.

Kümmel, R., 1982. The impact of energy on industrial growth. Energy, 7, 189-203.

Kümmel, R., Henn, J., Lindenberger, H., 2002. Capital, labor, energy and creativity: modeling innovation diffusion. Structural Change and Economic Dynamics, 13, 415-433.

Lanjouw, J.O. & Mody, A., 1996. Innovation and the international diffusion of

environmentally responsive technology. Research Policy, 25(4), pp.549–571.

Lean, H.H., Smyth, R., 2010a. Multivariate Granger causality between electricity generation, exports and GDP in Malaysia. Energy 35, 3640–3648.

Lean, H.H., Smyth, R., 2010b. On the dynamics of aggregate output, electricity consumption and exports in Malaysia: evidence from multivariate Granger causality tests. Appl. Energy 87, 1963–1971.

Liddle, B., 2012. The importance of energy quality in energy intensive manufacturing: Evidence from panel cointegration and panel FMOLS. Energy Economics, 34(6), pp.1819-1825.

Lindenberger, D. and Kümmel, R., 2011. Energy and the state of nations. Energy, 36, 6010-6018.

Lucas, R., 1988, On the Mechanics of Economic Development, Journal of Monetary Economics 22 (1) pp. 3–42.

Mankiw, N. G., Romer, D., & Weil, D. N., 1992. A contribution to the empirics of economic growth. The Quarterly Journal of Economics, 107(2), 407-437.

McKinsey (2010). Energy efficiency: a compelling global resource.

Menegaki, A. N. (2018). The Economics and Econometrics of the Energy-Growth Nexus.

Miketa, A. and P. Mulder (2005). Energy productivity across developed and developing countries in 10 manufacturing sectors: Patterns of growth and convergence, Energy Economics, Vol. 27, pp. 429-453.

Moral-Benito, E., 2012. Determinants of economic growth: a Bayesian panel data approach. Review of Economics and Statistics, 94(2), pp.566-579.

Mulder, P. and H. de Groot (2007), Sectoral energy- and labour-productivity convergence, Environmental and Resource Economics, No. 36, pp. 85-112.

Nadel, S. (2012). The Rebound Effect: Large or Small? Available at: https://aceee.org/files/pdf/white-paper/rebound-large-and-small.pdf

Narayan, P.K., Smyth, R., 2009. Multivariate Granger causality between electricity consumption, exports and GDP: evidence from a panel of Middle Eastern countries. Energy Policy 37, 229–236.

Nasreen, S. and Anwar, S., 2014. Causal relationship between trade openness, economic growth and energy consumption: A panel data analysis of Asian countries. Energy Policy, 69, pp.82-91.

Nesta, L., F. Vona, and F. Nicolli, 2014. Environmental Policies, Competition and Innovation in Renewable Energy. Journal of Environmental Economics and Management 67: 396–411.

Newell, R.G., Jaffe, A.B. and Stavins, R.N., 1999. The induced innovation hypothesis and energy-saving technological change. The Quarterly Journal of Economics, 114(3), pp.941-975.

Nordhaus, W.D., 1991. To slow or not to slow: the economics of the greenhouse effect. Economic Journal 101, 920–937

Nordhaus, W.D., 1994. Managing the Global Commons: the Economics of Climate Change. The MIT Press, Cambridge.

Oh,W., Lee, K., 2004. Causal relationship between energy consumption and GDP revisited: the case of Korea 1970–1999. Energy Econ. 26, 51–59.

Ozturk, I., 2010. A literature survey on energy-growth nexus. Energy Policy, 38, 340–349.

Pablo-Romero, M., and Sanchez-Braza, A., 2015. Productive energy use and economic growth: Energy, physical and human capital relationships, Energy Economics 49: 420-429.

Pao, H.T., Tsai, C.M., 2011. Modelling and forecasting the CO2 emissions, energy consumption, and economic growth in Brazil. Energy 36, 2450–2458.

Payne, J.E., 2010. Survey of the international evidence on the causal relationship between energy consumption and growth. Journal of Economic Studies, 37, 53–95.

Peters, M., M. Schneider, T. Griesshaber, and V. H. Hoffmann, 2012. The Impact of Technology-Push and Demand-Pull Policies on Technical Change – Does the Locus of Policies Matter? Research Policy 41: 1296–1308.

Popp, D., 2002. Induced Innovation and Energy Prices, American Economic Review, 92, 160-18.

Popp, D., 2010. Innovation and Climate Policy. NBER Working Paper No. 15673

Rahman, M.M., Mamun, S.A., 2016. Energy use, international trade and economic growth nexus in Australia: new evidence from an extended growth model. Renew. Sustainable Energy Rev. 64, 806–816.

Romer, P., M., 1994. The origins of endogenous growth. Journal of Economic Perspectives, 8(1),3-22.

Sadorsky, P., 2009. Renewable energy consumption and income in emerging economies. Energy Policy 37:4021–8.

Sadorsky, P., 2011. Trade and energy consumption in the Middle East. Energy Econ. 33, 739–749.

Sadorsky, P., 2012. Energy consumption, output and trade in South America. Energy Econ. 34, 476-488.

Saunders, H.D., (1992). "The Khazzoom-Brookes postulate and neoclassical growth". The Energy Journal. 13 (4): 131–148

Smulders, S., 2005. Endogenous technical change, natural resources and growth. In: D. Simpson and M. Toman (eds). Scarcity and Growth in the New Millennium. RFF Press, Boston.

Srinivasu, B., Srinivasa Rao, P., 2013. Infrastructure Development and Economic growth: Prospects and Perspective. Journal of Business Management & Social Sciences Research vol. 2(1).

Sterlacchini, A., 2019. Trends and determinants of energy innovations: patents, environmental policies and oil prices. Journal of Economic Policy Reform pp.1-18

Stern, D.I., 2000. A multivariate cointegration analysis of the role of energy in the US macroeconomy. Energy economics, 22(2), pp.267-283.

Stern, D.I., 2010. Energy quality. Ecological Economics, 69(7), pp.1471-1478.

Stern, D.I., 2011. The role of energy in economic growth. Annals of the New York Academy of Sciences, 1219(1), pp.26-51.

Tol, RSJ., 1995. The Damage Costs of Climate Change Toward More Comprehensive Calculations. Environmental and Resource Economics, 5(4): 353–74

Tol, RJS., 2009. The Economic Effects of Climate Change. Journal of Economic Perspectives, 23(2): 29-51

Toman, M., and Jemelkova, B., 2003. Energy and Economic Development: An assessment of the State of Knowledge. Resources for the Future, Washington, DC.

Trinomics, 2018. Sector coupling: how can it be enhanced in the EU to foster grid stability and decarbonise? Study for the European Parliament, ITRE Committee.

Trinomics, 2019. Study on impacts of EU actions supporting the development of renewable energy technologies.

van den Bergh, J.C.J.M. and P. Nijkamp, 1994. Dynamic macro modelling and materials balance: Economic environmental integration for sustainable development. Economic Modelling, vol. 11: 283 307.

Vivideconomics for the Climate Institute (2013). “Energy efficiency and economic growth”.

Warr, B., Ayres, R., 2010. Evidence of causality between the quantity and quality of energy consumption and economic growth. Energy 35, 1688–1693.

Warr, B. and Ayres, R.U., (2012). ‘Useful work and information as drivers of growth.’ Ecological Economics 73, 93-107.

6.3. Chapter 3 references

Introduction

Council of the European Union, 2019. 15665/18 Information note on Strategic Forum on Important Projects of Common Interest

European Commission, 2018a. In-depth analysis in support of the commission Communication com(2018) 773 - A clean planet for all - A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy

European Commission, 2018b. Annex 2 to the proposal for a regulation of the European Parliament and of the Council stablishing the InvestEU programme.

European Commission, 2019. Commission delegated regulation supplementing with regard to the operation of the Innovation Fund. C(2019) 1492 final.

Combined cycle gas turbines

Abani, A., 2018. Profitability of gas-fired power plants in Europe: is the storm behind us? Deloitte.

Bergek, A., Tell, F., Berggren, C., Watson, J., 2008. Technological capabilities and late shakeouts: industrial dynamics in the advanced gas turbine industry, 1987–2002. Industrial and Corporate Change vol. 17 2.

De Vita, A., Kielichowska, I., Mandatowa, P., 2018. Technology pathways in decarbonization scenarios. ASSET – Advanced System Studies for Energy Transition.

DG Competition, 2015. CASE M.7278 – General Electric / Alstom (Thermal Power – Renewable Power & Grid Business)

Eurostat, 2019. Net electricity generation, EU-28, 1990-2016. Available at https://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_production,_consumption_and_market_overview

Forecast International, 2018. Worldwide gas turbine forecast.

Grand View Research, 2018. Gas Turbine Market Size, Share & Trends Analysis Report

Hoefnagels et al., 2010. Combined Cycle Gas Turbine (CCGT) plants. In Technological Learning in the Energy Sector

IEA ETSAP, 2010. Technology Brief - Gas-Fired Power

IEA, 2018. World Energy Investment 2018

Komissarov, V., 2018. Gas Turbine Engines Market and Applications Overview

Lazard, 2008. Levelized cost of energy analysis – version 2.0

Lazard, 2018. Levelized cost of energy analysis – version 12.0

McCoy, 2018. Power reports – combined cycle quarterly, 3M’18 report of diesel engines and gas turbines. Journal of Global History Vol 2 3.

Smil, V., 2007. The two prime movers of globalization: history and impact

UKERC, 2012. UKERC Technology and Policy Assessment Cost Methodologies Project: CCGT Case Study

Watson, J., 2004. election environments, flexibility and the success of the gas turbine. Research policy Vol 33 8.

Lithium-ion batteries

Avicenne, 2010. Main trends for rechargeable battery - Market 2009-2020.

Battke et al., 2016. Internal or external spillovers—Which kind of knowledge is more likely to flow within or across technologies. Research Policy 45.

Blomgren, 2017. “The Development and Future of Lithium Ion Batteries”,. Journal of the Electrochemical Society, 164 (1), (2017)

Chung et al., 2016. Automotive Lithium-ion Cell Manufacturing: Regional Cost Structures and Supply Chain Considerations

GCIS, 2016. China's Lithium-ion Battery Market: Drivers behind it and its sustainability. Available at http://www.gcis.com.cn/china-insights/industry-articles/123-china-s-lithium-ion-battery-market-drivers-behind-it-and-its-sustainability

Greatbach et al., 1971. IEEE Trans. Biomed. Eng. 18.

Invest Korea, s.d.. Next Generation Batteries: the Case of Korea

Moreno-Brieva et al., 2019. Technology generation and international collaboration in the Global Value Chain of Lithium Batteries. Resources, Conservation & Recycling 146.

Stephan et al., 2017. “The sectoral configuration of technological innovation systems: Patterns of knowledge development and diffusion in the lithium-ion battery technology in Japan”,. Research Policy. (2017)

Stephan et al., 2017. The sectoral configuration of technological innovation systems: Patterns of knowledge development and diffusion in the lithium-ion battery technology in Japan. Research Policy

Suh, 2004. The Industrial Competitiveness of Korea’s IT Industry

Tack, 2016. Overview of Korea Rechargeable Battery Activities

Trinomics and DNV GL, 2019. Study on energy technology dependence - Detailed assessment on dependencies within the wind energy, solar PV and battery energy storage value chain (Task 4).

Triropolos, I., Tarvydas, D., Lebedeva, N., 2018. et al. “Li-ion batteries for mobility and stationary storage applications.”, JRC Science for Policy Report (2018)

Tutore et al., 2014. “Overcoming the barriers to the innovations diffusion through diffusion-oriented policies. The case of Li-Ion Battery for Electric Vehicles.”, Sinergie, rivista di studi e ricerche. (2014)

Vincent, C.A., 2000. “ Lithium batteries: a 50 year perspective, 1959-2009.”, Solid State Ionics 134 (2000) 159-167. Available at: https://las493energy.files.wordpress.com/2014/11/li-ion-batteries_-history-1959-to-2009.pdf

Wakuhara, 2001. , “Recent developments in lithium ion batteries”. , Materials Science and Engineering R33 (2001) 109-134.

Hydrogen fuel cells

Behling, N., 2013. Fuel cells – Current technology, challenges and future research needs. Elsevier.

Breeze, P., 2017 Fuel cells. Elsevier.

DOE, US Department of Energy, 2014. 2013 Fuel Cell Technologies Market Report.

Grand View, 2018. Fuel Cell Market Size Projected To Be Worth USD 24.81 Billion By 2025. Available at http://www.abnewswire.com/pressreleases/fuel-cell-market-size-projected-to-be-worth-usd-2481-billion-by-2025-grand-view-research-inc_86979.html

Huang, M., Yang, H. 2013. A Scientometric Study of Fuel Cell Based on Paper and Patent Analysis. Journal of Library and Information Studies 11(2).

IEA, 2015. Technology Roadmap – Hydrogen and Fuel Cells.

JRC, 2018. Monitoring R&I in Low-Carbon Energy Technologies. EUR 28446 EN

JRC, 2019. Global deployment of large capacity stationary fuel cells.

Larminie, J., Dicks, A., 2003. Fuel cell systems explained.

OECD, 2005. Innovation in fuel cells: a bibliometric analysis

Sasaki et al., 2016. Hydrogen energy engineering – a Japanese perspective

Schoots et al., 2010. Technology learning for fuel cells: An assessment of past and potential cost reductions. Energy Policy 38.

Zhang, F., Cooke, P., 2010. Hydrogen and Fuel Cell Development in China: A Review.

Carbon capture and storage

Zheng B.; Xu. J.; “Carbon Capture and Storage Development Trends from a Techno-Paradigm Perspective”, Energies 2014, 7, 5221-5250

European Court of Auditors. 2018. “Demonstrating CCS and innovative renewables at commercial scale in the EU: intended progress not achieved in the past decade”.

Global CCS Institute, 2018. The Global Status of CCS: 2018. Australia

Solar PV

Trinomics, Study on impacts of EU actions supporting the development of renewable energy technologies, 2018

Trinomics, Assessment of Photovoltaics, 2016

SolarPower Europe, Global Market Outlook 2018-2022, 2018. Available at: http://www.solarpowereurope.org/wp-content/uploads/2018/09/Global-Market-Outlook-2018-2022.pdf

Nemet, G., 2012. Solar Photovoltaics: Multiple Drivers of Technological Improvement. Historical Case Studies of Energy Technology Innovation in: Chapter 24, The Global Energy Assessment. Grubler A., Aguayo, F., Gallagher, K.S., Hekkert, M., Jiang, K., Mytelka, L., Neij, L., Nemet, G. & C. Wilson. Cambridge University Press: Cambridge, UK.

Husmann, D., 2011. {U.S.} Photovoltaic Breakthroughs from 1947 To 1993: their Identification, Origin, and Commercialization. M.S. Master’s thesis, University of Wisconsin, Madison

Zhang, S. et al., 2013. Analysis on the development and policy of Solar PV in China. Renewable and Sustainable Energy Reviews 21 (2013) 393-401.

JRC, 2018. PV Status Report 2018. Available at: http://publications.jrc.ec.europa.eu/repository/bitstream/JRC113626/pv_status_report_2018_online.pdf

Autonomous road vehicles

Anderson et al., 2014. Chapter 4: Brief History and Current State of Autonomous Vehicles. In Autonomous Vehicle Technology.

BCG, 2015. Revolution in the Driver's Seat: The Road to Autonomous Vehicles

Bengler, 2014. Three Decades of Driver Assistance Systems – Review and Future Perspectives

Catapult, 2017. Market forecast for connected and autonomous vehicles

Eureka network, s.d.. Available at https://www.eurekanetwork.org/project/id/45

European Patent Office, 2018. Patents and self-driving vehicles

Frost & Sullivan, 2018. Global Autonomous Driving Market Outlook 2018

Gandia, R. et al, 2019. Autonomous vehicles: scientometric and bibliometric review. Transport Reviews Vol. 39(1).

Kamyia, G., Teter, J., 2019. Commentary: Shared, automated… and electric? IEA. Available at https://www.iea.org/newsroom/news/2019/march/shared-automatedand-electric.html

Park, J., Choi, J., Bae, Y., 2013. Scientometric Analysis of Autonomous Vehicle through Paper Analysis of each Nation. The Journal of the Korea institute of electronic communication sciences vol 8(2).

Popper, 2017. Light. The Verge, available at https://www.theverge.com/2017/10/18/16491052/velodyne-lidar-mapping-self-driving-car-david-hall-interview

Pizzuto, L., Thomas, C., Wang, A., Wu, T., 2019. How China will help fuel the revolution in autonomous vehicles. Available at https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/how-china-will-help-fuel-the-revolution-in-autonomous-vehicles

SAE, 2018. Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles. Available at https://www.sae.org/standards/content/j3016_201806/

Schladover, 2017. Connected and Automated Vehicle Systems: Introduction and Overview. Journal of Intelligent Transportation Systems Vol. 22 3.

Tsugawa, 1992. Concept of super smart vehicle systems and their relation to advanced vehicle control systems

Wakabayashi and Conger, 2018. Uber's Self-Driving Cars Are Set to Return in a Downsized Test. New York Times. Available at https://www.nytimes.com/2018/12/05/technology/uber-self-driving-cars.html

Weber, 2014. Where to? A History of Autonomous Vehicles. Available at https://www.computerhistory.org/atchm/where-to-a-history-of-autonomous-vehicles/

Wu, J., Liao, H., Wang, J., Chen, T., 2019. The role of environmental concern in the public acceptance of autonomous electric vehicles: A survey from China. Transportation Research Part F: Traffic Psychology and Behaviour, vol. 60.

6.4. Chapter 4 references

Acemoglu, D., Aghion, P., Bursztyn, L., & Hemous, D., 2012. The environment and directed technical change. American economic review, 102(1), 131-66.

AMPERE, 2014. AMPERE Project Public Database. Available at https://tntcat.iiasa.ac.at/AMPEREDB

Bertram, C. et al., 2015. Complementing carbon prices with technology policies. Nature Climate Change 5.

Capros, P. et al. 2013. “Report on potential co-benefits of mitigation for Europe”. Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates. http://www.e3mlab.eu/e3mlab/reports/potential%20co-benefits%20of%20mitigation%20for%20europe.pdf

Capuano, C., Grassi, I., 2018. Spillovers, product innovation and R&D cooperation: a theoretical model. Economics of Innovation and New Technology.

Ciarli, T., Maria, S., 2019. Modelling the Evolution of Economic Structure and Climate Change: A Review. Ecological Economics 158.

Elmar K. et al., 2015. Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. Technological Forecasting and Social Change, Volume 90.

Fragkos, P., Fragkiadakis, K., Paroussos, L., et al., 2018. Coupling national and global models to explore policy impacts of NDCs. Energy Policy 118:462–473

Gualdi, S., Antoine, M., 2018. Endogenous Growth in Production Networks. Journal of Evolutionary Economics 29(1).

Hötte, K., 2019. How to accelerate green technology diffusion? An agent-based approach to directed technical change with coevolving absorptive capacity. Universität Bielefeld Working Papers in Economics and Management; 01-2019.

König, M., Liu, X., Zenou, Y., 2014. R&D Networks: Theory, Empirics and Policy Implications. Working Paper No. 142, University of Zurich, Department of Economics.

Lamperti, F., Napoletano, M. and Roventin, A., 2019. "Green transitions and the prevention of environmental disasters: market-based vs. command-and-control policies." Macroeconomic Dynamics: 1-20.

Lavrijssen, S., Carrillo, A., 2017. Radical innovation in the energy sector and the impact on regulation.

Ponta et al., 2018. An Agent-based Stock-flow Consistent Model of the Sustainable Transition in the Energy Sector. Ecological Economics 145

Takalo, T., Tanayama, T., Toivanen, O., 2013. Market failures and the additionality effects of public support to private R&D: Theory and empirical implications. International Journal of Industrial Organization 31

Vrontisi, Z., Fragkiadakis, K., Kannavou, M., et al., 2019. Energy system transition and macroeconomic impacts of a European decarbonization action towards a below 2 °C climate stabilization. Climatic Change. https://doi.org/10.1007/s10584-019-02440-7

7. Annex A: technology transitions case studies

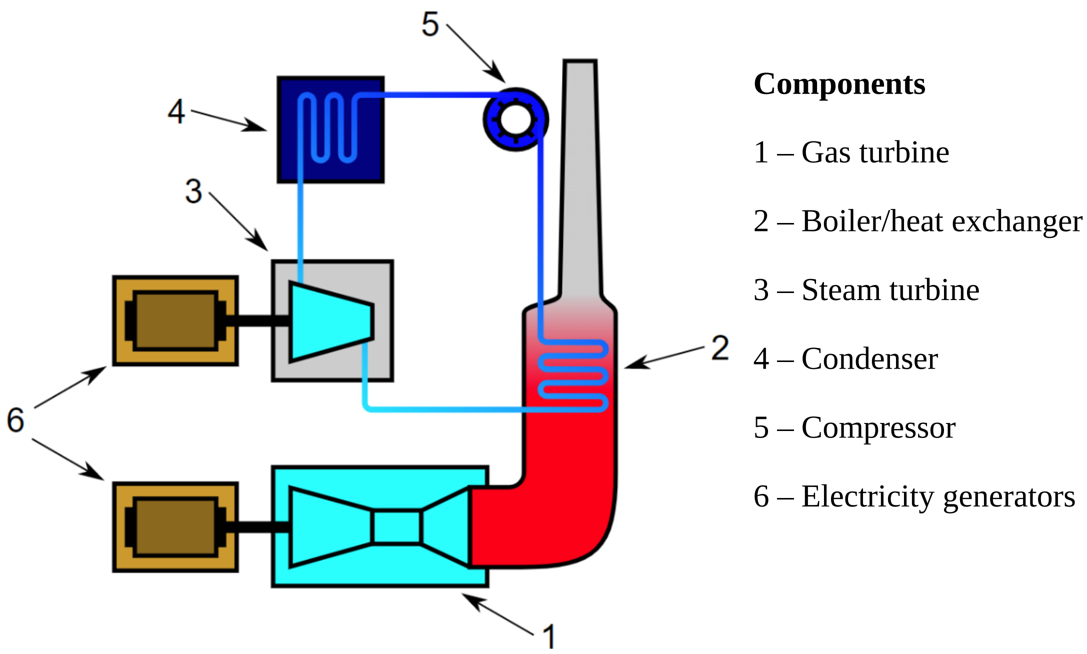
7.1. Case study 1: Combined cycle gas turbines

Technology and market overview

Short description of the technology

The main elements of a combined cycle gas turbine (CCGT) are a gas turbine, a heat recovery steam generator and a steam turbine. While the gas and steam turbines drive one or more electricity generators, the heat recovery system uses the heat of exhaust gases of the gas turbine to provide steam for the second. With this system, CCGTs are capable of reaching an electric efficiency above 60%[17] (Hoefnagels, 2010).

Figure 0-13 Diagram showing how a combined-cycle gas turbine works



Cost reductions in combined-cycle gas turbines

Combined cycle gas turbines are a mature technology, making only marginal investment cost and efficiency improvements in the last decade. Lazard estimates plant capital costs to have changed from 900 - 1100 USD/kW in 2008 to 700 – 1300 USD/kW in 2018 in nominal terms (Lazard, 2008, 2018). Nonetheless, historically CCGTs have seen important cost reductions, with different studies estimating the learning ratio at 10% in the maturity phase after 1997 and ranging from 10% to 25% in the pre-1997 commercialization phase. An analysis of the capital costs of large European and North American plants indicates a cost reduction of 25% in the 1991-1997 period, to around 400

[17] That is, over 60% of the total energy input is converted into electricity.

USD_{1990}/kW. Concerning the electric efficiency of the most performing turbine vintage, it increased from 54% in 1987 to 60% in 2010, and is expected to reach 64% by 2020, stabilizing afterwards to 2030 (Bergek, 2008; IEA ETSAP, 2010). The recent ASSET study is more conservative (dealing not with state-of-the-art but average values for modelling), assuming an electric efficiency of 60% in 2020 which increases to 63% in 2050 (De Vita, 2018). The efficiency of CCGTs is relevant in the context of costs because fuel costs for the operation of the turbines represent the major component of the levelized cost of energy.

The main components of a CCGT (gas turbine, steam turbine and HRSG) respond for 60% of total investment costs, while other plants costs such as project, general facilities and interest charges account for the rest. The gas turbine can account for over 55% of the costs for the main components, the steam turbine for around 26% and the heat recovery steam generator for the remaining 19% (Bergek, 2008).

Market status

Table 0-10 Summary of the past, present and future market status for CCGTs

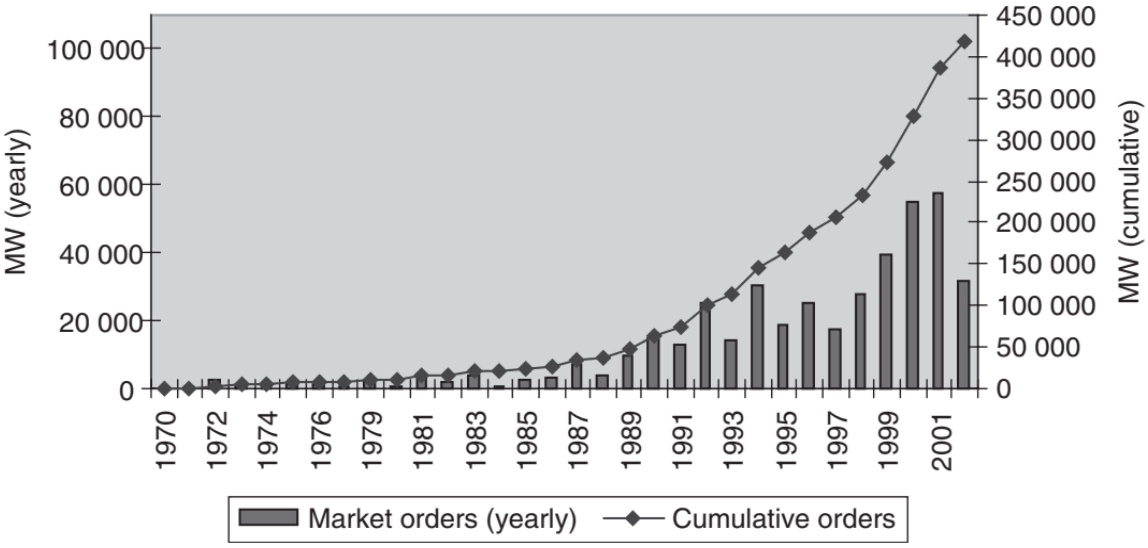
	Unit	2000s	2014-2018	2018-2028
Market size	GW	60-80 (gas turbines)	50	60 (gas turbines)
Lead countries	%	US (54%) Germany (22%) France (15%)	US (40%) Germany (26%) Japan (13%)	US (50%) Germany (27%) Japan (13%)

Source: Bergek et al. (2008) Technological capabilities and late shakeouts: industrial dynamics in the advanced gas turbine industry, 1987–2002. Industrial and Corporate Change vol. 17(2).

McCoy, 2018. Power reports – combined cycle quarterly, 3M'18 report.

Forecast International, 2018. Worldwide gas turbine forecast.

Figure 0-14 CCGT market development 1970-2002

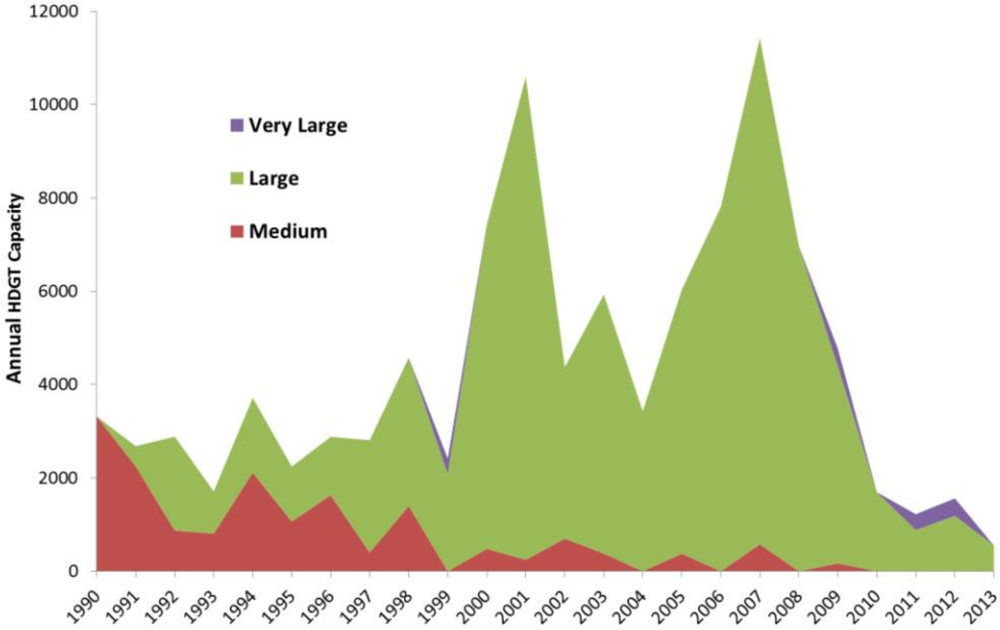


Source: Bergek et al. (2008) Technological capabilities and late shakeouts: industrial dynamics in the advanced gas turbine industry, 1987–2002. Industrial and Corporate Change vol. 17(2).

Globally, although there was an increase in the 2011-2015 period with gas-fired generation investments reaching almost 80 GW/year, this decreased in 2017 to around 50 GW (IEA, 2018). The yearly market in the 2014 to March 2018 period was about 50 GW, with total orders being led by the US (approximately 50 GW in the period) and China (43 GW), although regionally Asia led with more than 130 GW. While power generation is the biggest market for gas turbines, industrial applications (especially oil & gas) constitute a market of similar size, while aviation represents less than half the volumes of either power generation or industry (Grand View Research, 2018). The market for CCGTs in Europe has decreased from a peak of almost 12 GW in 2007 to under 1 GW in the last years (

Figure 0-15). The market from 2013 to the 1st quarter of 2018 was led by General Electric (around 130 GW sold), Siemens (90 GW) and Mitsubishi Hitachi, with 46 GW (McCoy, 2018). Hence, while GE has lost part of its market share, it remains the most important manufacturer. This however, in a market which has lost part of its size due to the climate policies and cost reductions driving the deployment of renewable energy technologies in developed and developing economies.

Figure 0-15 Annual 50 Hz CCGT sales in the European Economic Area



Source: DG Competition, 2015. CASE M.7278 – General Electric / Alstom (Thermal Power – Renewable Power & Grid Business)

Development of the combined cycle gas turbine

Summary of the combined cycle gas turbined development

Sustained by important markets and public support through R&D and market demand, military and civilian aviation turbine technology played a central role in the beginning years of development for electricity generation. Moreover, this interaction can be noted in later years, with corporations active in the aviation and power generation markets (in the case of GE) or partnering with aviation turbine manufactures such as Rolls Royce and Pratt & Whitney. To a lesser extent, industrial applications of gas turbines further increase the market for gas turbines, especially in the early years.

The relevance of jet engine technology and the growing pains the CCGT industry faced with many of the new vintages highlight the knowledge-intensiveness of the technology in multiple fields, with the leaps in efficiency and size requiring radical rather than incremental innovations, especially in the latter phase. However, the CCGT turbine proved to be a flexible technology apt for many applications and markets with different configurations regarding regulation, importance of security of supply and access to natural gas. This flexibility was paramount in the history of the technology, given the multiple factors which influenced its viability, especially environmental and security of supply requirements, fossil fuel prices and competition with coal-fired steam turbine technology.

This summary indicates that combined cycle gas turbine technology is historically characterized by important intersectoral knowledge diffusion including spillovers from the aviation and to a lesser extent oil & gas sector, within and between industrial conglomerates in the US, Germany and Japan especially. In the late 1990s mergers and acquisition also appear as an important form of knowledge diffusion. The technology flexibility allowed it to tap into multiple markets due to several demand pull drivers which maintained the technology attractiveness in a changing environment, which nowadays still provide some market opportunities despite decarbonization trends. The varied applications provided the funding for the supply push necessary, driven by learning-by-searching from the industrial conglomerates. Here competition between the conglomerates drove the development of clear vintages which provided performance leaps in the technology. The R&D intensiveness of the technology also formed an entry barrier to new entrants, with market shares remaining stable throughout the technology history and in the short-term future.

Table 0-11 Summary of main technology innovation characteristics

	Development of the CCGT 1940s-1950s	Breakthrough and maturing 1960s-1980s	Performance improvements and maturity 1980s-Present
Milestones in tech. development	Application of gas turbines for power generation 1st development of CCGT Breakthrough in industrial market	Breakthrough in security of supply market	GE launches Frame F7
Main actors involved	Aviation and power equipment corporations US power utilities	Aviation and power equipment corporations Power utilities	Aviation and power equipment corporations Power utilities
Main countries/regions	US, UK, DE	US, JP, FR, CH, DE, UK	US, DE, JP, FR, UK
Main innovation aspects	**Knowledge diffusion:** Post-war to national conglomerates **Supply push:** R&D by conglomerates for efficiency, size and reliability **Spillovers:** From military & civilian aviation, industrial gas turbines (R&D and finance) **Spillovers:** Intra-conglomerate	**Demand pull:** For security of supply and continuous power generation in US, UK, JP **Supply push:** R&D by conglomerates for efficiency, size and reliability **Spillovers:** International and from military & civilian aviation, industrial gas turbines (R&D and finance) ▪ Technology licensing ▪ Knowledge transfer partnership **Spillovers:** Intra-conglomerate **Communication channels:** client perception of reliability	**Demand pull:** For security of supply and continuous power generation in global markets **Supply push:** R&D by conglomerates **Vintages**: performance leaps driven by competition and knowledge transfer **Incremental innovation**: to address reliability issues **Spillovers:** International and from military & civilian aviation, industrial gas turbines (R&D and finance) ▪ Technology licensing ▪ Knowledge transfer partnership • **Knowledge diffusion:** Mergers & acquisitions

First development of the combined cycle gas turbine[18]

The commercial gas turbine was developed in parallel for airplane propulsion in the 1930s and 1940s in the UK, Germany and the US, with the British and German designs making a late participation in the second World War. However, the technology would mature only after the war, with large national corporations developing it further in each of the countries – Rolls Royce in the UK, Siemens in Germany and GE and Pratt & Whitney in the US. The gas turbine and military airplane designs were adapted after the war originating the successful line of Boeing's jetliners (Smil, 2007). Simultaneously, military support for the development of aviation turbines would continue for decades to come.

In the late 1940s gas turbines were already commercialized, but this was not successful as the technology was still inefficient and too small compared to steam turbines. This led to increases in the efficiency of gas turbines by manufacturers, but the reliability was still too low to attract interest from power utilities. Nonetheless, gas turbines were able to find a niche market serving as compressors for oil & gas pipelines. Together with continuous development of civilian and military gas turbines for aviation, this would allow improvements in the size and scale of CCGTs which allowed for the technology to breakthrough in electricity generation.

Breakthrough and maturing of gas turbines for electricity generation

In the early and mid-1960s, blackouts in the US and UK led power utilities to install gas turbines for emergency power restoration given their fast start-up capabilities. This provided additional revenues for the manufacturers, allowing further improvements in the size and efficiency of the turbines. Additionally, it enabled the utilities to become familiarized with the technology and to foresee its application not only for not only emergency but also continuous power supply. The modularity of CCGT allowed also their combination in order to compete in size with existing coal power plants. Finally, another factor was the availability of cheap natural gas in the US, which improved the competitiveness of the technology (Watson, 2004).

Also, environmental pressures provided further support to the deployment of CCGTs. While the costs of the technology increased in the initial development phase of the technology up to the end of the 1980s, those of coal-fired steam turbines more than doubled due to environmental compliance and higher construction costs and delays, while nuclear power plants faced even higher increases (Watson, 2004). Nonetheless, CCGTs were affected by the increase of gas prices with the 1st and 2nd oil shocks as well as reliability issues which compromise their market.

After the 1970s an increasing number of equipment manufacturers in the US and elsewhere explored CCGT solutions, such as GE and Westinghouse in North America, Siemens, ASEA, Brown Boveri, GEC, and Alsthom in Europe, and Toshiba, Mitsubishi, and Hitachi in Asia. Here, Alsthom licensed the technology from GE, while Mitsubishi did so from Westinghouse (Bergek, 2008).

This competition together with efficiency and cost improvements made the technology highly attractive to utilities in the US, UK and Asia, which helped the buyers to overcome their reluctance given lingering reliability issues. In Europe, a factor which slowed down the deployment of CCGTs was Directive 75/404 which restricted the use of natural gas for baseload electricity generation purposes and was revoked only in 1991. Hence, the balance of drivers and barriers to CCGTs resulted in a low but continuous inflow of orders

[18] This section is based on Watson (2004).

which led the installed capacity to increase from practically nothing in 1970 to more than 25 GW in 1986 (Bergek, 2008).

Performance improvements and market maturity

In 1987 GE launched the Frame 7F model which doubled the turbine size and increased the combined electric efficiency by 4%. Coupled with the fall of oil and gas prices in 1986 this heralded a new phase for CCGTs (Bergek, 2008). GE's competitors Westinghouse (in partnership with Mitsubishi), Siemens and ABB responded launching comparable models some years later. In 1993 ABB surpassed GE's Frame 7F efficiency by 3%, leading to a new cycle of mode launches increasing the size and efficiency of the turbines. In this phase, Westinghouse associated with not only Mitsubishi but also Rolls Royce and was supported by a DOE R&D program, while Siemens partnered with Pratt & Whitney.

Simultaneously, the liberalization of energy markets in countries such as the US and the UK provided opportunities for independent power suppliers to enter the market with CCGTs. The technology also found strong growth in markets where security of supply was crucial or with important domestic supplies of natural gas. The technology improvements coupled with adequate market conditions led to a strong growth in the 1990s, with a sustained yearly demand of 10 GW and reaching over 50 GWs in the early 2000s.

This market was dominated by GE, Siemens, ABB and Westinghouse, which had more than 90% of the market. However, they all suffered reliability issues by the mid-1990s arising from the innovations introduced in the new turbine vintage, incurring significant costs in R&D and servicing of the turbines and leading to the divestment of Westinghouse's division to Siemens and ABB's to Alstom.

Hence, only three major manufacturers remained to take advantage of the boom in CCGT orders of the early 2000s, led by GE, enjoying a market share of 91%. By then CCGTs had become the technology of choice for utilities around the world, driven by demand increases and the replacement of aging baseload generation capacity (UKERC, 2012).

However, after the initial peak, factors such as environmental pressure, fossil fuel costs and improvements in coal-fired steam turbines have provided a more challenging environment for CCGTs. Nonetheless, the technology still enjoyed market growth despite a slowdown of US markets in the 2005-2015 period, driven by China, Middle East and North Africa and the peak in European demand from 2006-2008 (IEA, 2018; DG Competition, 2015). By 2018, GE had acquired Alstom's power business and Mitsubishi Hitachi caught up some market share, although the market concentration historically observed continued (McCoy, 2018).

Future growth and sectoral interactions

The market for CCGTs for power generation has decreased since the 2000s and early 2010s driven by the stable electricity demand levels (which in 2016 where comparable to 2003 following Eurostat, 2019), deployment of renewable energy technologies and competition with coal-fired generation (Abani, 2018). Nonetheless, demand for gas turbines overall is still poised to moderately grow to 2025 (Grand View, 2019). Interestingly, this may be driven by the same deployment of renewables, as gas turbines may be an important flexibility source for the power system with lower emissions than coal or oil-based power plants. However, this will be affected by the ability of alternative technologies to provide system flexibility, especially demand response, electricity storage, power-to-gas and gas-to-power and transmission technologies. Another important driver for the demand of CCGTs and gas turbines in general is the phase out of coal generation, creating a dynamic where the potential future growth for gas turbines is influence by the positive driver of coal phase out and the mixed driver of deployment of renewables.

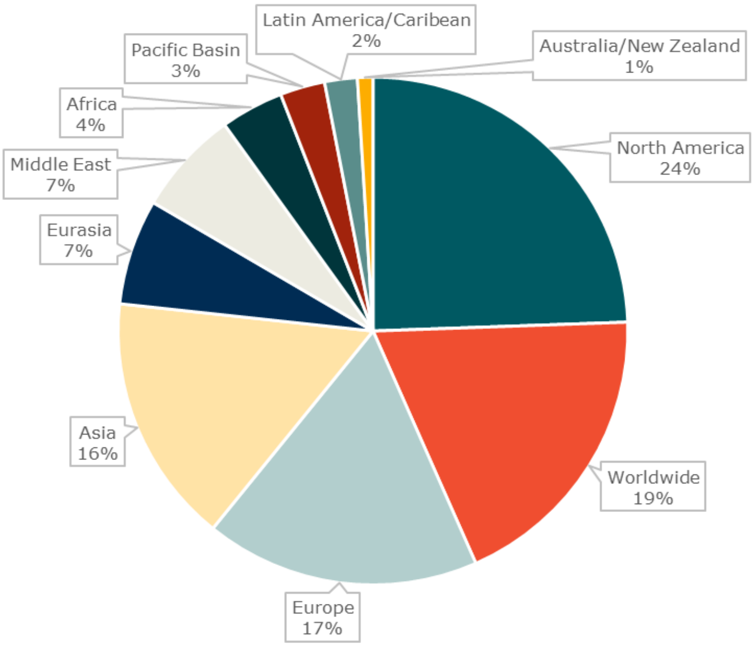
In the long term, gas with CCS could provide some additional market to CCGT technology, but the fall in demand for CCGT generation and the consequent decommissioning of gas turbines without CCS technology would more than compensate for this potential market. Additionally, the CCGT directly interacts with gas turbines applied for other uses, including in cogeneration of heat and power and through microturbines for industrial applications. Although the latter is a marginal market segment (91 MW shipped in 2015, mainly to the US and Russia), the potential market could reach over 1 billion USD (Komissarov, 2018). Therefore, while there are multiple drivers affecting the technology demand in the medium-term, in the long-term there should be no prospects for a strong demand growth for CCGT technology using natural gas. On the other hand, there could be a market for the firing of low-carbon gases (especially hydrogen) in gas turbines, including CCGTs.[19] In this case, the potential application will depend on the competitiveness of the low-carbon gas supply (dependent for renewable hydrogen on electrolyser and electricity costs) and alternative gas-to-power conversion technologies such as fuel cells.

Regarding the geographic distribution of demand for gas turbines, the main markets would be North America (a quarter of the demand in 2018-2027), Europe (over 17%) and Asia (around 16%), as shown in

[19] With on-going experiments such as in the Netherlands (Magnum plant). See https://www.ispt.eu/nuon-statoil-gasuni-join-forces-use-hydrogen-co2-free-energy-plants/

Figure 0-16. North America would see slight growth after the mid-2020s, while European demand for gas turbines would remain constant. In Asia, China is a major market but the deceleration of the economy and the energy policy priorities create uncertainty for the gas turbine market. GE is poised to maintain its manufacturing leadership with half of the market to 2027, followed by Siemens (26%) and Mitsubishi Hitachi, at 12% (Forecast International, 2018).

Figure 0-16 Share of gas turbines additional installed capacity for 2018-2027



Source: Forecast International, 2018. Worldwide gas turbine forecast.

Although CCGTs are still undergoing innovations which are for example bringing the efficiency to 65%, being a mature technology and with limited market growth, improvements are more incremental. Thus, the ASSET study reviewing the expected cost evolution of different technologies assessed that conventional CCGTs would see a reduction in investment costs of 4% between 2020 and 2030, and 12% between 2020 and 2050. Cost reductions for advanced CCGTs would be even of 6% to 2030 and 9% to 2050 (De Vita, 2018).

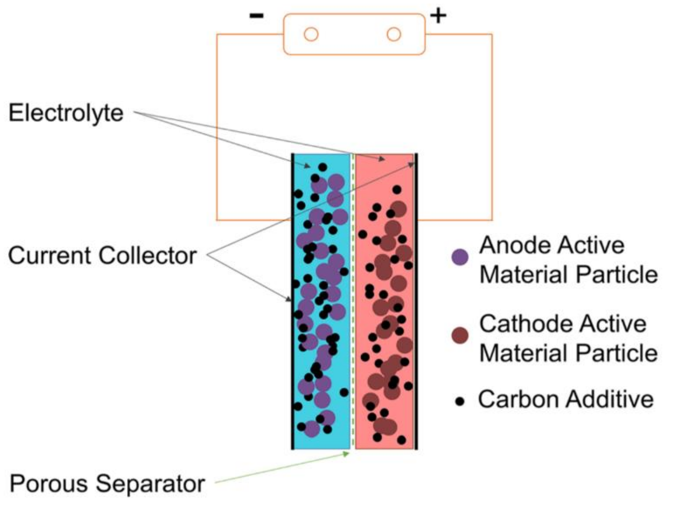
7.2. Case study 2: Lithium-ion batteries

Technology and market overview

Short description of the technology

Lithium (Li) Ion Batteries (LIB) operate based on the movement of lithium-ions from a negative (anode) to a positive (cathode) electrode while using a non-aqueous electrolyte solution as a conductive medium. Lithium is the lightest metal and has a very high standard reduction potential (> -3.0V). These characteristic give Li a favourable energy content.

Figure 0-17 Diagram showing how LIB works



The value chain for LIB comprises the following steps (Trinomics, 2018):

- Raw materials extraction & components production: the mining and refining of raw materials (such as lithium, manganese, cobalt, nickel, silicon and carbon) as well as the manufacturing of components (such as separators, electrode materials, electrolytes and sensors);
- Battery manufacturing & integration: manufacture of the main components and of the battery cells, which are then assembled into modules, packs and systems;
- Commissioning: transport of storage systems to site, installation and grid connection;
- Operation and maintenance: guaranteeing the operation of the energy storage system;
- Decommissioning: recycling and safe disposal of the battery system elements (dismantling, recollection, sorting and recycling).

Cost reductions in lithium-ion batteries[20]

There are multiple cathode chemistries possible for lithium-ion batteries, for electric vehicles (EV) the main ones being Nickel Manganese Cobalt oxide (NMC) and Nickel Cobalt Aluminum oxide (NCA). For these, the cathode represents 15 to 25% of the costs of an EV battery pack and the anode slightly over 5%, but still other costs besides the main components represent over 50% of total costs. For stationary storage, materials represent 65 to 80% of total battery pack costs, with the rest amounting to labour, overhead, margins and other costs. But while the main components (anode, cathode, electrolyte and separator) represent most of the costs of a stationary battery pack, when considering the total system cost these represent around 30% of the battery storage system.

Battke (2016) identify a relationship between the battery knowledge types (specialized or diversified, core or peripheral) and the flow of knowledge between different battery and non-battery technologies. In this way, specialized, core knowledge is more likely to flow within a single battery technology and is mostly related to materials (the production, composition and use of chemical elements or compounds) and to a lesser extent principal components (electrodes, separators, or electrolytes). On the other hand, diversified knowledge flows more to other battery and non-battery technologies, impacting non-core components such as cell systems, chargers and casing. Therefore, the knowledge type plays a direct role when analysing supply-side spillovers from batteries.

Costs for EV battery packs have seen strong cost reductions in the last years, with average observed values falling from around 870 €/kWh in 2010 to 170-215 €/kWh in 2017 (Tripopolos, 2018). Similarly, the costs of battery system for stationary storage have fallen from 1800-1900 €/kWh in 2010 to 1100-1700 €/kWh in 2015. These may have fallen further to around 600 €/kWh in 2017 and even lower in specific projects, although the values differ according to exactly which system costs are included.

Market status

Table 0-12 Summary of the past, present and future market status for LIBs

	Unit	2010	2016	2030
Market size	GWh	20	100	1200-1600
Manufacturing lead countries	%	Japan (48%) South Korea (25%) China (24 %)	China (51 %) South Korea (21%) Japan (16%)	

Source: Tripopolos, I., Tarvydas, D., Lebedeva, N., 2018. Li-ion batteries for mobility and stationary storage applications. JRC Science for Policy Report (2018)

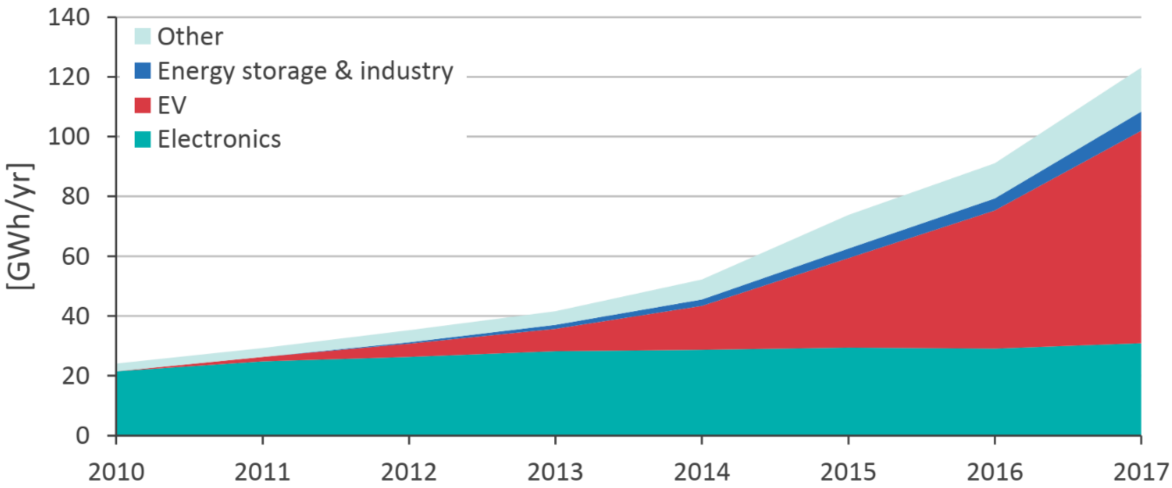
Trinomics and DNV GL, 2019. Study on energy technology dependence - Detailed assessment on dependencies within the wind energy, solar PV and battery energy storage value chain (Task 4).

Avicenne, 2010. Main trends for rechargeable battery - Market 2009-2020.

[20] This section is largely based on Tripopolos (2018)

Since 2010 the market volume for LIB has multiplied by a factor of 6, to more than 120 GWh/year as indicated in Figure 0-18, about 24 billion €. The main applications of lithium-ion batteries currently are electric mobility (with 57% of the LIB market in 2017) and electronic devices (with 26% of the market in 2017). An area with rapid growth and further development potential in which LIB can find applications is in stabilization and storage for the electricity grid. In 2017, the global electrochemical system storage capacity represented around 1.6 GW, or approx. 2.8 billion euros in value. Of this LIB, accounted for around 81 percent of the total.

Figure 0-18 Global Li-ion batteries sales in main market segments



Source: Triropolos, I., Tarvydas, D., Lebedeva, N., 2018. Li-ion batteries for mobility and stationary storage applications. JRC Science for Policy Report (2018)

Current manufacturing capacity is concentrated in China, with around 100 GWh, representing two thirds of the global capacity, followed by South Korea and Japan, and to a lesser extent North America, while Europe stands at around 5 GWh (Trinomics, 2019). Correspondingly, Asian companies maintain a leading market share on battery cell manufacture representing a concentration ration CR4 of 57%, as attested in Table 1. Asian countries also hold the major share of global EV sales, with around 55 percent in 2017, led by China. The EU on the other hand, has a strong presence in the downstream segments of the value chain such as battery pack assembly, recycling and repurposing.

Table 0-13 Top Li-ion battery manufacturing companies (2017) and countries (2016)

Company	Country	Manufacturing capacity GW	Country	Manufacturing capacity %
LG Chem	South Korea	17	China	51
BYD	China	16	South Korea	21
Panasonic	Japan	8.5	Japan	16
AESC	Japan	8.4	US	7
CATL	China	7.5		
Guoxuan	China	6		
Samsung SDI	South Korea	6		
Lishen	China	3		
BAK	China	2.5		
CALB	China	2.4		
LEJ	Japan	2.3		
Wanxiang	China	2.1		
Others		22		

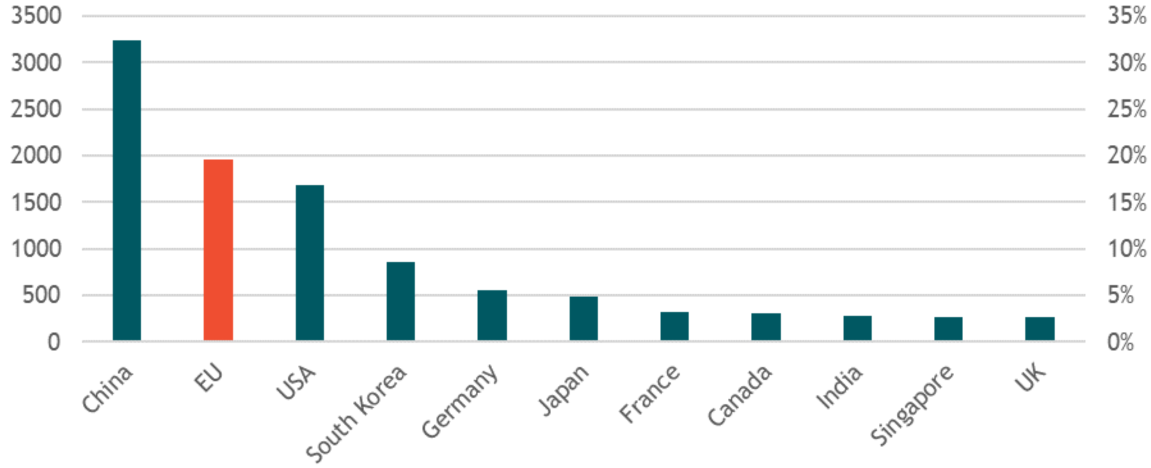
Source: Bloomberg New Energy Finance, 2017. Lithium-ion Battery Costs and Market.

Trinomics and DNV GL, 2019. Study on energy technology dependence - Detailed assessment on dependencies within the wind energy, solar PV and battery energy storage value chain (Task 4).

The study on Energy Technology Dependence by Trinomics (2019) highlights the strategic importance of the technology for the EU, as attested by the European Battery Alliance initiative and the Strategic Action Plan for Batteries. The main dependencies for batteries comprise the supply of raw cobalt and the manufacture of battery cells.

China leads in the number of publications in the 2014-2016 period with a 32% share, followed by the EU as a whole (20%) and the US (17%). The individual EU Member States with the highest shares are Germany (5%) and France (3%).

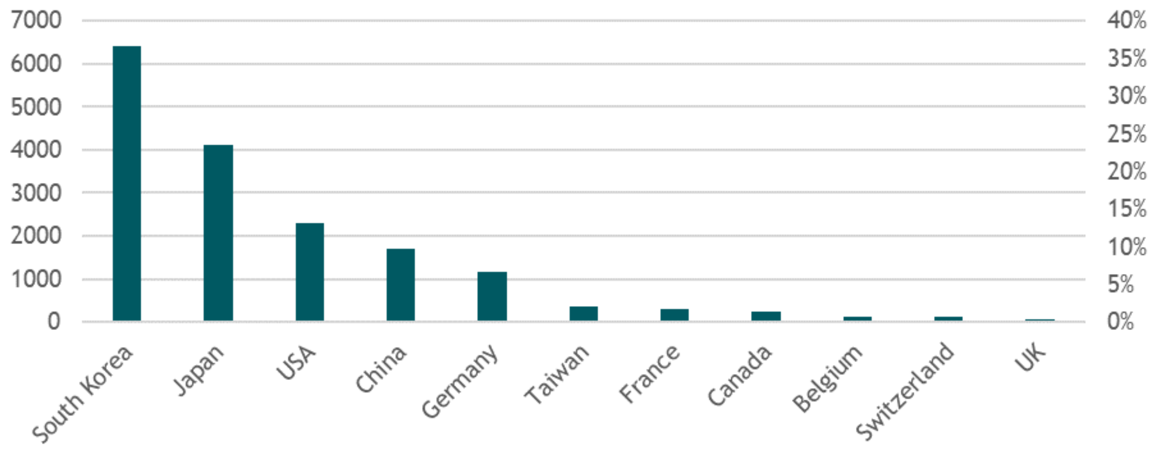
Figure 0-19 LIB global publications top 10 countries and share in 2014-2016



Source: Trinomics and DNV GL, 2019. Study on energy technology dependence - Detailed assessment on dependencies within the wind energy, solar PV and battery energy storage value chain (Task 4).

The five leading publishing countries remain ahead in patent applications for secondary LIBs, but with important order changes. South Korea leads with over 38% of the patents, followed by Japan (24%). The leading EU Member States are again Germany (7%) and France (2%).

Figure 0-20 Number of secondary LIB patent applications



Source: Moreno-Brieva et al., 2019. Technology generation and international collaboration in the Global Value Chain of Lithium Batteries. Resources, Conservation & Recycling 146.

Development of the lithium-ion battery

Summary of the LIB development

The development of the lithium-ion battery started with niche military and medical applications in the US. This was followed by the growth of rechargeable batteries for portable device markets from 1985, when simultaneously Japan took the lead in technology development from the US. Since the 2010s the market for portable devices has remained stable, while energy and climate policies worldwide focus on lowering GHG emissions, the need for electric vehicles (EV) will increase. Currently the EV sector forms the lead application for the LIB technology. With the rise of low-carbon mobility LIB, China is at the forefront of manufacturing and use for electric vehicles, with Japan and South Korea following in manufacturing. The rise of Japan in the field was due to factors such as cross-sectoral cooperation driven by a strong national innovation system, various government support policies from 1992 and the role of Japanese corporations such as Sony, in a context of development of the portable electronics industry. Following the Japanese lead, South Korea developed its battery industry from the late 1990s around national champions (LG Chem and Samsung SDI) targeted at the portable industry, soon followed by sustained and varied government support on R&D, (foreign) manufacturing investments and industry cooperation to develop battery clusters. In the 2000s China applied the same strategy, with government support, important economies of scale and driven by electric mobility as a relevant market additional to portable devices.

Despite these shifts in markets and lead geographies, the technology has been marked by strong R&D by academia and industry. Public support for R&D has existed since the first development phases, but recently public efforts have widened, to include more actions regarding production and demand support, providing guidance, promoting industry & academia cooperation, and developing secondary infrastructure (for electric vehicle charging).

As the technology developed, cost reductions have been driven not only by innovation but also economies of scale as shown by the recent Chinese example. This is directly related to the development of the EV market, as the market for portable applications has remained more stable in the last decade. The EV and to a lesser extent the stationary mobility markets provide important growth opportunities for the Asian, North American and European economies. More indirectly, due to their flexibility batteries may enable further growth through channels such as deployment of renewable energy sources, of remote sensors and of embarked systems in general.

Thus, lithium-ion batteries have been characterized by supply push from industry and academia R&D throughout its history, also with policy support in the form of public R&D investments. However, the drivers of demand pull have changed significantly in time, passing from niche space, military and medical applications to portable devices, and more recently electric vehicles and stationary power storage. Accompanying this was a relocation of the supply chain from the US to Japan from the late 1980s, and then later to China and South Korea. These shifts were always characterized by two aspects: the knowledge diffusion between market actors within a national innovation system combining the electronics, car and battery industries, power utilities and academia, supported by varied government policy going beyond R&D funding, to for example providing guidance, fostering cooperation and providing supply and demand incentives. The latter can be evidenced by the strong growth of the EV market in China, although the country has not yet managed to translate its leadership in becoming a leader in technology development. Recently, with the growth of the battery market, increasing returns due to economies of scale in the Asian supply chain have strongly reduced the battery costs, a trend which will be sustained by the growth of the EV market.

Table 0-14 Summary of main technology innovation characteristics

	Non-rechargeable LIB (1950s- 1985)	Rechargeable LIB (1985-2000)	Present day LIB
Milestones in tech. development	Research on electrochemistry of non-aqueous solvents Understanding of metal stability principle	Research leading to the development of rechargeable batteries First commercial LIB by Sony in 1990	Development of EVs and need for stationary storage in the 2000s
Main actors involved	Academic organizations Government bodies (military, NASA, Department of Defense)	Academic organizations Private companies (Exxon, Moli Energy, Sony, Murata group etc.) Government bodies (USABC)	Academic organizations Private companies Governments (USA, Japan, EU)
Main countries/regions	US	JP, US	CN, JP, KR, US
Main innovation aspects	**Technology push**: Academia and industry R&D **Knowledge diffusion/spillovers:** Of diversified knowledge to other battery techs in non-core components		
	Market pull: Space, military and medical applications **Policy:** Public R&D investment	**Market pull:** consumer portables **Knowledge diffusion:** of electronics, battery manufacturers, utilities, automotive firms and universities due to strong national innovation system (JP) **Policy:** ▪ Public R&D investment ▪ Industry cooperation for new applications (mobility and stationary storage) ▪ Demonstration ▪ Standardization	**Market pull:** consumer portables, low-carbon mobility and stationary storage **Knowledge diffusion:** of electronics, battery manufacturers, utilities, automotive firms and universities ▪ **Increasing returns:** economies of scale in the Asian supply chain **Policy:** ▪ Guidance ▪ Public R&D investment ▪ Manufacturing and demonstration financing ▪ Tax exemptions ▪ Cooperation ▪ EV charging infrastructure

Developments of primary (non-rechargeable) cells

The LIB is based on principles of electrochemistry of non-aqueous solvents, which gained prominence in academia in the late 1950s and early 1960s. Until around 1970 much of the work on lithium batteries in the United States was promoted by NASA and the Department of Defense. During this period research focused on finding the right conditions to improve conductivity and on finding appropriate materials for the cathode. Major problems during this period included low discharge efficiencies and poor shelf life.

During this time period, rapid advancements in the understanding of the electrochemical processes associated with lithium batteries were made. In addition, a wide range of primary battery technologies became commercial during this period. An important finding was related to the stability of the lithium metal in the electrolyte solution. Experimentation also focused on finding mixed solvent systems to maximize both electrolyte and electrode performance. Other areas of research focused on reducing the safety risks and environmental hazards associated with the battery components.

In the early 1970s, primary cells started to be commercialized with an initial emphasis on military applications. By the early 1980s cells with capacities ranging from 5 mAh (milliampere hour) to many thousands of Ah were widely available. Lithium primary batteries also found applications in a range of medical implants, with the first proposal for a pacemaker application described in the early 1970s (Greatbach, 1971).

Development of secondary (rechargeable) cells: 1985-2000

The development and commercialization of secondary cells was made possible through the discovery of electrodes that can undergo repeated charge/discharge cycles without losing significant capacity. The first ideas on these type of electrodes can be traced back to 1841, but the development of modern secondary cells was based on a series of papers produced in 1973.

Companies such as Exxon and Moil Energy developed secondary cells based on materials such as titanium disulfide (TiS_2) or molybdenum disulfide (MoS_2). In the mid-1970s, Exxon announced its intentions to commercialize a coin cell batteries for electronic watches. Other companies such as A&T Battery, the Bell Laboratory group, Matusushuta, Sanyo, Sony, Ultralife and Japan Storage Battery became interested in developing their own batteries based on other materials for plating. Researchers continued to work on finding suitable host compounds in order to optimize electrochemical, electrical and chemical properties of the cells. One of the most important advancements at the time was the development of the lithium polymer battery (LPB). The LPB was a result of collaboration between Hydro-Quebec and the 3M Company under the patronage of the United States Advanced Battery Consortium (USABC).

Demand for consumer electronic products and in particular the ‘3Cs’ cellular telephones, camcorders and (portable) computers was the main driver for the development of secondary lithium batteries. Commercial batteries required optimisation of size, ensuring operability at ambient conditions and ensuring the highest possible safety standards. In order to ensure greater safety graphite and non-graphite disordered phases were introduced.

In the period Japan became the leading country in LIB R&D and manufacturing. The technology was strongly support by the Japanese government, not only through R&D support but also fostering academia and industry cooperation (including for the novel applications of mobility and stationary storage). Leadership in the field and cooperation was also enabled by the strong technical innovation system of the country (Stephan, 2017). The first consumer lithium-ion cell was marketed by Sony in 1990. By early 2000s the world-wide production of lithium secondary batteries approached 500 million units per annum. Sony was the industrial leader in the field for a number of years, but increased competition eventually led to the transfer of the battery business to Murata group and the withdrawal of Sony from the battery market. In the early 2000s Japan supplied around 90 percent of the total battery market (Wakuhara, 2001).

Present day LIB

The market use of LIB has been presently extended to many other applications such LCD and fluorescent lights, e-cigarettes and vaporizers, medical devices, e-bikes, hoverboards and toys among others. From 2010 on LIBs have been growing annually at a rate of 26 percent based on production output and by 20 percent in terms of value.

Since the 2000's South Korea and China have caught up with Japan and even taken the lead in LIB manufacturing. The South Korean progress was driven by the strong demand for LIBs in portable application and was based on an ecosystem of companies working around LG Chem (which launched an LIB in 1999) and later Samsung SDI, who launched the Battery R&D Association of Korea in 1997. The Korean government followed soon after in promoting the sector through R&D and manufacturing support (including through foreign direct investments), cooperation, skills development, and development of upstream industries and clusters (Suh, 2004; Tack, 2016; Invest Korea, s.d.).

LIB development in China occurred due to the drivers of fostering low-carbon mobility and expanding the supply chain into higher value-added activities. The Chinese government used instruments such as R&D programs, tax incentives and investment incentives in order to develop the supply chain. More recently the Chinese government has provided subsidies for EVs. Government support has led to economies of scale arising from increased manufacturing capacity, which was a more important driver to cost reductions than innovation in battery technology. As both the South Korean and Chinese industries developed, they sought to develop their industry clusters further and reduce the dependence on Japanese suppliers (Chung, 2016; GCIS, 2016).

The Energy Technology Dependence study notes that currently LIBs are characterized by high competition between manufacturers for technology development and correspondingly protection of intellectual property is high. Also, economies of scale are important in the sector and experience in the technology also leads to competitive advantages in battery manufacturing. These factors combined with high start-up capital investments and fixed costs form an important market entry barrier to the European battery industry.

Current developments and main technology issues include the continued search for improved cathode materials. Key materials and their applications are summarized in the table below. Nickel Manganese Cobalt Oxide (NMC) based batteries in particular have been developing rapidly due to their flexibility for both high energy and high power applications. A patent issue in the US has complicated their commercialization, as two patent holders, BASF-Argonne National Laboratory and 3M have competing patents (Blomgren, 2017).

Climate change concerns and the need to reduce greenhouse gas emissions have led companies and governments to become interested in the development, production and commercialization of electric vehicles (EVs). This has generated a strong market pull for developing LIB with increased capacity and energy with lower cost to fulfil the requirements of such vehicles. The cost element is particularly relevant in the case of plug-in hybrid vehicles (PHEV) and battery electric vehicles (BEV). In their analysis of barriers to innovations diffusion, Tutore (2014) identify cost as the strongest barrier to diffusion of LIB into the automotive industry. In particular, they point out that in order to integrate the LIB to the vehicle other proprietary technologies need to develop. This is associated with several costs: searching costs to identify and invest in the best technologies, learning and switching costs and opportunity costs. A second important cost barrier is due to the high cost of network transformation related to building charging stations and the associated infrastructure (Tutore, 2014).

In the US, the 2009 American Recovery and Reinvestment Act (ARRA) had a discernible impact on advancing the LIB and transforming the national advanced battery industry by, for example, providing financial support to develop a domestic supply chain of LIB for EVs and by helping with intra-firm diffusion of the technology. In addition to supporting R&D the program also helped to establish or strengthen the US manufacturing plants that played a key role across the value chain including materials, components and production of cells and battery packs (Tutore, 2014). In addition, the US has provided tax incentives and has promoted demonstration projects to reduce the uncertainty of potential adopters.

Japan is another country which has been very successful in implementing policies to support the development of the LIB industry and has become a world leader in the sector. The country has developed different programs to develop LIB since 1992 and continues to have ambitious development targets for the future. Policy began by supporting the electronics industry but has since also focused on EVs and grid applications. Japan has fostered cross-sectoral collaboration between electronics, battery manufacturers, utilities, automotive firms and universities (Stephan, 2017).

Like in the case of EVs, cost is an important driver for the use of LIB for storage however, some applications such as frequency stabilization are not as cost sensitive. Furthermore, other factors such as the availability of materials and especially lithium carbonate, will play an important role.

Future growth and sectoral interactions

This case study identifies multiple interactions between economic sectors and actors. Initially, military and medical applications provided market pull while public R&D efforts constituted the technology push. In later phases, especially, the electronics, utilities and automotive firms interacted with LIB battery manufacturers, with both private and public R&D investments providing technology push.

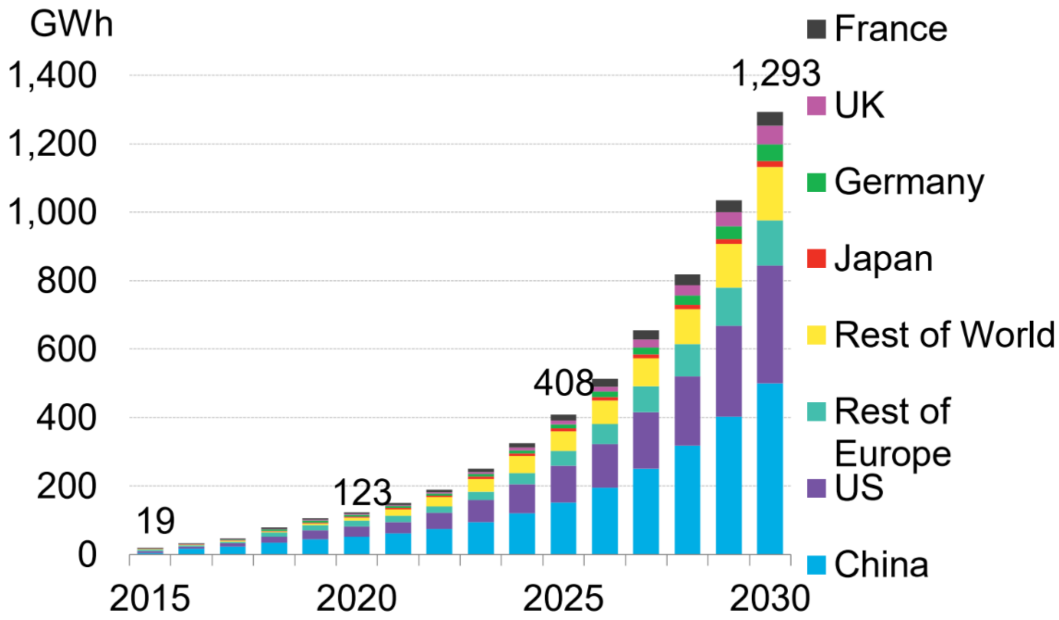
Given the versatility of applications (portable, mobility, stationary), LIB provide a number of conventional and unconventional sectoral interactions (some of which have already played an important role in the past):

- Increased flexibility of power systems, allowing for high penetration of renewable electricity sources and a 100% renewable energy system in the long-term;
- Development of portable devices leading to a comfortable lifestyle and the expansion of remote sensors contributing to the internet of things;
- Reduced use of fossil fuels in isolated power systems (e.g. islands) reducing expenditures and negative impacts of local pollution and GHG;
- Better options for emergency power backup used for critical equipment, e.g. for security surveillance or medical equipment;
- Deployment of plug-in hybrids and full-electric vehicles.

By 2025, the global market for LIBs should grow to 65 billion €. Moreover, LIB technology will enable important growth in its two main applications. Estimations of the global EV fleet by 2030 range from 50 to 225 million vehicles, up from 3 million in 2017. Then, stationary storage market estimates with significant LIB deployment range from 100 to 400 GWh by 2030, up from 3.5 GWh in 2017.

The market volumes are expected to grow significantly in the long-term, ranging from 1200 to 1600 GWh/year by 2028, with the majority of this volume will be for electric vehicles (Triropolos, 2018). Of the LIB demand for electric vehicles, China will represent more than a third of demand until 2030, followed by the US with a quarter of demand (Figure 0-21). Following the expected increase in demand, manufacturing capacity should reach up to 600 GWh in 2022, with China maintaining the leadership, and Europe catching up with North America in manufacturing shares.

Figure 0-21 Forecasted demand for lithium-ion batteries from EVs



Source: Bloomberg New Energy Finance, 2017. Lithium-ion Battery Costs and Market.

Accompanying the deployment of lithium-ion batteries, costs are project to fall further, with BNEF estimating that they could reach as much as 74 USD/kWh by 2030 (BNEF, 2019). This matches the analysis of the JRC, which predicts cost reductions EV battery packs falling to under 100 €/kWh by 2030 and up to 50 €/kWh by 2040. On its hand, utility scale energy-designed stationary storage systems may fall to less than 300 €/kWh by 2030 and 250 €/kWh and lower by 2040 (Triropolos, 2018).

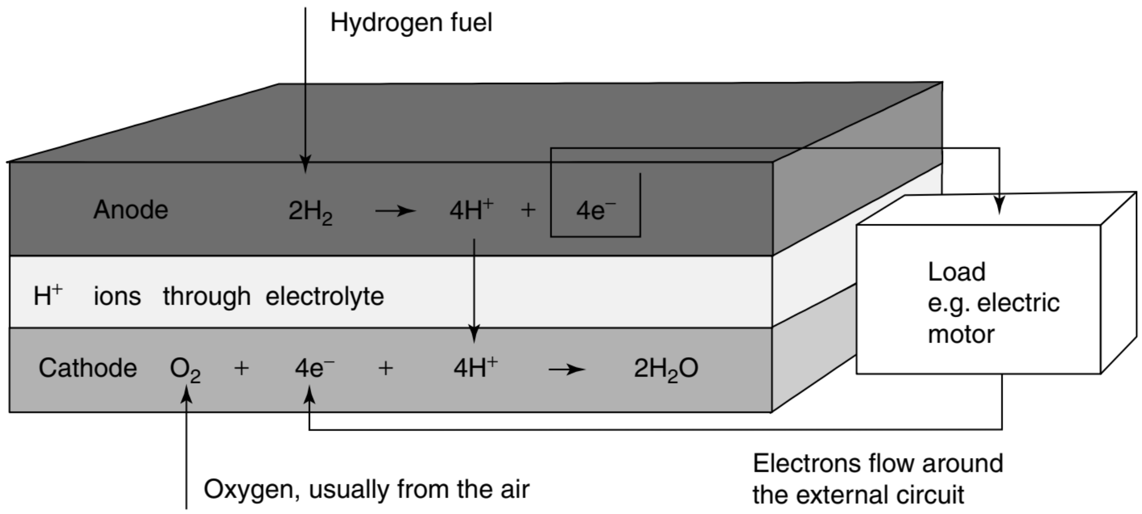
7.3. Case study 3: Hydrogen fuel cells

Technology and market overview

Short description of the technology

The basic elements of fuel cells are the anode and cathode, separated by an electrolyte. H^+ ions from the hydrogen fed through the anode move through the electrolyte and react with the oxygen fed through the cathode to form water. The electrons released from the hydrogen ionization provide the electrical supply from the fuel cell. There are six main types of fuel cells: alkaline (AFC), proton exchange membrane (PEMFC), direct methanol (DMFC), phosphoric acid (PAFC), molten carbonate (MCFC), and solid oxide (SOFC). Alternatively, fuels containing hydrogen such as methanol, natural gas or diesel can be directly fed into some high-temperature fuel cell types, such as the SOFC and DMFC.

Figure 0-22 Diagram showing how a hydrogen fuel cell works

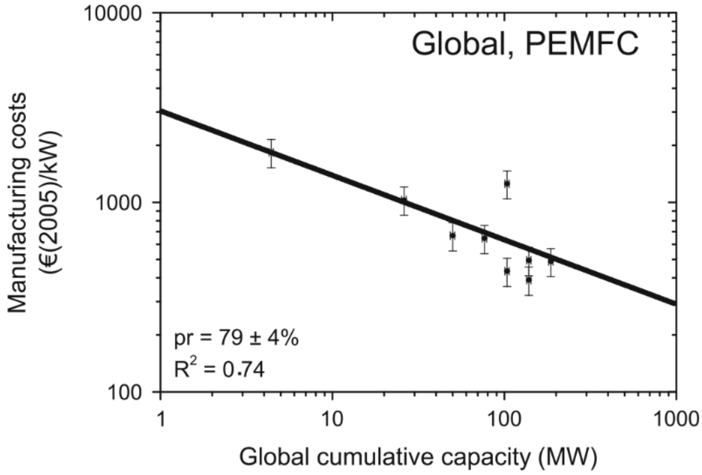


Cost reductions in fuel cell technology

Fuel cells are highly modular, so that increases in total capacity of the stack can be achieved by adding further cells. The main cost drivers of fuel cell packs are the membrane electrodes (anode and cathode) assemblies, the flow plates for fuel and oxygen, and the balance of plant. In 2007 the share of these components for a PEMFC were 23%, 15% and 61%, leading to a final cost of 859 EUR_{2005}/kWh for a 250 kW fuel assembly.

Schoots et al. (2010) find a global learning rate in the 1995-2006 period of 21% for transportation PEMFCs, the current leading fuel cell technology, with an error margin of 4%, as presented in Figure 0-23. Analysing manufacturer learning rates for AFC, PAFC and PEMFC the authors find learning rates of 18 to 30%, with error margins placing all within the common estimate of 20% for PEMFC, leading to a reduction of more than 80% from 1995 to 2006 in PEMFCs.

Figure 0-23 Learning curve for PEMFCs in transportation between 1995 and 2006



Source: Schoots et al. (2010) Technology learning for fuel cells: An assessment of past and potential cost reductions. Energy Policy 38.

While the authors do not separate the learning-by-searching, learning-by-doing and economies of scale, they indicate that R&D efforts have played a central role to the development of fuel cells, and thus learning-by-searching was an important driver in cost reductions. Furthermore, the authors indicate that R&D should remain a central factor in driving future cost reductions in fuel cells.

Market status

Table 0-15 Summary of the past, present and future market status for fuel cells

	Unit	2010	2016	2020-2030
Market size	MW	96	500	Upwards of 400 000
Lead countries	%	Asia (51%+) ▪ South Korea (39%) ▪ Japan (12%) US (33%)	Asia (62%) North America (36%)	Determined by CN developing technology and EU developing manufacturing

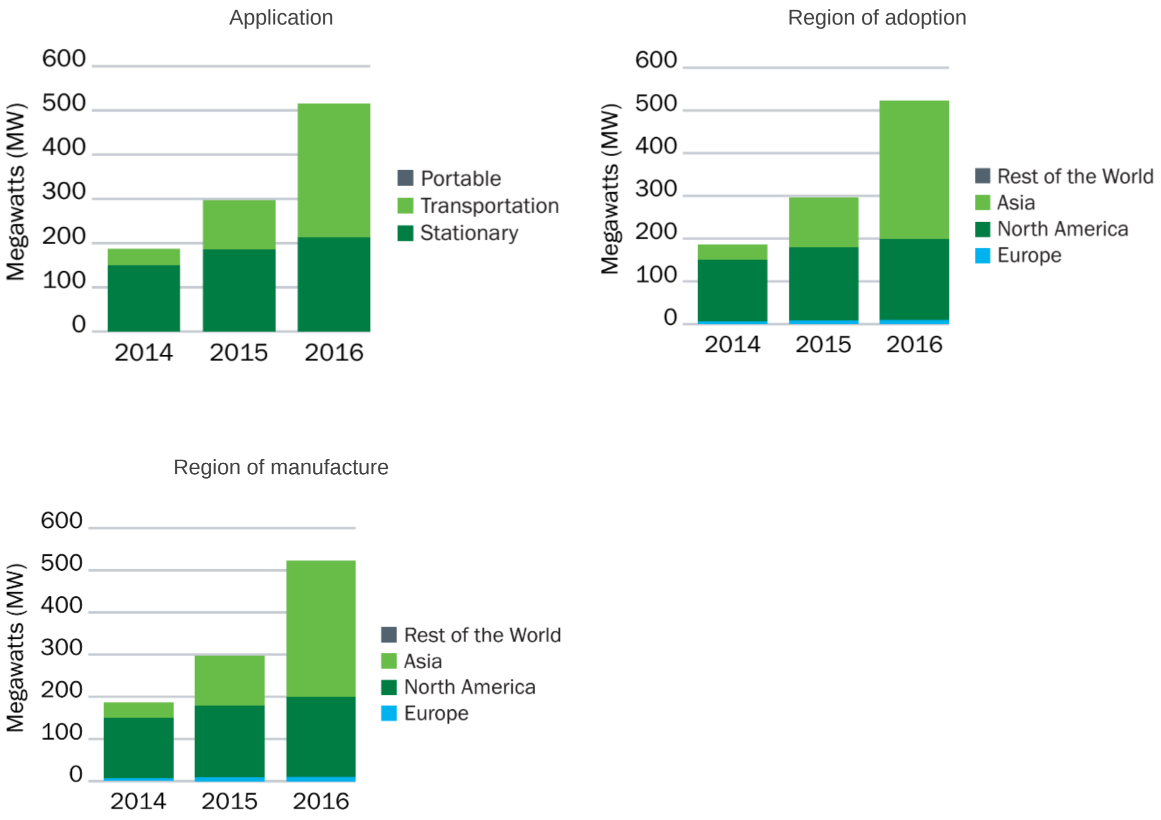
Source: IEA, 2019. Tracking Clean Energy Progress – Hydrogen.

IEA, 2015. Technology Roadmap – Hydrogen and Fuel Cells.

US Department of Energy (2017) Fuel Cell Technologies Market Report 2016.

The main current applications by capacity for fuel cells are stationary applications (around 200 MW in 2016) and transportation (300 MW in 2016), while portable device applications are not significant and have decreased in the last years.

Figure 0-24 Fuel cell shipped capacity per application, region of adoption and of manufacture



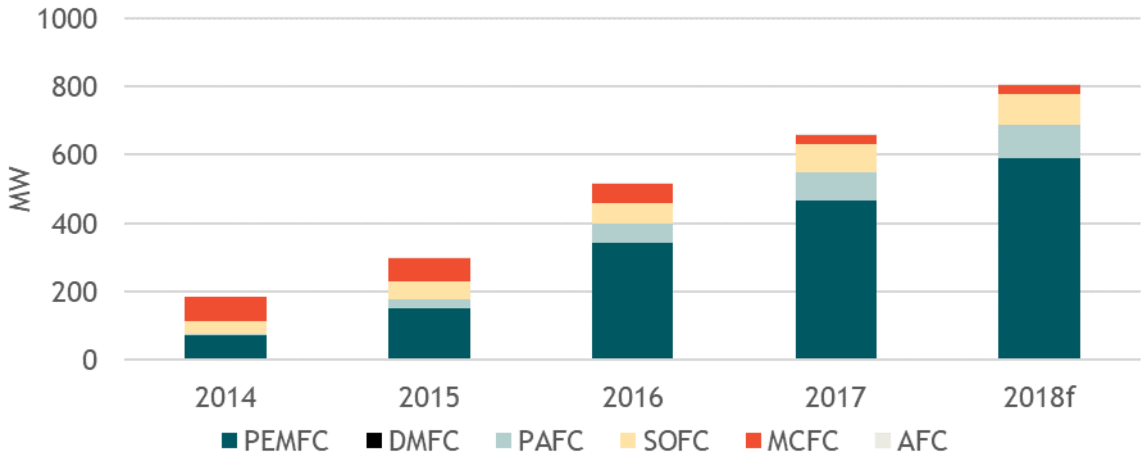
Source: US Department of Energy (2017) Fuel Cell Technologies Market Report 2016

For stationary applications the US and South Korea were responsible in 2017 for more than 90% of the global cumulative installed capacity, with over 500 and 250 MW installed, respectively.[21] This is in line with the trends for fuel cells in general, with North America and Asia dominating adoption in 2017 (332 and 286 MW respectively).[22] Leading publicly-listed fuel cells companies are located in the US (FuelCell Energy, Plug Power), Canada (Ballard and Hydrogenics), the UK (Ceres) and Germany (SFC Energy). Figure 0-25 presents the capacity shipped per technology in the last years, clearly demonstrating that PEM fuel cells are the leader (being the main vehicle technology), with PAFC and SOFC having a smaller but significant share and with MCFC passing from being a lead technology to playing only a minor role.

Figure 0-25 Global fuel cell shipped capacity by cell technology

[21] JRC (2019) Global deployment of large capacity stationary fuel cells

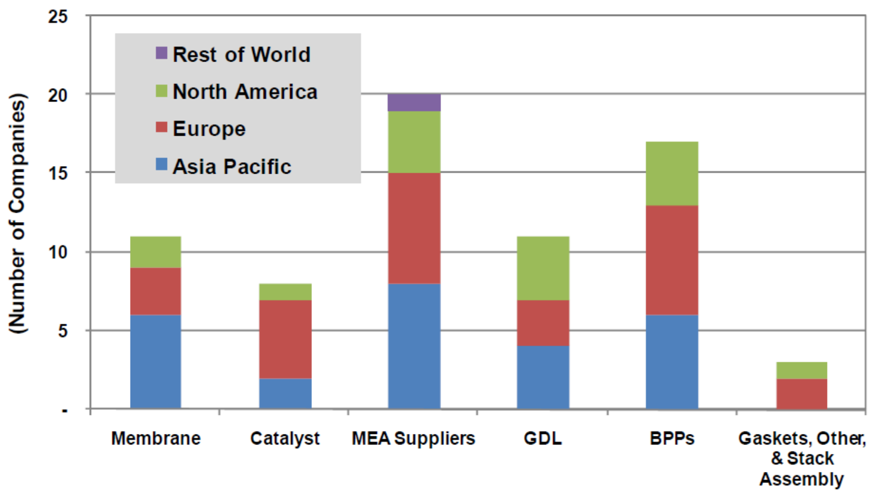
[22] E4tech (2018) The fuel cell industry review 2018



Source: E4tech (2018) The fuel cell industry review 2018

Europe and Asia Pacific have the largest number of manufacturers for these components, as can be seen in Figure 0-26, and therefore Europe has a higher representation in the manufacture of components for fuel cells than for the manufacture of the cells themselves.

Figure 0-26 Commercial suppliers for the components of fuel cells per region

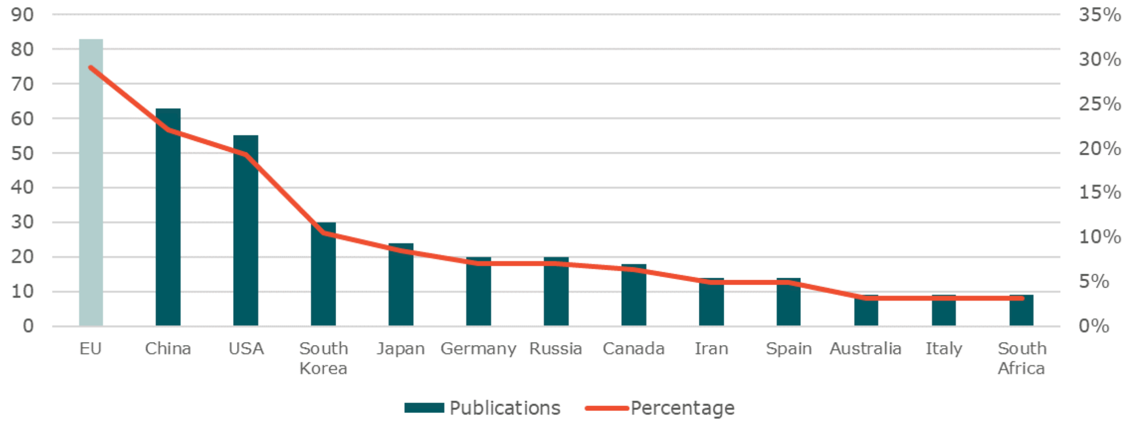


MEA: membrane electrode assemblies, GDL: gas diffusion layer, BPP: bipolar plates.

Source: Milburn & Adamson, 2012 in Trinomics, 2019. Energy Technology Dependence – Task 3.

The EU leads in the number of publications in the 2014-2016 period with a 29% share, followed by China (22%) and the US (19.3%). The individual EU Member States with the highest shares are Germany (7%) and Spain (5%).

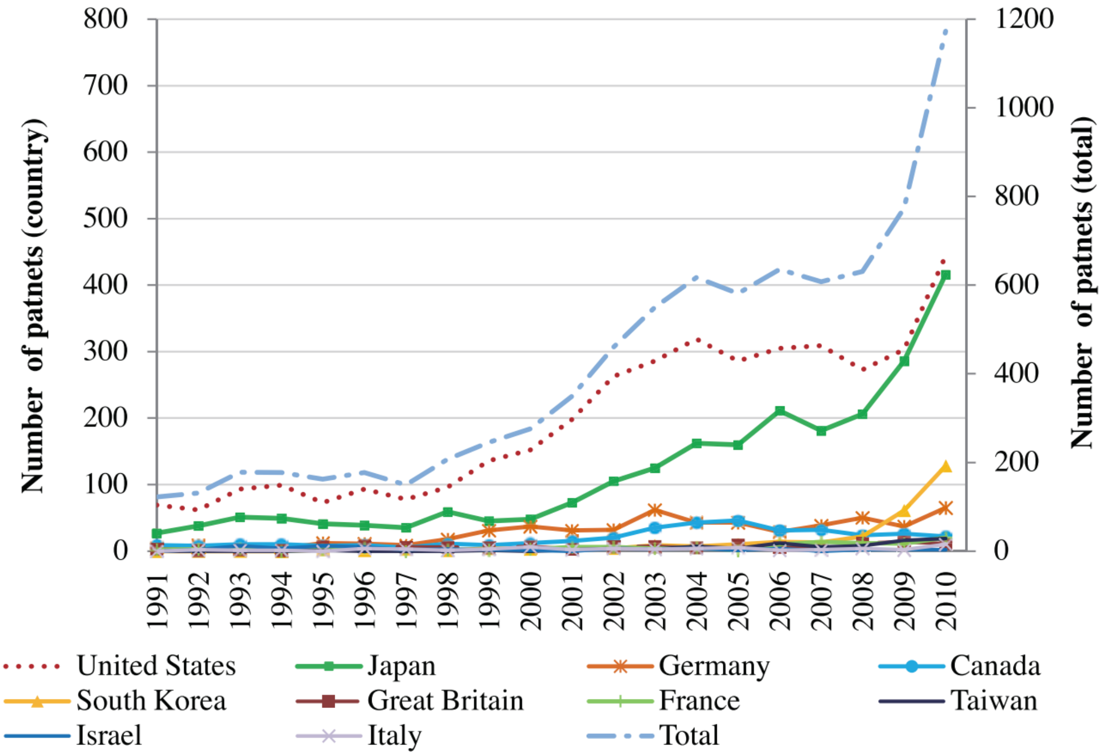
Figure 0-27 Lead countries in hydrogen fuel cell publications in 2014-2016



Source: Trinomics, 2019. Energy Technology Dependence – Task 3.

Moreover, in 2014 the EU accounted for 23% of the global patents for hydrogen technologies (JRC, 2018). Globally, the leading countries in 2010 were the US and Japan with over 400 patents each. South Korea came a distant third with less than 150 patents and Germany was the lead European country at under 100 patents (Figure 0-28).

Figure 0-28 Number of hydrogen fuel cell patent publications, 1991-2010



Source: Huang, M., Yang, H. 2013. A Scientometric Study of Fuel Cell Based on Paper and Patent Analysis. Journal of Library and Information Studies 11(2).

Developments of fuel cells

Summary of the fuel cell development

Fuel cells have a long development history, with prototypes for all major current variants being developed by the 1960s or earlier. Following this, AFCs saw the first applications on space in the 1960s. Since then, the leading fuel cell variants and markets saw significant changes, with first stationary applications and later mobility (electric vehicles) taking the lead, resulting in the emergence of PEMFCs as the most successful variant.

Nonetheless, despite recent market growth and increased interest in the potential of hydrogen and fuel cells to decarbonize the economy, the technology is not competitive in the short- or medium-term and remains dependent on subsidies. Government support for low-carbon mobility has made China the largest fuel cell market globally. However, three decades of Chinese support for technology development and manufacture were not translated into leadership into either, although recently Chinese companies have established partnerships or acquired stakes in North-American companies.

Other countries have been more successful in developing technology and manufacturing capacity. The US has maintained leadership since the first fuel cell applications, being caught up by Japan and more recently South Korea. Japan managed to develop the industry from the 1980s through the cooperation of industrial corporations, research organizations and power and gas utilities supported by government programs, establishing also partnerships with US organizations. South Korea on its hand managed to develop especially the market for stationary fuel cells which resulted in significant manufacturing market share from a capacity but not shipped units measure, specializing in the PAFC. Here, varied government policies and knowledge transfer through acquisition of US technology managed to develop the Korean industry, as opposed to Chinese attempts.

The situation is markedly different in Europe. While various Member States have a long R&D history in specific fuel cell variants, the continent never developed significant manufacturing capacity or demand for the technology. Efforts (where historically the EU Framework Programs played a significant role) are however translated in an important share of the global knowledge creation as manifested through the number of publications and patents. Moreover, Europe is a major supplier of the main fuel cell components.

Hence, the fuel cell segment has seen important market, technology and leading country changes in the last decades, with high potential growth in the electric vehicle market. The technology is still considered strategic by a number of countries worldwide, despite the competition it faces from batteries for electric mobility.

This summary indicates that fuel cell technology is historically characterized by important policy influence in the form of R&D support and fostering of cooperation, with the public sector also providing the initial market pull from aerospace and military applications. However, the main market drivers changed throughout the technology history, with portable electronics and power supply overtaking these initial niches, and being replaced on their turn by mobility as the lead application. While the technology initially develops within large US industrial conglomerates providing the funding for the supply push in combination with government support, the shift to portable electronics is accompanied by the industry development in Japan, where knowledge diffusion takes place through government programs and multiple partnerships (US-JP, manufacturer-utilities, industry-academia). In the last decades South Korea specialized in stationary applications spearheaded by industrial conglomerates (with latter government support) leading to important market growth. On the other hand, Chinese policies managed to create the largest market globally for fuel cells, but have failed to translate into significant innovation or manufacturing in the country. Nonetheless, mobility is the largest fuel cell market with strong national targets to 2030 including in China, showing important interactions with the overall electric, connected and/or autonomous vehicle market.

Table 0-16 Summary of main technology innovation characteristics

	Prototypes and space applications 1950s	Diversification of applications 1960s to 1980s	Research acceleration and difficulties 1990s-2000s
Milestones in tech. development	1st prototype and small-scale application	Large-scale prototypes and initial commercialization	Scaling up of commercialization
Main actors involved	US corporations, NASA, US Army	Corporations (GE, Siemens, Japanese) Research organizations Power and gas utilities	Automakers Corporations, specialized manufacturers Research organizations Power and gas utilities
Main countries/regions	US	Multiple variants: US, Japan Specific variants: Germany, UK, Netherlands, other MSs	US, Japan, Canada, China, Korea, Europe
Main innovation aspects	**Market pull:** ▪ Technical performance issues ▪ High material cost (platinum)		
	Market pull: ▪ Military and aerospace **Knowledge diffusion:** ▪ International technology replication	**Market pull:** **A**erospace, military, mobility, power back-up **Supply push:** ▪ Multi-fuel cell technology, long-term R&I programs ▪ Corporate in-house funding • **Policy:** ▪ R&D support ▪ Cooperation **Knowledge diffusion:** ▪ Private JP-US cooperation, academia-private partnerships (for research and manufacturing) ▪ Manufacturer-utilities partnerships ▪ **Mergers, technology acquisition**	**Market pull:** ▪ Mobile applications, stationary storage ▪ Competition with batteries for EVs **Supply push:** ▪ Multi-fuel cell technology, long-term R&I programs ▪ Corporate in-house funding **Knowledge diffusion:** ▪ Academia-private partnership level varying per country ▪ Technology purchasing ▪ Low international cooperation • **Policy:** ▪ R&D support ▪ Infrastructure ▪ Cooperation • **Technology diffusion:** varying roles in commercialization per continent and actor (e.g. academia in the EU)

Prototypes, first applications in the 1960s and experimentation until the 1980s

The first fuel cells are developed in the 1920s and 1930s, with prototypes for all variants being developed by the 1960s in the US and Europe. Government-funded research by private companies played a central role in the early commercial applications of fuel cells, with the use of PEMFC in space in the 1960s marking the first use of the technology.

In the 1960-1990 period the experience and first commercial applications varied much across the different fuel cell types, with a number of actors involved and different levels of success, although overall no technology managed to break through beyond niche applications.

Embarked fuel cells in vehicles started to be experimented from the late 1960s to 1980s, with AFC applications by private companies and academia in the US, Japan and Europe, with mixed success of government programs for hydrogen and fuel cells. Notably, after the abandonment of PEMFCs by GE in 1984, the Canadian government purchased the technology believing in its strategic potential, and continuously supported the Ballard company in furthering it from the 1983 on, which would become the global leading in the technology.

The stationary power storage and supply market for fuel cells was developed from the late 1960s. In the US, together with gas and power utilities UTC starts programs to develop commercial PAFCs for industrial use, to which Japanese utilities also participate in a later stage. Complementing the industrial applications, PAFCs are developed for power supply by technology providers and power utilities in the US and Japan, with the 1980s being characterized by increasing scale and applied experimentation, despite setbacks due to the lack of experience in the technology.

Picking up on early Dutch efforts, large-scale research into MCFCs starts in the 1960s in the US Army, followed in the 1970s in the Department of Energy, partnering with private companies. In Japan the programs also supported the technology, and interest is revived in Netherlands, Italy and Germany with important support of the EU from the mid-1980s. Nonetheless, interest and research remains limited and geographically restricted.

Japan started the Moonlight program in 1981, with an explicit goal to catch up with the US in variants such as the PAFC, MCFC and SOFC, starting with national research laboratories but later scaling up and commercializing the technologies. As part of this, in order to rapidly catch up with the US, several private companies establish partnerships with US developers.

Research acceleration and difficulties in the 1990s and 2000s

There was significant acceleration in fuel cell research in the 1990s, as demonstrated by the increase in scientific publications and patents, particularly in the EU. More countries were active in research than technology development, with patenting concentrated in the US, Europe and Asia (Japan and South Korea) while academic publications were conducted by a broader range of countries.

Countries still concentrate in specific fuel cell variants, with important differences across countries. Larger economies address several variants while smaller economies focus on a single one, with EU Member States focusing on specific technologies according to their national energy profile and potential applications. The national focus in the 1990s also represented the sectoral interests of each country, including the electrical, automotive, electronics and aerospace industries. For multiple variants such as SOFC and MCFC the EU played a significant role in funding R&D in fuel cells, complementing national programs. Due to the interaction dynamics in funding for fuel cell R&I in the EU, European, national and industry funding are often comparable in volume, with research programs in multiple Member States complementing EU funding.

International cooperation in the 1990s revolved around the US, UK and Germany. Nonetheless, cooperation was low for most fuel cell technologies, with leading countries cooperating proportionally less. Here, national priorities and industrial competition hindered cooperation.

The role of industry and of academia in basic and applied research varied by country, but the link between research and technology application for the different fuel cell technologies is increasing. Academia represented the largest share of publications in leading countries except Japan, and also was responsible for a minority share of patents in Europe, with much lower participation in the US. In the EU, research organizations are more proactive in commercializing fuel cell technologies.

In the US, DOE funding shifts from PAFCs to MC and SO fuel cells, and upon acquiring Westinghouse, Siemens launches an important SOFC research program. In Japan, government funds research in PAFCs for stationary power supply applications with the participation of technology providers and power and gas utilities, which also participate in the formation of a research association and fund research by manufacturers.

SOFC development in the 1990s follows different trends per region, but no country has been able to develop an economically and technically viable SOFC. Japan and the US targeted alternative designs in different moments, with research agendas moving in opposite directions. In Japan the government succeeded in promoting close cooperation between the public sector and private companies, targeting residential applications and in the 2000s became the lead country in SOFCs, ahead of the US which for decades was the pioneer in the technology (and still leads in SOFC large stationary power generation). Research on SOFCs was restarted in Europe following the Chernobyl disaster in countries such as Denmark, Finland, Germany, the Netherlands, Switzerland and the UK. Research has been conducted by a handful of actors, with varied importance of research organizations and private companies, and Europe has been unable to support research in SOFCs in a targeted, continuous and coordinated manner.

A global race around PEMFCs had started by the 2000s, driven by the potential application of the technology to fuel cell vehicles and the leadership of the Daimler/Ford/Ballard partnership which stirred other auto and bus manufacturers to follow suit. These partnered with their governments to develop the national industry (especially in Japan), both for mobility and stationary applications. However, despite being the most advanced fuel cell technology, PEMFCs have failed to demonstrate their full commercial viability, leading many car manufacturers to adapt by using fuel cells as auxiliary power or range extenders, developing battery electric vehicles in parallel or stopping fuel cell vehicle development altogether.

Trends observed in the 2000s continued in the 2010s. Despite the lack of fuel cell technologies capable of competing with alternatives in mainstream markets such as mobility or stationary power supply, North American (US and Canada) and Asian (Japan, South Korea and China) countries remain the global leaders in research. The research in fuel cells remains dependent on government subsidies, with Japan providing the most funding and most stable policies. The EU now primarily supports fuel cells through the Fuel Cells and Hydrogen Joint Undertaking, a European public private partnership. While EU public spending is similar to the US, European private companies spend significantly more in fuel cell R&I, resulting in a higher aggregate spending. However, the US registered a higher number of patents than the EU since 2000, and European companies are generally less resilient than their Japanese or North-American counterparts, exiting more often the fuel cell sector. Europe has an important presence in the supply of fuel cell components and as end-use markets for the technology, but North America and Asia dominate manufacturing.[23]

[23] Trinomics (2018) Study on energy technology dependence - Broad Brush Assessment Results (Task 3)

In South Korea, high energy demand and decarbonization policies led to an accelerated deployment of stationary fuel cells from practically no capacity in 2007 to almost 300 MW in 2017. This is second only to the US, which is also the lead supplier of fuel cell technology to South Korea (JRC, 2019). Patenting followed a similar trend of rapid acceleration, as show in Figure 0-28. The focus on stationary fuel cells results in an important manufacturing market share in capacity for Korea, even though the number of fuel cell systems manufactured is proportionally much smaller (DOE, 2014). PAFCs form the base of this development, with the Doosan group having acquired an US company in 2014 (JRC, 2019). The growth in fuel cell deployment in South Korea was partly the result of a policy shift by the government, who in 2003 identified the technology as a strategic renewable energy technology (Haslam, 2012). To sustain fuel cell development, the Korean government then provided installation subsidies, established minimum requirements for renewable energy in public building, supported demonstration projects and financed R&D. Moreover, natural gas and district heating grids provide adequate fuel supply and heat demand for distributed generation from fuel cells (JRC, 2019).

In China, reducing air pollution and improving security of supply (especially for oil) were the main drivers for deployment of fuel cell technology in the 2000s. Thus, while programs have promoted both basic and applied research, in the 2000s efforts concentrate in the development and deployment of fuel cell vehicles, in line with other policies such as stricter emission standards for vehicles. These initiatives led to the development of technology clusters in Beijing and Shanghai with some manufacturers and multiple research-oriented organizations (Zhang, 2010). In the last years the Chinese government has established minimum quotas for the deployment of electric vehicles, including fuel cell ones, which however face competition from battery electric vehicles. Until now, the push for fuel cell electric vehicles has not been reflected significantly either in manufacture capacity or technology development, with China lagging behind the US, Japan and South Korea, although it has become the biggest mobility market worldwide. Nonetheless, recently Chinese companies have established partnerships or acquired stakes in North-American companies in an attempt to change this (FT, 2019).

Future growth and sectoral interactions

Although certain fuel cell technologies are suitable to use fuels such as methanol or natural gas forming one of their main advantages, in general the historical development and business case for fuel cells is directly related to the development of hydrogen production technologies. The main hydrogen production technologies comprise steam reforming of natural gas and water electrolysis, with more recently experiments being conducted in fermentation of biomass. Electrolysers are especially relevant for fuel cell development as some technologies may work in reverse mode to produce hydrogen. Hence, PEMFCs developed by GE from the late 1950s found markets not only for power supply in space but also for oxygen and hydrogen supply through electrolysis in submarine applications.

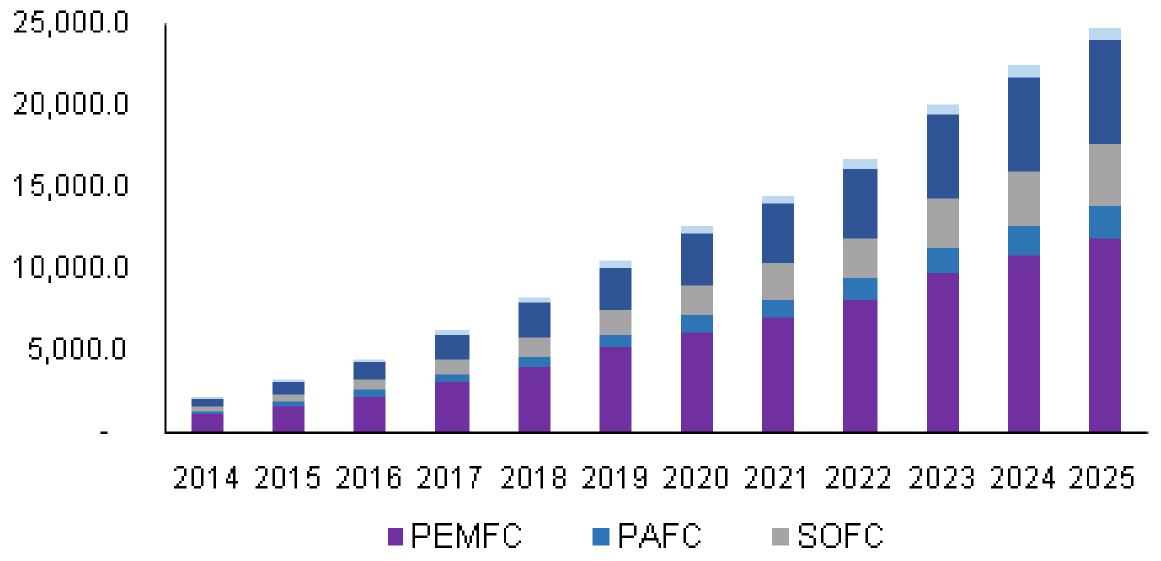
The viability of fuel cells is also driven by the potential end-use applications. In the past, space and military applications have been important drivers in triggering government-funded fuel cell research. As seen more recently applications in the stationary (primary and back-up power, combined heat and power) and mobility markets (fuel cell electric vehicles, and more recently trains and buses and heavy duty vehicles) form the bulk of demand for fuel cells. The development of mobility applications requires the simultaneous design and deployment of secondary infrastructure in the form of hydrogen refuelling stations.

Potential sectoral interactions and knowledge spillovers of hydrogen and fuel cell technology include:

- Niche transport applications facilitate the latter application in other ones, for example from road passenger transport to road freight, maritime and rail transport;[24]
- Regional industrial clusters with high potential for hydrogen production and demand may provide the human capital, infrastructure, financial and R&D resources necessary for hydrogen and fuel cell development, for example in oil and gas products, chemicals, aerospace, automotive and others, with companies in these traditional sectors investing and partnering with fuel cell companies;[25]
- The falling costs of solar PV and wind (both onshore and offshore) may provide a cheap source of electricity while electrolysis and fuel cell provide storage to match energy supply and demand profiles.

If fuel cells sustain the important growth observed in the last years the market could grow to 25 billion USD by 2025, with PEMFC responsible for more about half the market as presented in *Figure 0-29*.

Figure 0-29 Fuel cell markets to 2025 by technology variant



Source: Grand View, 2018. Fuel Cell Market Size Projected To Be Worth USD 24.81 Billion By 2025.

Mobility is the largest market for fuel cells, with South Korea leading the way with 1.8 million fuel cell vehicles targeted by 2030, followed by the US and China with 1 million vehicles each (*Table 0-17*). In a hydrogen-centred scenario, the IEA forecasts that cumulative sales could amount to 8 million vehicles by 2030. At an unit cost of 30 000 USD, this could lead to a cumulative market of 240 billion USD by 2030 (IEA, 2015).

[24] Farrell et al. (2003) A strategy for introducing hydrogen into transportation. Energy Policy 31 Issue 13.

[25] Madsen (2010) Innovative regions and industrial clusters in hydrogen and fuel cell technology. Energy Policy 38 Issue 10.

Table 0-17 National fuel cell electric vehicle targets

	2020	2022	2023	2025	2028	2030
US	13 000	40 000				
California						1 000 000
Japan	40 000			200 000		800 000
France		5 000			20 000- 50 000	
China	5 000			50 000		1 000 000
Netherlands	2 000					
*South Korea**			81 000			1 800 000

** production target*

Source: IEA, 2019. Tracking Clean Energy Progress – Hydrogen.

The IEA considers in its roadmap that the efficiency of PEMFC for hydrogen conversion will increase from 43% in 2015 to 54% in 2030 and 57% in 2050, accompanied by a reduction in investment costs from 3200 USD/kW in 2015 to 830 USD/kW in 2030 and 660 USD/kW in 2050. AFCs will slightly increase from 50% in 2015 to 53% in 2050, while investment costs will drop from 700 USD/kW to 360 USD/kW.

7.4. Case study 4: Carbon capture and storage

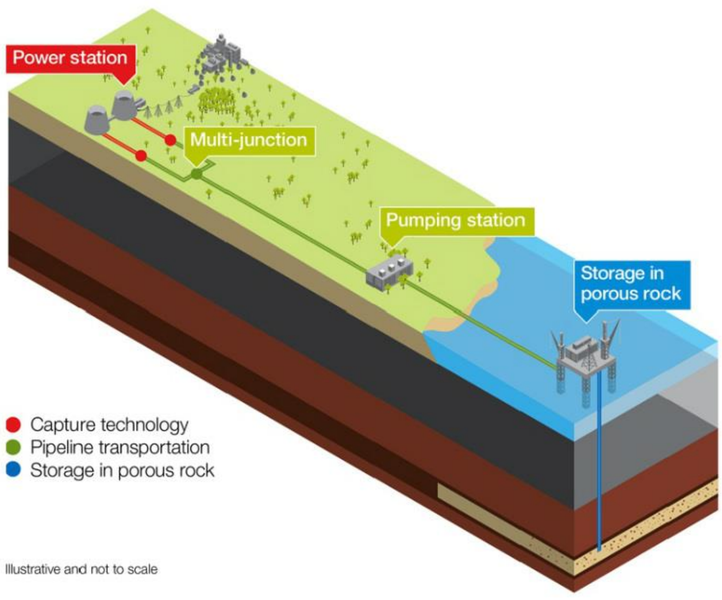
Technology and market overview

Short description of the technology

Carbon Capture and Storage (CCS) is a technology developed to capture carbon dioxide (CO_2). The technology has the potential to reduce the net emissions of CO_2 to the atmosphere and thus contribute to climate change mitigation. The technology consists of three components: capture, transport and storage. Capture consists in separating CO_2 from other gases produced during electricity generation or in industrial processes. There are three methods: pre-combustion capture, post-combustion capture and oxyfuel combustion. The captured CO_2 is transported by pipeline or ship to the storage location, if necessary. Finally the gas can be stored in geological formations (often depleted oil reservoirs or saline aquifers) located several kilometres below the surface of the earth. The capture and storage components of CCS are generally considered to require most technological research as the transport component is based on largely established technology.

Post-combustion CO_2 capture, as the name suggests, refers to the removal of CO_2 from flue gas. The separation is commonly based on amine-based solvents that selectively bind CO_2. In pre-combustion capture coal or natural gas are first converted into "syngas", a mixture of primarily hydrogen, carbon monoxide and carbon dioxide. Carbon monoxide is further reacted to produce more hydrogen and CO_2. The CO_2 is then separated from the hydrogen, which is used as a fuel. In contrast to post-combustion capture technologies, pre-combustion ones are not suited to be retrofitted int conventional power-plants. However, the advantage of this technology is that it can remove CO_2 more efficiently (and thus use less energy). Finally, oxy-fuel combustion is based on using pure oxygen, as opposed to air, for fuel burning. This has the advantage of producing more concentrated CO_2 that can be separated more easily, through simple CO_2 purification. Since the three main capture methods have different advantages, each one is best suited to be used in different set-ups and the technologies do not necessarily compete with each other.

Figure 0-30 CCS Technology overview



Source: Department of Energy and Climate Change, UK

Market status

The analysis of Zheng and Xu (2014) using a techno-paradigm perspective to describe CCS development trends points out the CCS techno-paradigm differs from other technologies. The authors show that the development of CCS technologies is seriously impeded due to the absence of sufficient financial benefits.[26] From the perspective of the private sector there is little incentive for investment as long as the cost of abatement of emissions is higher than the carbon prices and standards/norms (policies) are lacking. In addition, in the absence of (perceived) urgent environmental or societal pressures, governments are only willing to provide low funding for research.

The business case for CCS technologies remains one of the major barriers to the widespread use of CCS. However, a study by Market Research Future projects that the CCS market will have a compound annual growth rate (CAGR) of more than 8.0 % between 2018 and 2023. Currently, the US is leading in terms of number of CCS projects. It has 16 out of the 22 major projects in operation or construction worldwide. Major industrial players in the CCS market include Cansolv Technologies Inc (Canada), Fluor Corporation (U.S.), Dakota Gasification Company (U.S.), Aker Solutions (U.S.), Japan CCS (Japan), NRG Energy (U.S.), The Linde Group (Germany), Chevron Corporation (U.S.), Climeworks AG (Switzerland), and Shell (NL/UK).

The main factor driving the deployment of CCS technologies is the need to reduce CO_2 emissions while at the same time facing a growing energy demand globally and solar and wind additions coming in too slow. [27] According to the database from the Global CCS Institute there are currently 18 large-scale facilities in operation worldwide with capture capacities ranging between 0.4 and 1 million tonnes of CO_2 per year. Tens of other large-scale facilities are being developed.

Figure 0-31 Costs of CCS technologies at the reference location (USA) first-of-a-kind

	PC super-critical	Oxy-comb. super-critical	IGCC	NGCC	Iron and steel	Cement	Natural gas	Fertiliser	Biomass to ethanol
Levelised cost	US$/MWh	US$/MWh	US$/MWh	US$/MWh	US$/tonne	US$/tonne	US$/GJ	US$/tonne	US$/litre
Without CCS	75-77	-	95	49	280-370	101	3.75	400-450	0.40-0.45
With CCS - FOAK	124-133	118-129	141	78	114	69	0.061	13	0.018
With CCS - NOAK	108	107	102	62	95	58	0.058	12	0.017
Increase for FOAK w. CCS	60-70%	51-64%	45%	57%	30-41%	68%	2%	3-4%	4-5%
% decrease FOAK to NOAK	-13 to -19%	-9 to -16%	-28%	-21%	-17%	-16%	-5%	-8%	-6%
Cost of CO_2 avoided (US$/tonne CO_2)									
FOAK	74-83	66-75	97	89	77	124	21.5	25.4	21.5
NOAK	55	52	46	43	65	103	20.4	23.8	20.4

Source: Global CCS Institute, 2017

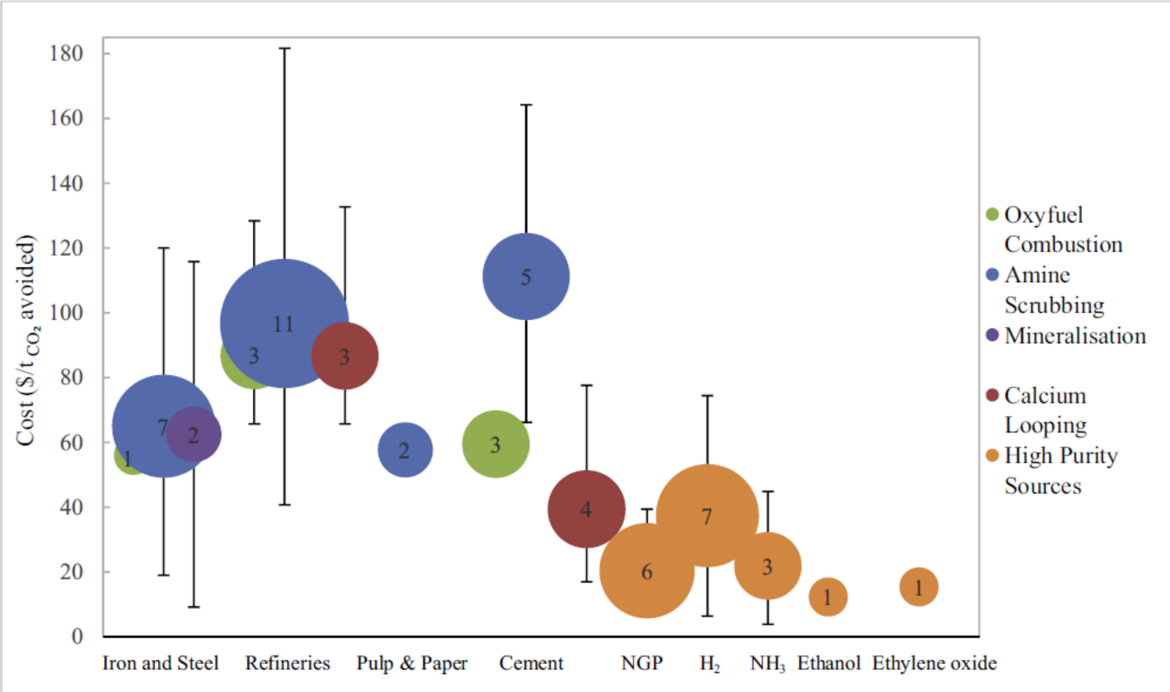
Figure 0-31 presents the costs of incorporating CCS in first-of-a-kind and nth-of-a-kind facilities in a variety of different sectors using the USA as a reference location. The costs of CCS installation for first-of-a-kind CCS plants vary significantly depending on the sector (2%

[26] Zheng B.; Xu. J.; “Carbon Capture and Storage Development Trends from a Techno-Paradigm Perspective”, Energies 2014, 7, 5221-5250

[27] https://www.marketresearchfuture.com/reports/carbon-capture-storage-market-1862

for natural gas facilities and up to 70% for PC super-critical facilities). Figure 0-32 shows the results of the throughout techno-economic study conducted by Leeson et al. in relation to the CCS technologies in the iron, steel, cement, oil refining and pulp and paper industry. The figure shows that the costs of capturing and storing CO_2 are highest in the cement industry and refineries. Costs are lowest for high purity sources.

Figure 0-32 Mean costs of capture technologies in different industries



Source: Leeson et al. 2017

Note: NGP stands for Natural Gas Processing

Development of CCS

Summary

The beginnings of CCS can be traced back to the 1960's. In the 1970's CO_2 began to be captured in order to inject it into oil fields in Texas to boost oil recovery. Thus, the motivation for capturing it was economically motivated (demand-pull). In the late 1970's the concept of capturing CO_2 to avoid releasing GHG emissions into the atmosphere began to be discussed in academia. By the late 1990's some national governments (US, EU) began policies to support CCS for climate mitigation. The development of the first CCS projects began during the 1990s mostly in the US, Canada and Norway. By the early 2000 CCS as a technology to abate CO_2 began to gain further prominence among some Asian countries. In 2005, China included the CCS technology into its Chinese National Medium- and Long-term Science and Technology Development Plan towards 2020. During the 2008 G8 Tokyo Summit support to CCS was given and a plan to create at least 20 CCS projects by 2010 was put forward. In the EU CCS technology was supported via initiatives such as the European Energy Programme for Recovery (EEPR), New Entrants' Reserve 300 and the Framework Programmes (NER300). Whereas the first two instruments were focused on supporting demonstration projects the later one was more focus on supporting R&D in early Technology Readiness Level (TRL) stages. These instruments did not succeed in supporting large-scale deployment of CCS technologies in Europe as was envisioned. The main reason for this was the financial viability of the projects. In light of the Paris Agreement and the growing consensus on the urgent need to reduce GHG emissions to mitigate climate change CCS technologies are beginning to gain renewed attention. CCS technologies represent a unique case of technology where the business case, which currently does not account for externalities such as pollution, is not a favourable one and where the primary driving force is climate-driven.

	1960s-2008	2008-2017	2018-Future
Milestones in tech. development	Injection of CO_2 into oil fields to enhance oil recovery (EOR) Inauguration of research centre at MIT	The Statoil CCS project at the Sleipner gas field in Norway becomes operational Weyburn-Midale Carbon Dioxide Project to research storage options Support to CCS given by the Chinese government and during the 2008 G8 summit EU supports tech development and demonstration projects via the EEPR, NER300 and FP programs	Operation of 6 CCS large-scale, commercial facilities in the US First large-scale CCS facility in power generation became operational in Canada Abu Dhabi CCS facility is the first fully commercial large-scale facility in the iron and steel industry ▪ Sleipner and Snøhvit facilities in Norway achieved a milestone of capturing 20 Mt of CO2
Main actors involved	Oil companies Universities	National governments	National governments Private companies: Cansolv Technologies Inc (Canada), Fluor Corporation (U.S.), Japan CCS (Japan), The Linde Group (Germany), Climeworks AG (Switzerland), and Shell (U.S.)
Main countries/regions	US, CAN, NO	US, CAN, NO, NL, BR, JP, AU	US, CAN, NO, NL, BR, JP, AU, SA, UAE
Main innovation aspects identified	**Spillovers:** Spillovers from the geology sector Spillovers and application for the steel and iron, cement, chemical and fertilizers industries Spillovers in power-generation Can be used to produce carbon-neutral hydrogen from steam reforming Capture and transport technologies can be used for Carbon Capture and Utilization (CCU)		
	Policy: ▪ CO_2 emissions tax (NO) **Knowledge diffusion:** ▪ Technology know-how developed by the oil industry ▪ Know-how from the geology sector **Supply-push:** ▪ Research programs e.g. MIT's Carbon Sequestration Initiative	**Policy**: ▪ Policy incentives based on climate change mitigation needs ▪ Implementation of the EmissionsTrading Schemes, carbon pricing ▪ Policies to mitigate **uncertainty** and high technology risk ▪ Policies to mitigate high capital expenses/initial costs ▪ Policies to mitigate **path dependence** and policy lock-ins	**Policy:** ▪ Policy incentives based on climate change mitigation needs ▪ Carbon pricing ▪ Policies to mitigate uncertainty ▪ Policies to mitigate high capital expenses/initial costs ▪ Policies to mitigate path dependence and policy lock-ins **Social systems:** ▪ Increased public acceptance due to awareness on climate change

	Demand-pull: ▪ Commercial interest in recovering additional oil		

Historical development of instruments and policies to support CCS

Many of the chemical absorption systems for post-combustion capture were developed in the 1960s and thus techniques associated with this form of CO_2 separation existed before World War II, being the most developed form of capture. Technology to capture CO_2 has been used since the 1920s in order to remove the CO_2 often found in natural gas reservoirs. In this process the CO_2 was removed in order to obtain a purer stream of methane gas. At the beginning of the 1970's CO_2 captured in this way started to be injected into oil fields in Texas in order to boost oil recovery. Today, this process continues to be used and it is known as Enhanced Oil Recovery (EOR). In 1977, the basic concept of capturing CO_2 as a tool to mitigate greenhouse gas (GHG) emissions into the atmosphere was formulated.[28] In 1989, the CCS Technologies Program was inaugurated at the Massachusetts Institute of Technology (MIT). In 2000 MIT launched the Carbon Sequestration Initiative. From 1998 to 2003 the US budget for research on CCS increased from $1 million to $54 million.

In Europe, the Norwegian CCS projects in the Sleipner gas field operated by Statoil became operational in 1996. The project was the first commercial example of a CCS project with a storage in deep saline aquifers. This was a direct result of a CO_2 emissions tax imposed by the Norwegian government in 1991. In 1997 the Great Plains Synfuels Plant in Beulah, North Dakota, USA announced that it would send all its waste gas (96% CO_2) to the Weyburn oil field in Saskatchewan, Canada to be used for enhanced oil recovery (EOR). The Weyburn-Midale Carbon Dioxide Project began in 2000 and it is dedicated to the scientific research to assess the technical feasibility of CO_2 storage in geological formations with a focus on oil reservoirs. In Algeria, the In Salah CO_2 storage facility began operating in 2004. Between 2004 and 2010 the facility captured and injected around 4 Mt of CO_2 into a depleted gas reservoir at the Krechba formation.[29] In 2003 the Bush administration committed to providing support to a project at the Department of Energy (DOE) called FutureGen. This project consisted of a public-private partnership to build the first coal-fired power plant with net zero emission. The project was designed to test several new technologies in combination including coal gasification, emissions controls, hydrogen production and CCS. The original project was restructured in 2008 mostly due to exceedingly high costs. In 2005, China included the CCS technology into its Chinese National Medium- and Long-term Science and Technology Development Plan towards 2020. During the 2008 G8 Tokyo Summit support to CCS was given and a plan to create at least 20 CCS projects by 2010 was put forward.

In the fall of 2005 the newly elected Norwegian government pledged to make Norway the forerunner in CCS and allocated € 19 million to R&D activities in the field. In the EU, two important instruments were designed to support the deployment of CCS and other renewable energy technologies in Europe: the European Energy Programme for Recovery (EEPR) launched in 2009 and the New Entrants' Reserve 300 (NER300) created in the same year. In 2008 the EU's Emission Trading Scheme came into force representing the largest transnational, multi-sector emission trading scheme in the world. In the summer of the same year the EU proposed a mechanism in order to ensure the construction and operability of 12 commercial-scale CCS demonstration plants by 2015. The EEPR was to be used as an instrument to contribute to this objective, the programme allocated a budget of one billion euro for CCS demonstration projects. This money was granted to six projects and by the end of 2017, the Commission had paid out 424 million euros. Another

[28] IEAGHG, "A brief history of CCS and current status"

[29] GCCSI, The Global Status of CCS, 2018.

EU instrument to support CCS technology development were the Framework Programmes. For example, an important project under FP6 was the Cooperation Action within CCS China-EU (COACH Project) which took place between November 2006 and October 2009. A recent publication by the European Court of Auditors that analysed the effectiveness of these instruments in deploying CCS technologies and concluded that the intended progress has not been achieved in the past decade.[30] Among the main barriers and shortcomings of the programs the following were identified: adverse investment conditions, uncertainty in regulatory frameworks and policies, lock-ins due to program design, lack of success in de-risking demonstration projects and overly complex project selection and decision-making processed.

Since 2009 five large EOR facilities in the US commenced operating. Two of the facilities are dedicated to natural gas processing, one for hydrogen production, one for fertiliser production and one for power generation. Moreover in 2017 the Bioenergy CCS (BECCS) Industrial facility in Illinois commenced operating.

The first large-scale CCS facility in power generation became operational in 2014 at the Boundary Dam Unit 3 in Saskatchewan, Canada, storing 2 Mt of CO_2 by March 2018. Another facility in Canada, the Shell-owned Quest-facility began operating in 2015. In 2015 projects in Brazil (Petrobras Santos Basin CO_2-EOR) and Saudi Arabia (commercial scale Uthmaniyah CO_2-EOR demonstration project). The Abu Dhabi CCS facility which began operating in 2016 is the first fully commercial large-scale facility in the iron and still industry. In 2017 the Sleipner and Snøhvit facilities in Norway achieved a milestone of capturing 20 Mt of CO_2.

Future growth and sectoral interactions

As described above, the origins of CCS technologies were developed by the oil and gas sector and the technology is still often used for enhanced oil recovery. Nonetheless, the current technological developments and investments are largely motivated by the need to mitigate climate change and in particular:

As an instrument to decarbonize carbon-intensive industries such as steel and iron, cement, chemicals and fertilizers production;

CCS technologies can support the decarbonization of the energy sector (fossil fuel and biomass-fired power generation, biomass gasification);

CCS can be coupled to hydrogen production via steam reforming of natural gas to produce carbon-neutral hydrogen.

Moreover, technologies to utilize (CCU) the captured CO_2 instead of storing it are being explored and developed. Such technologies could allow for utilizing CO_2 as a carbon feedstock in the production of chemicals and even synthetic fuels. Here, both applications can share technological developments in carbon capture.

[30] "Demonstrating CCS and innovative renewables at commercial scale in the EU: intended progress not achieved in the past decade", European Court of Auditors, 2018

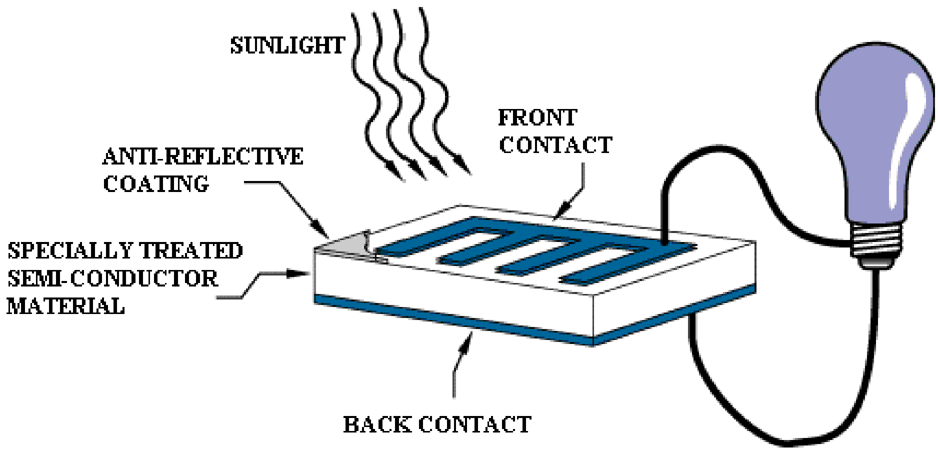
7.5. Case study 5: Solar PV

Technology and market overview

Short description of the technology

Solar PV cells are based on the photovoltaic effect. This effect describes the creation of voltage and electric current upon light irradiation of two dissimilar materials. Solar PV cells are made of one or two layers of semi conducting material displaying photovoltaic properties. The electricity flow is proportional to the intensity of light irradiation. A number of solar PV cells are wired together to make a solar PV panel. Solar PV panels are in turn joined together to create a solar PV panel system. The energy from sunlight is converted into direct current (DC) electricity. An inverter converts DC power into alternating current (AC) which can be used for home appliances. Traditionally, silicon- based cells have been the most prevalent however, in recent years other materials have been also used such as in the case of organic-based PV cells.

Figure 0-33 Basic functioning of a solar photovoltaic cell



Market Status

Table 0-18 Summary of the past, present and future market status for solar PV

	Unit	2011	2017	2018-2022
Market size	GW	~ 70	~ 404	1270.5 GW (high scenario) 1026.2 GW (moderate scenario)
Manufacturing lead countries	%	China 64.3% USA 11% Japan 9% Germany 9%[31]	China & Taiwan 70% Rest of Asia-Pacific & Central Asia 14.8 % USA & Canada 3.7 % Europe 3.1 %[32]	Annual global market shares forecast 2022: Europe: 11.7 – 16.8% America: 13.8-14.9 % APAC: 58.9 – 65.2 %

[31] Trinomics 2016, Assessment of Photovoltaics. The data refers to module manufacturing.

				MEA: 8.1 – 10.4%[33]

The PV market has experienced very fast growth showing a close to 40% Compound Annual Growth Rate (CAGR) of global installed capacity between 2000-2017, making it one of the fastest growing industries in the world (Trinomics, 2018). In 2017 a total of 99.1 GW of grid-connected solar power were installed globally. This number represents a 30 per cent year-on-year growth compared to 2016 (SolarPower Europe, 2018). The total global power capacity reached 400 GW in 2017.

[32] Fraunhofer ISE (2018) Photovoltaics Report 2017. Available: https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf

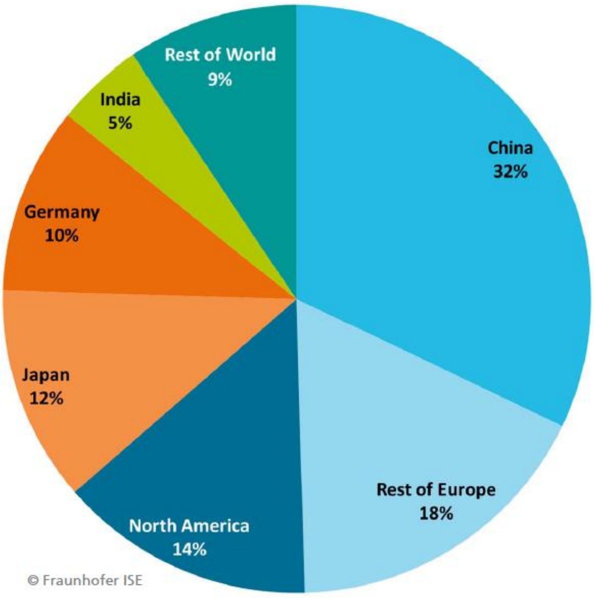
[33] Solar Power Europe, Global Market Outlooked for Solar Power 2018-2022. Available at: http://www.solarpowereurope.org/wp-content/uploads/2018/09/Global-Market-Outlook-2018-2022.pdf

Figure 0-34 shows the percentage of the global cumulative PV installation per region in 2017. From the figure, the dominance For residential and commercial systems, the capital expenditure (capex) costs have decreased from € 8 000/kW and higher in the 2000s to less than € 2 000/kW in recent years. Utility scale plants saw capex falling from € 3 000/kW in 2008 to below € 1 000/kW in 2016, cutting costs by two thirds in only eight years. The reduction in capex and the pressure to reduce the costs for solar PV electricity has contributed to the reduction in operational expenditure (opex) costs. Similarly, driven by the substantial reductions in capex module efficiency improvements, the levelized cost of electricity (LCOE) of solar PV has experienced a rapid decrease during the past 20 years from more than 50 €ct/kWh to less than 10 €ct/kWh. The LCOE for utility scale PV projects has reached a level that is competitive with conventional electricity sources, with an LCOE close to or below 3 €ct/kWh in the latest PPA (Power Purchase Agreements) in Chile and the United Arab Emirates (Trinomics, 2018).

Figure 0-35 shows the falling levels of LCOE between 1998 and 2017.

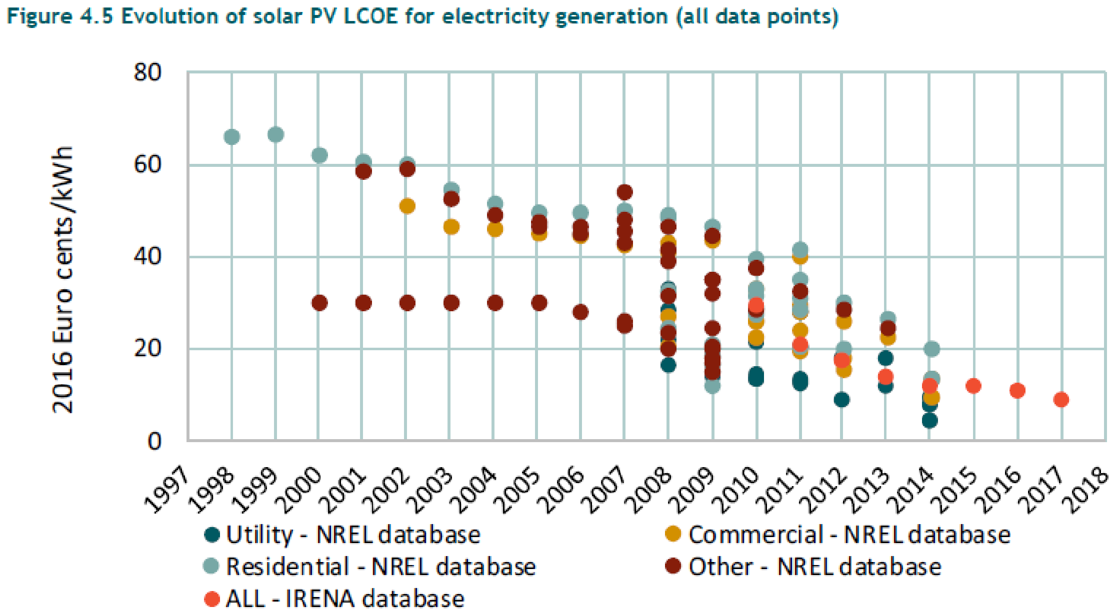
Figure 0-36 shows the evolution in global total solar PV installation during the period 2000-2017. In 2015, the biggest solar module producers included: Trina Solar (CH), Canadian Solar (CAN), Jinko Solar (CH), JA Solar (CH) and Hanwha Q CELLS (SK).

Figure 0-34 Percentage of Global Cumulative PV Installation by Region, 2017



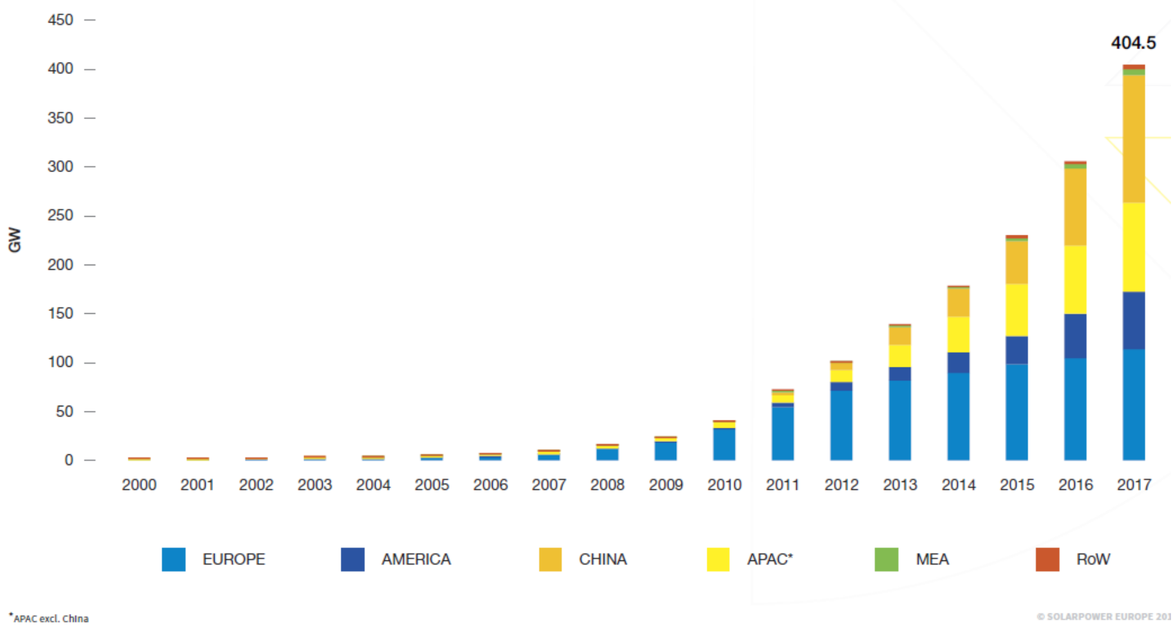
Source: Fraunhofer ISE, 2019

Figure 0-35 Evolution of solar PV LCOE for electricity generation



Source: Trinomics, 2018

Figure 0-36 Evolution of global total solar PV installed capacity



Source: SolarPower Europe 2018

Development of Solar PV

Summary

Research and development of the solar PV technology commenced in the 1940's although the scientific underpinnings for the technology were laid out already in the 19th century. Initially the technology was developed mostly in the US during the 70's and 80's. Early development of the technology benefited from having **niche markets** that were less-sensitive to higher electricity prices (off-grid applications, electricity in space).

Early cost reductions in the technology were largely based on efficiency improvements. Much of the work done to make the technology more efficient came from the academia. Further efficiency improvements during the early 2000s were also motivated by the material shortage of silicon. The PV market has moved from early and expensive niche market developments in the 1990s to a large-scale, globally deployed and increasingly competitive market. This development has been accompanied by technical change, **economies of scale** and strong **policy support**. The impressive growth can in part be attributed to economies of scale that managed to bring the costs of PV down to an attractive level for many economies in the world.

Different countries have followed different strategies in promoting the deployment of solar PV. The focus of both Japan and China has been mostly on **demand-side policies**. In the 80's and 90's R&D and net-metering initiatives provided Japan with technical leadership. Japan's market shares peaked in 2003 at 52 per cent (see Figure 0-35). In 2003, Japan reduced support for solar and instead introduced technology-neutral polices such as the renewable portfolio standard.

China has not invested a lot of money into R&D activities, instead it has focus on developing a strong manufacturing sector. Traditionally, China's PV industry has been mostly export-oriented. Before the mid-2000s, the focus in China was on supporting labour intensive downstream manufacturing (modules and cells) because of accessibility to technology and **low energy prices**. After the mid-2000s, support from the Chinese Government became broader and more structured under the Renewable Energy Law. It encompassed national targets, support to PV manufacturing through innovation funds for small technology based firms, regional investment support policies issued by some Chinese city governments and simplified loan and credit conditions.

The European Union has provided much more support to **supply-side** measures compared to Japan and China.

Figure 0-39 shows that in 2015 EU's public **R&D** budget was significantly larger than any other country. In spite of the large R&D spending the PV industry in Europe has been in decline (see section below). Faced with this EU research has focused on less mass-produced and higher added-value products to create new opportunities for the EU industry to grow. Various high-efficiency PV technologies (e.g. CPV), next generation concepts (e.g. organic PV and perovskite) and new applications (e.g. BIPV) were stimulated in addition to continued support for the development of crystalline silicon and thin-film technologies (Trinomics, 2019). On the other hand, demand-side initiatives that can be implemented at the EU level are limited and tend to focus on soft measures such as consumer campaigns.

Table 0-19 Summary of main technology innovation characteristics

	Early developments: 1940s-2000	2000-2008	Chinese dominance: 2008-Present
Milestones in tech. development	Boron dopants (1947), anti-reflective coatings (1961), hydrogen passivation (1975), ethylene vinyl acetate (EVA) as a laminating material (1975), and reactive ion etching (1976)	Developments in technology to recycle silicon and use it more efficiently. Developments in technologies with improved efficiency	Cost reductions New tech: thin film, CSP, third generation cells
Main actors involved	National governments US Space department US Defense department Universities	National Governments Solar PV Manufacturers	Solar PV Manufacturers National Governments
Main countries/regions	US, JP, DE, EU	CN, EU, DE, JP	CN, JP
Main innovation aspects identified	**Policy:** ▪ Public R&D investment ▪ Long-term policies to reduce **uncertainty** **Supply-push:** ▪ Research in academia **Knowledge diffusion:** ▪ From academia to industry **Demand – pull:** ▪ Niche markets **Spillovers:** ▪ Electronic connectors ▪ Chip-making industry ▪ Lithography ▪ Microprocessors and LCD	**Policy:** ▪ Incentives to overcome the carbon lock-in effect associated with institutionalisation of fossil-fuel based energy production → policies to reduce **path dependence** ▪ Renewable portfolio standards ▪ Renewable Energy Law – binding national targets ▪ RES and RED directives – establish national targets **Supply-push:** ▪ Public R&D investments mainly by the EU and US **Demand-pull:** ▪ Support to downstream manufacturing → growth of the energy-intensive processes due to low energy prices in China	**Policy:** ▪ Tax credits ▪ 13th Five Year Plan **Increasing Returns** due to economies of scale **Social system:** increased public acceptance and public awareness on climate change.

The discovery of the photovoltaic effect in 1839 is credited to Alexandre Edmond Becquerel. More than 100 years later in 1941 Russell Ohl invented the first solar cell. The modern solar power systems based on silicon PV cells was invented in 1954 by Calvin Souther Fuller, Daryl Chapin and Gerald Pearson - at the Bell Labs in New Jersey.

Work by Hussman identified important breakthroughs in PV technology between the 1940s and 1970s. These breakthroughs include: Boron dopants (1947), anti-reflective coatings (1961), hydrogen passivation (1975), ethylene vinyl acetate (EVA) as a laminating material (1975), and reactive ion etching (1976) (Husmann, 2011).

The first commercial solar PV systems were developed in the 1970s. Between 1970’s and 1985 R&D efforts focused on improving efficiencies and manufacturing techniques of crystallized silicon PV. In the period between 1979 and 2001 improvements in efficiency represented almost one third (30 %) of the cost reductions in the overall costs for solar PV cells. Nemet, identifies public sector R&D, mostly in government and university programs, as a central factor to attain these efficiency improvements. During the decades of the 1960s and 70s developments in solar PV technologies benefited from a number of niche markets in which the customers were less sensitive to higher-prices and instead had a strong preferences for grid independence. During these two decades the US space program and Department of Defense accounted for more than half of the global market for solar PV. The high cost of electricity in space made it possible for solar PV to be competitive even at an early stage of development when electricity was above $ 200/kWh. In 1964, NASA introduced the first Nimbus spacecraft, a satellite able to run entirely on a 470-watt solar array. In 1966, it launched the world's first Orbiting Astronomical Observatory, powered by a one-kilowatt array (Beinhart, 2018). Other niche markets during this time included off-grid homes and other off-grid applications, telecom repair stations and consumer electronics (watches, calculators etc.).

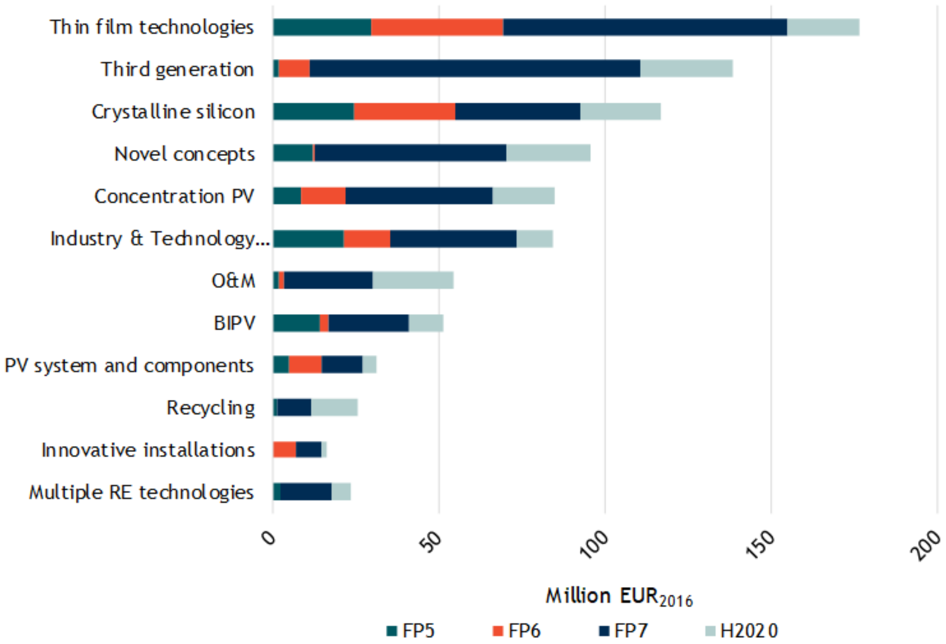
In 1985 the US inaugurated the Carrisa Plain PV power station with a capacity of 5.6 MW. At the time, this plant was one of the largest in the world. In 2005, the Bavaria Solarpark power station in Germany, surpassed the American one. The plant’s capacity was of 6.3 MW.

Mono-silicon PV cells had over 80% of the global market share in the 1990s. This share has been decreasing over time in favour of multi-silicon cells and thin-film cells. In the early 2000s the price of polysilicon as a raw material was low, approximately $30/kg. This low price did not provide any incentive to silicon manufacturers to expand production. In 2005, the solar PV industry experience a silicon shortage due to a radical increase in demand. The increased demand was largely due to increased deployment of solar PV in Europe as a result of governmental programmes in addition to a growing demand from semiconductor manufacturers. Silicon prices reaches as much as $400/kg for long-term contracts and spot prices. The response from the solar industry to this shortage focused on improving silicon-recycling processes and development of alternative processes of producing polysilicon than the traditional Siemens Process. The silicon shortage lasted until 2008. During this time the PV industry developed technology to lower the number of silicon grams/watt by, for example, reducing wafer thickness and increasing yields in the manufacturing steps. By 2009, new polysilicon plants became operational building up the production capacities. The price of polysilicon dropped to $15/kg and stabilized at ~ $20/kg. Between 2009 and 2013 the solar PV sector experience overcapacity due to a gap between global PV deployment and a much lower global demands. This overcapacity leas to large fall in PV price. However increased global demand from 2014 onwards led to normalization of the supply-demand gap.

In terms of technological evolution, the Study on Impacts of EU Actions Supporting the Development of Renewable Technologies contains telling information on the amount of funding by the EU (through Framework Programmes) in the period (1994-2018). Although the figures are EU-specific they provide a general overview of the evolution of research topics over the last 20 years.

Cell and module efficiencies have increased dramatically across all PV technologies, and over the last ten years the efficiency of average commercial wafer-based silicon modules has increased from about 12 % to 17 %. Current trends in innovation include process improvements for crystal growing, further cell efficiency improvements and additional innovations in the module assembly among others.

Figure 0-37 EU funding per sub-technology/area (2016 million euros)



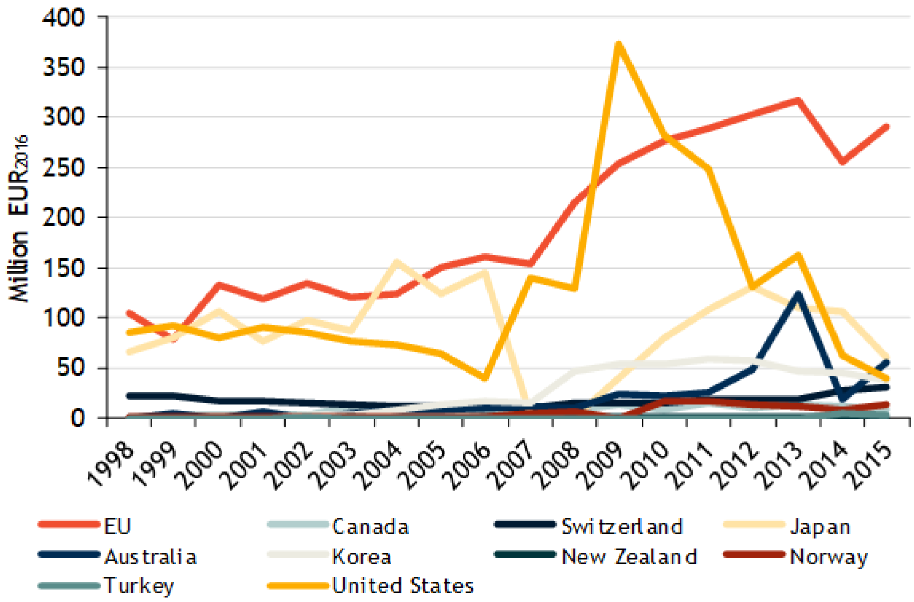
Source: Trinomics, 2018

Overview of National/Trans-national Government Strategies

The public sector not only contributed to the development of solar PV through R&D investments, public programs played an important role in reducing uncertainty for investors by setting clear expectations for the long-term. Japan's Sunshine program is a good example of this. The program reduced uncertainties over a long time horizon while also gradually reducing subsidies such that they were completely eliminated after ten years of the program. Germany's feed-in tariffs (FIT) introduced in the 2000s also had a positive effect of providing long term certainty. More generally, the German program succeeded in creating external economies of scale based on the emergence of machine tool manufactures now producing specialized PV equipment. The California Solar Initiative launched in 2006 is an initiative that aimed to install 3,000 MW of additional solar power by 2016. Namet argues that such programs have been more effective at enabling economies of scale than generous subsidies which can be discontinued at any given time. In 2002, Japan was considered the world leader in PV manufacturing, with four Japanese companies out of the 10 top PV manufacturing companies in terms of solar cell sales. However, by 2007 the Germany company Q-Cells took over and the number of Japanese companies in the top-10 list fell to 3. In 2010, Chinese companies took over the top positions displacing both Japan and Germany and by 2012 seven of the top ten companies while neither Japanese nor Germany companies featured in the list. Currently, China is the major manufacturing country for solar cells and modules, followed by Taiwan and Malaysia.

Figure 0-38 provides an overview of the international, public R&D spending on technology development for solar PV. China is not included in the figure since information on Chinese public spending is not readily available. However, traceable figures of Chinese public R&D spending for solar are in the order of € 70 million in total between years 2000 and 2015 (Trinomics, 2019). This is substantially less than the EU or the US.

Figure 0-38 Comparison of international, public R&D funding for solar PV



Source: Trinomics, 2019 based on OECD/IEA (2018)

Japan[34]

The support to manufacturers that led to Japan's technological solar leadership and global production market share took the form of generous and long-term R&D support combined with a programme of government sponsored demonstration projects which created the initial demand for solar cells. In the 1990's the Japan's government programs provided both support to R&D and policies supporting strong demand-side policies. The government adopted renewable energy deployment targets starting with 10 MW at a time. Targets aimed at 250 MW by 2000 and 4, 600 MW by 2010. These ambitious targets prompted private electricity utilities to voluntarily agreed to initiate a solar net metering program. The program managed to attract early adopters of PV and led to a steady increase in the number of residential rooftop arrays. In 1994, the Sunshine programme offered a capped 50% contribution to the capital cost of residential rooftop installations between 1-5 kW. The cap was later changed a number of times. The national installation subsidy supported over 250,000 residential installations and contributed to a substantial reduction in system costs. In 2003 a renewable portfolio standard (RPS) was introduced,

[34] This section is based on: Trinomics, Assessment of Photovoltaics, 2016

establishing a compulsory target for electricity suppliers, determining the proportion of renewable energy in the power mix and the rate at which it needed to increase over time. Since the RPS was technology neutral the focus was on the cheapest renewable energy technologies (at the time onshore wind and biomass). The policy did not have a big effect on boosting the growth of the solar market. In 2009 a new policy framework was enacted to stimulate both the supply and demand for solar. The policy instituted compulsory purchasing requirements on general electricity suppliers ensuring a market for small producers. In 2011 Japan introduced a tax credit for residential and some non-residential PV.

China[35]

The Chinese Government's approach to the PV industry has evolved over time, reflecting changes in economic and environmental priorities as well as responses to market events. Initially, China's PV industry was mostly export-oriented. Before the mid-2000s, the focus in China was on supporting labour intensive downstream manufacturing (modules and cells) because of accessibility to technology and low energy prices. During this period, the government launched several national projects to promote the development of the manufacturing industry. The first policy measure signalling a shift in the Chinese Government's interest for domestic PV deployment was the 2006 Renewable Energy Law. The Renewable Energy Law became effective in 2006, among other things it established national targets for the development of renewable energy. As discussed earlier, providing long-term certainty is of crucial importance to encourage investments. Moreover, the Renewable Energy Development Special Fund was created to support science and technology research. In 2011, China introduced a national FIT scheme to support the domestic solar industry. The 12th Five Year Plan for Renewable Energy Development set targets for solar power capacity and generation of 21 GW and 25 GW respectively (Zhang, 2013). The 13th Five Year Plan (2016-2020) foresees 86.5 GW of new PV capacity. An additional 45 GW of PV capacity is foreseen as part of the Poverty Alleviation Programme (which is part of the 13th Five Year Plan). These additions together with the already existing 11 GW could bring the total capacity to over 240 GW in 2020 (JRC, 2018).

European Union[36]

The EU established an early lead in the production of solar PV, driven by investment in demand side and supply side programmes. Demand side programmes were initially mainly in the form of capital grants and programmes to demonstrate the technology and installation processes. Supply side programmes included research, development and demonstration (RD&D) and support to establish production facilities (e.g. in Germany.) The European Directive 2001/77/EC, also known as the RES Directive, was the first attempt at EU level to promote the use of renewable resources in electricity production. The Directive set non-binding, targets for renewable electricity production in each Member State. This was replaced in 2009 by the 2009/28/EC Renewable Energy Directive (RED) which contained national binding targets for renewable energy deployment in Member States by 2020.

---

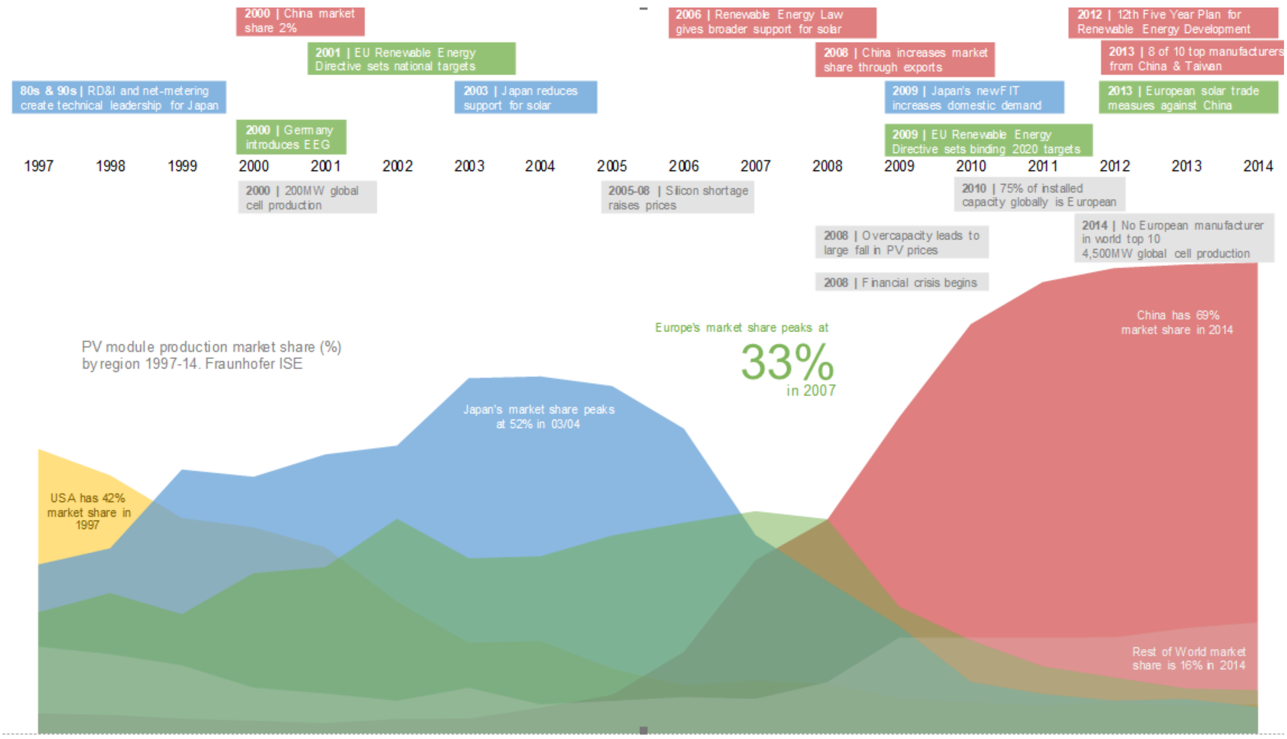
[35] This section is largely based on: Trinomics, Assessment of Photovoltaics, 2016

[36] This section is based on: Trinomics, Assessment of Photovoltaics, 2016

From 2008 onwards, Europe has lost considerable market share in PV cell and module manufacturing, mainly to China. In the mid-2000's, until around 2007, European PV manufacturing held a global production market share of around 30%. After 2007, European production output continued to increase but not as fast as global output. Eventually, by 2012, European production started to fall amid continued global growth. Until around 2012, global production growth was largely driven by European demand, which until recently dwarfed installation levels in all other world regions. The study by Trinomics on the Assessment of PV identifies a number of factors for this decline:

- Material costs: a sharp rise in polysilicon costs from 2004/2005 until 2008 – a challenge that led some companies to enter into take-or-pay contracts at high prices, while others created their own lower cost polysilicon production capacity – creating a divergence in the cost of materials;
- Energy costs: lower industrial electricity prices in China and some examples of rebates for the first year of operation of solar PV manufacturing;
- Labour costs: lower manufacturing labour rates in China;
- Overall manufacturing costs: large scale manufacturing offers advantages of scale, in purchasing power, rapid expansion in China provided the benefits economies of scale, in material costs and vertical integration of the supply chain;
- Finance: a tightening of finance available in the EU to fund expansion following the 2008 financial crisis, compared to finance from within China and from US finance markets that led to overproduction in China and falling prices;
- Market expansion: increasing markets in Germany, followed by the UK, creating an opportunity for increasing Chinese production to gain market share.

Figure 0-39 Timeline of developments of solar PV by key players



Source: PV module production market share from Fraunhofer ISE. Timeline points summarise the findings stated throughout this report.

Source: Trinomics, 2018

Future growth and sectoral interactions

Developments in the Solar PV industry have benefited from the adoption of innovations in other industries. Examples include:

- Innovation in electronic connectors to ease installation
- The use of excess purifies silicon from the chip-making industry
- The use of screen printing techniques from lithography
- For crystallized silicon PV cells, a number of manufacturing techniques from microprocessors
- For thin film PV cells, a number of manufacturing techniques from Liquid-crystal displays (LCD).

In the future the solar PV is expected to interact with technologies that enable distributed power generation e.g. microgrids and storage technologies. Forecasts of future worldwide PV deployment have continuously been raised and although current forecasts and scenarios vary significantly they all point to strong growth for the deployment of PV, ranging from a 16 to 40-fold growth in PV installed capacity by 2050 (Trinomics, 2016).

7.6. Case study 6: Autonomous road vehicles

Technology and market overview

Short description of the technology

Automated vehicles make use of a driving automation system to take over (partially) the tasks of drivers. As such, there are various levels of automation, with SAE's taxonomy being the most widely used (Figure 0-40). Driving automation systems are composed of hardware and software. Hardware includes internal and external sensors (e.g. accelerometer, gyroscope, LIDAR, imaging), processing units, actuators and communication equipment. Software comprises the vehicle control system and human-machine interface, as well as mapping capabilities (SAE, 2018).

Autonomous vehicles are strongly related to electric and shared vehicles, with multiple synergies. However, they are not synonymous to the latter, and there are there are also barriers to the combination of vehicle electrification and automation, e.g. higher electricity consumption of automation systems and charging downtime in the case of shared autonomous vehicles (Kamiya, 2019).

Figure 0-40 Levels of driving automation

	Level 0	**Level 1**	**Level 2**	**Level 3**	**Level 4**	**Level 5**
What the driver has to do?	Drive whenever driver support features are engaged			Not drive while automated driving features are engaged		
	Constantly supervise support features			When the feature requests, drive	No take-over of driving required	
	Driver support features			Automated driving features		
What do the features do?	Provide warnings and momentary assistance	Steering **OR** speed support	Steering **AND** speed support	Drive under limited conditions, not operating if not met		Drive under all conditions
Example	▪ Automatic emergency braking ▪ Blind spot warning	▪ Lane centring • **OR** ▪ Adaptive cruise control	▪ Lane centring • **AND** ▪ Adaptive cruise control	▪ Traffic jam chauffeur	▪ Local driverless taxi ▪ Pedals/ steering wheel may not be present	▪ Same as level 4, but under all conditions

Source: SAE, 2018. Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles.

Market status

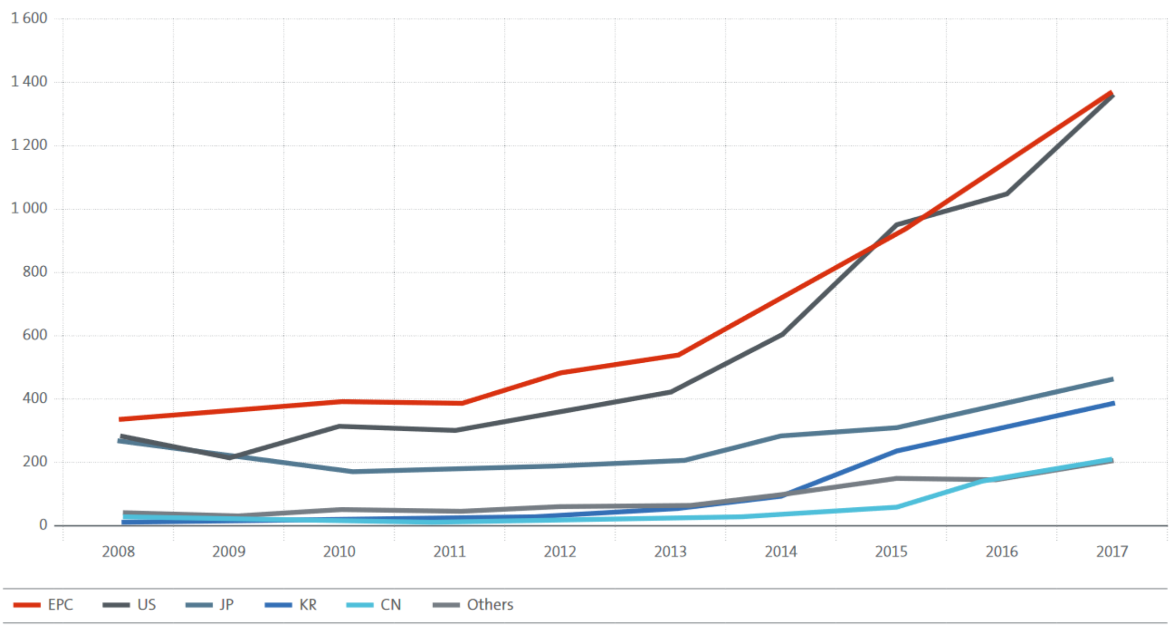
Table 0-20 Summary of the past, present and future market status

	Unit	1980s-2000s	Present	Future
Market size	Billion USD	NA	No significant market in 2019	60-77 billion USD by 2030
Lead countries		US, Germany, Japan	US, Germany, China, Japan	

Highly automated vehicles were not commercially available in 2018, but then several companies had level 2 models. (Frost & Sullivan, 2018).

From the major autonomous driving patent holders in 2017, 6 were German, led by Bosch (958), Audi (516) and Continental (439). Therefore, the list contains 2 equipment suppliers (Bosch and Continental) as well as a disruptor, Waymo/Alphabet, with 338 patents (Frost & Sullivan, 2018). Regarding the evolution at the global level patents, submissions in the countries of the European Patent Organisation increased from less than 400 in 2008 to almost 1400 in 2017, at the same level as the US. Japan follows at over 400 patents in 2017, with a strong growth from Korea, reaching also 400 patents. The leading European Patent Office Member State is Germany, with 2151 patents in 2017, followed by France at 715 patents.

Figure 0-41 Origin of patents at the European Patent Office



Note: EPC countries include the EU28 Member States, European Free Trade Agreement Member States, candidate countries (North Macedonia, Serbia and Turkey), and Albania, Monaco and San Marino.

Source: European Patent Office, 2018. Patents and self-driving vehicles

Park (2013) indicated already in 2010 the leadership of the US at over 100 publications in the year, followed by China which increased the publications from almost nothing in 2001 to over 30 in 2010. Gandia (2018) conducts a bibliometric analysis on autonomous vehicles, confirming the leadership of the US until 2018, followed by China and Germany.

Table 0-21 Total papers on autonomous vehicles by country to 2018

Country	Total	Country	Total
US	3.078	Netherlands	229
China	1.484	Sweden	216
Germany	897	Portugal	182
France	612	Singapore	167
South Korea	527	Brazil	163
Japan	477	Taiwan	162
Spain	476	Switzerland	97
England	465	Turkey	96
Italy	411	Brazil	163
Canada	325	Taiwan	162
Australia	302	Switzerland	97
India	231	Turkey	96

Source: Gandia, R. et al, 2019. Autonomous vehicles: scientometric and bibliometric review. Transport Reviews Vol. 39(1).

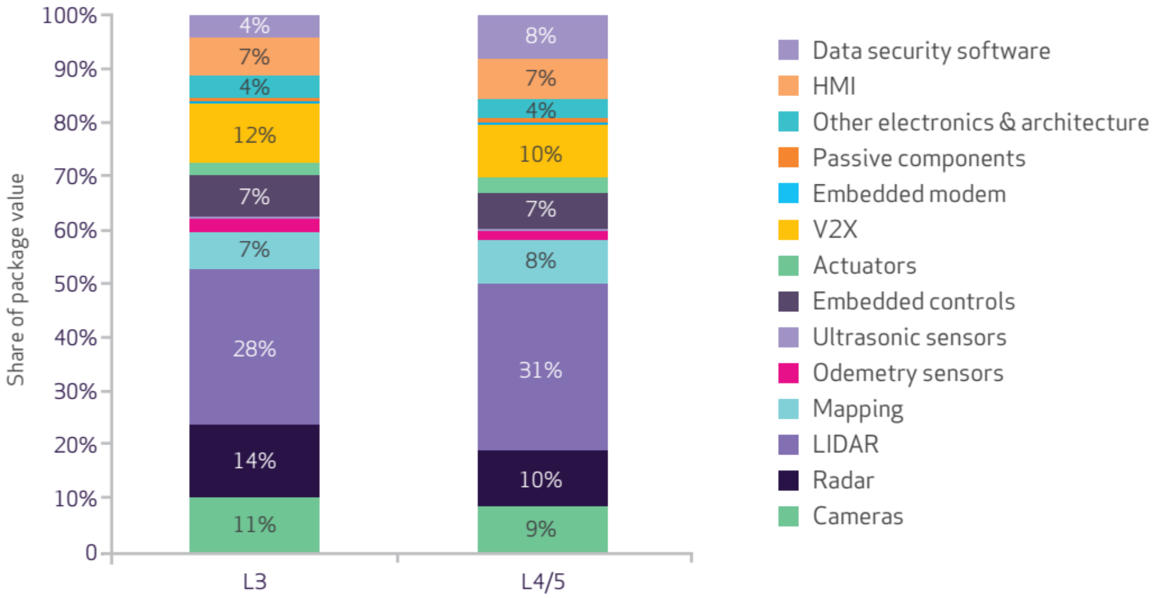
Cost reductions in autonomous vehicles

Given the technology maturity, few cost estimates for autonomous vehicles are available. Nonetheless, sensors arise as the crucial component driving cost and uncertainty, especially Lidars, whose cost ranges from 90 to 8000 USD. Catapult (2017) estimates current costs at 2500 USD for level 3 systems and almost 4500 USD for level 4/5 systems.

Catapult (2017) provides a breakdown of estimated component cost shares for different autonomy levels in connected vehicles, as presented in

Figure 0-42. The main sensors (LIDAR, radar and cameras) make up 50% or more of the costs of the technology.

Figure 0-42 Breakdown of autonomy package costs



Source: Catapult, 2017. Market forecast for connected and autonomous vehicles.

Development of autonomous road vehicles

Summary of the autonomous road vehicle development

Building on spillovers from digital technology and autonomous vehicle developments in air, space and marine applications, academic research in autonomous road vehicles accelerates in the 1980s in the US and Germany especially. In the end of the decade and 1990s both the Japan and the EU provide important funds to academia-industry partnerships, strengthening the technology beyond the US and Germany to Japan and Italy especially. This research bears fruits with various demonstrations of the technology in long-duration tests.

However, autonomous road vehicle innovation would really take off only in the 2000s, with a series of government-sponsored challenges in the US and later in Europe, where learning effects (by doing and researching) are strengthened by spillovers from vehicle safety and comfort features, audio technology and digitization and platform technologies. These spillovers are accelerated by the entrance of disrupting actors (Google), which serves to strengthen the interest of car manufacturers in the US, Germany, Japan and other European countries (France, Sweden).

Driven by economic and environmental considerations, varied support of the Chinese government to electric vehicles is poised to turn the country into the largest market for autonomous vehicles, highlighting the strong interaction between both markets. Chinese and foreign players are actively developing the technology in the country, with digital and mobility service companies leading the way. This is reflected in a recent increase in the academic and technology production of the country as evidenced by publications and patents, indicating important indigenous technology development.

This summary indicates that autonomous road vehicle technology is historically characterized by important intersectoral **spillovers**, e.g. from vehicle safety & comfort, digital and mobility service companies, and electric vehicle manufacturers (mainly Tesla). This led in the first place to the market disruption by North-American companies, which required the reaction from incumbent car manufacturers, highlighting the overall interaction of the car industry in general and the increasing importance of the provision of mobility services instead of cars, creating an entire **new technology system**. These interactions explain the advances China has made in the field regarding both technology development and creation of a market. Historically, the field has been characterised by **knowledge diffusion** among academia and industry, with important **learning effects** from learning-by-searching. Historically government **policy** has supported the development of the technology, first by providing guidance through the challenges, and recently due to the need for regulation for deployment and upscaling and due to the relevance of policy for the Chinese case.

Table 0-22 Summary of main technology innovation characteristics

	Research and practical demonstrations 1980s-2000s	Maturity and commercialization 2000s-present
Milestones in tech. development	Research programmes launch in US and EU in the 1980s Road demonstrations in the mid-1990s	DARPA Challenges (2004-2007) Google announces 500 000 miles driven (2013) Level 2 launches (2016)
Main actors involved	Universities Car manufacturers Governments (including EU)	Universities Car manufacturers (electric and incumbents) Digital and mobility service companies Governments (including EU)
Main countries/regions	US, DE, JP, IT, EU	US, DE, JP, CN
Main innovation aspects	**Policy:** ▪ Public R&D investment ▪ Consumer awareness ▪ Safety regulation **Supply push**: Academia and to a lesser extent industry R&D **Knowledge diffusion:** Industry-academia partnerships **Spillovers:** ▪ Digital technology ▪ Vehicle safety & comfort ▪ Air/space/marine vehicle automation technology	**Policy:** ▪ Public R&D investment ▪ Consumer awareness ▪ Demand-side incentives ▪ Guidance **Knowledge diffusion:** Industry-academia partnerships with researcher mobility **Supply push:** R&D by academia, car manufactures, mobility service, digital companies **New technology systems:** Mobility services with connected and autonomous vehicles **Spillovers:** ▪ Digital and platform technologies ▪ Audio technology (Lidar) ▪ Connected vehicles

Research and practical demonstrations on autonomous road vehicles

Autonomous road vehicles were already imagined in the late 1930s by GM, and an autonomous highway system was developed with RCA (a radio manufacturer) by 1950. This was followed by research at the Ohio State University in the US from 1964 to 1980 (Schladover, 2017). Nonetheless, until the 1980s, autonomous vehicles were developed and deployed mainly for air, space and marine applications in the civilian and military domains (Weber, 2014). In this and the next phases, autonomous road vehicle technology was made possible by digital technology, which forms a central knowledge field by empowering data acquisition, processing and vehicle actuation.

Autonomous road vehicle innovation only accelerates in the 1980s, when universities start research in two areas. First, in automated highway systems, with Caltrans and the University of California launching the PATH program in 1986, which culminated in the National Automated Highway Systems Consortium of 1994-1998 and further collaboration until 2003 (Schladover, 2017). Second, with research in (semi-)autonomous vehicles, such as in the Bundeswehr University Munich in Germany from the early 1980s, which also participated in the EU Eureka PROMETHEUS project, from 1987-1995 with 749 M € (Eureka network, s.d.). PROMETHEUS consisted in a collaboration between research institutes, universities, car manufacturers and other large companies and SMEs, leading to projects in other Member States such as ARGO in Italy (Weber, 2014). In Japan, work started in 1990 with the SSVS program, funded by the MITO ministry (Tsugawa, 1992) with further demonstrations of automation and platooning (Bengler, 2014), while Carnegie Mellon University's NavLab ran from the mid-1980s to the 2000s (Anderson, 2014).

Many of these research programs bore fruits in the mid-1990s, with PATH, NavLab, the Bundeswehr University Munich and the PROMETHEUS projects all logging long hours with level 1-3 prototypes. A further milestone in the demonstration of autonomous vehicles were the three Grand Challenges organized by the US Defense Advanced Research Projects Agency between 2003 and 2007. By providing prizes to research teams, the Challenges ultimately led to successful demonstrations in off-road and urban environments and innovations in sensor systems, algorithms and mapping (Anderson, 2014). Most of the 2007 finishing teams used Lidar technology from Velodyne, which started as an audio technology company (Popper, 2017).

Simultaneously with research, several support technologies were developed by the automotive industry which would later be employed in autonomous vehicles. This started with internal sensors and control technologies such as the Automated Breaking Systems (ABS) introduced in 1978 in Germany and the Electronic Stability Control (ESC) from 1995 on. These were followed in the 1990s by external sensors and communications, such as GPS navigation, parking assistance systems, automatic cruise control, forward collision prevention and lane departure warning. These innovations were driven by safety and comfort considerations, resulting not only from efforts by car manufacturers, but also due to research programs such as the EU PREVENT and regulations obliging adoption, such as for ESC (Bengler, 2014).

Maturity and commercialization of autonomous vehicles

Research programs as well as the DARPA Challenges further fostered the collaboration between universities and car manufacturers in the US in the late 2000s, with several researchers contributing to Google's efforts in the field, including its management. Google supported autonomous vehicles as part of its program for development of near-market technologies, logging 500 000 miles of autonomous driving in public roads by 2013. By then, car manufacturers including Audi and Toyota, were also actively working on the technology (Weber, 2014).

The Grand Cooperative Driving Challenge of 2011 started by the Dutch publicly-supported TNO and HTAS was the first international competition on autonomous driving, with mainly European teams of collaborating universities and car manufacturers and some North-American participation. In the 2010s, further demonstration continued in leading organizations in leading countries such as Germany and Italy (Bengler, 2014).

By 2018, at least four traditional car manufacturers were working on level 3 models, while at least four others were expected to skip them completely in favour of the introduction of level 4 vehicles by 2021 or after. But presently automation is often related to connected vehicles, where communication technologies are used to communicate with the driver, other vehicles, infrastructure and/or the cloud. It is also related to electric vehicles and the sharing economy, with key car manufacturers working towards the integration of the four aspects - automated, connected, shared electric vehicles (Frost & Sullivan, 2018).

Therefore, in addition to traditional car manufacturers, new players are joining the race following Google's lead. Tesla introduced level 2 functionality in 2016, while Google's subsidiary Waymo launched an autonomous car service in Phoenix, US, partnering with mobility service provider Lyft. Uber resumed autonomous vehicle testing in late 2018 after a fatal accident the same year (Wakabayashi, 2018).

Future growth and sectoral interactions

Autonomous road vehicles combine a number of hardware and software elements necessary for sensoring, data processing and control of the vehicles. Higher levels of automation have in the last decades leveraged individual technologies deployed by car manufacturers due to safety and comfort considerations. Automation was supported by public R&D funds, regulation and events such as the DARPA Challenges. These high-visibility events and publicity for autonomous vehicles have also been pivotal in increasing public acceptance and the awareness of traditional car manufacturers. (Bengler, 2014).

The developments of these individual solutions has been enabled by digital technology, and more recently digitization and the platform economy are enabling the integration of mature solutions (e.g. lane departure warning) as well as innovative ones (e.g. Lidar) for the near-term commercialization of highly autonomous vehicles. This was accompanied by the disruption of the market by new companies such as Google, Tesla and Uber. Although traditional car manufacturers and new players are now spearheading automation as the sector enters the commercialization phase, academia has been and remains pivotal, leading multiple demonstration projects and providing human capital and partnering with industry.

Given the need for demonstration and upscaling of highly and fully autonomous vehicles, regulation permitting the deployment in cities by mobility service providers is paramount to reduce the risks faced by them, such as in the case of accidents or municipal prohibition of autonomous vehicles. In recent years authorities at different levels have played a major role in enabling or blocking the technology, e.g. with on-going tests in urban environments due to city regulations in the US or nationwide and city support in China.

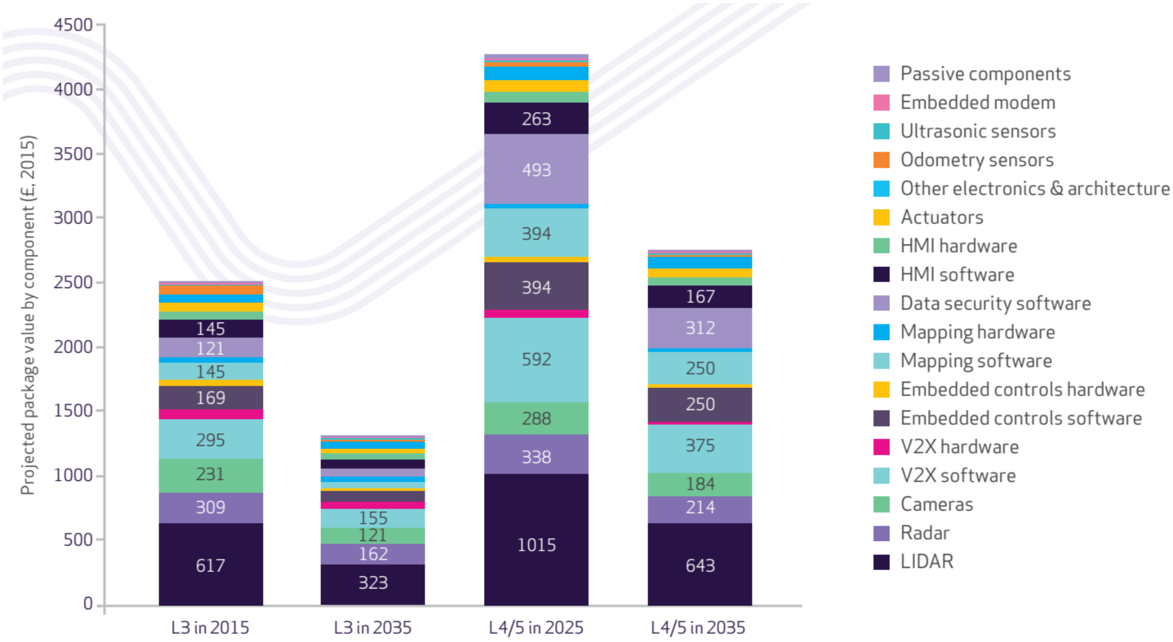
Level 4 models should be commercialized from 2021 on and level 5 models from 2026. The market for level 3 models is limited and expected to reach a peak of less than 10 billion USD by 2026, against 26 billion USD for level 4. Level 5 models could grow from practically nothing in 2026 to a 14 billion USD market by 2030. By 2030 the largest markets will be in China, the US and Europe, each market reaching around 5 billion USD or more (Frost & Sullivan, 2018). BCG estimates a total market of 42 billion USD by 2025 for partially and fully automated vehicles, increasing to 77 billion USD by 2035 (BCG, 2015). Catapult (2017) on its hand estimates connected and autonomous vehicle technology to reach a 63 billion GBP market by 2035, feeding a market of 907 billion GBP for autonomous vehicles in general.

The mobility services market enabled by autonomous vehicles shows a large growth potential, amounting to 100 billion USD by 2025 in the US alone, growing to over 600 billion USD when autonomous vehicles reach level 5, being able to drive in all conditions, such as snow (Walker, 2016).

China will in the long-term become the biggest market, already being the largest car market worldwide. The Chinese government supports low-carbon vehicles since 2009, driven by environmental considerations, which has led the country to become the largest electric vehicle market in 2016. Policies now supporting autonomous and electric vehicles include multiple instruments, such as funding, guidance and setting test zones, while companies of the Chinese platform economy (e.g. Alibaba, Baidu) and foreign are also investing heavily (Wu, 2019; Pizzuto, 2019). Hence, the overall market size for electric vehicles in China strongly influences the market growth for autonomous vehicles.

Concerning cost evolutions, automation equipment costs for level 4 vehicles will amount to 3700 USD in 2022, falling to 2300 USD by 2032, while for level 5 vehicles costs will start at 6500 USD in 2025, falling to 2700 USD by 2035 (excluding a 50% mark-up from equipment manufacturers) according to BCG (2015). Catapult (2017) estimates that costs will fall from 2500 USD for level 3 in 2015 (the level in the beginning of the case study) to under 1500 USD in 2035, while level 4/5 autonomy systems will fall from over 4000 to 2500 USD in 2035.

Figure 0-43 Project costs of autonomy packages by component



Source: Catapult, 2017. Market forecast for connected and autonomous vehicles.

8. Annex B: Review of macro-economic and integrated assessment models[37]

8.1. Agent-based model: EURACE@Unibi

Model Name	EURACE@Unibi
Model extensive name	NA
Main developer	Bielefeld University
Modelling paradigm	Agent-based macroeconomic model
Geographical coverage	Closed economy
Geographical resolution	Regions in closed economy
Temporal coverage	NA
Temporal resolution	Daily to yearly
Represented innovation aspects	**Vintages** for capital goods with frontier advances driven by R&D investments **Diffusion**: adoption dynamics for capital goods **Incremental innovation:** Consumption good quality differentiation **Human capital:** general and job-specific **Learning effects**: learning-by-doing for job-specific skills
Link	http://www.wiwi.uni-bielefeld.de/lehrbereiche/vwl/etace/Eurace_Unibi/
Documentation	https://pub.uni-bielefeld.de/download/2622083/2643518

Brief model description

The Eurace@Unibi model is an agent-based closed macroeconomic model with a spatial structure, thus representing heterogeneous agents interacting on different economic sectors and regions. The main objective is to provide a micro-founded macroeconomic model that can be used as a unified framework for policy analysis in different economic policy areas and for the examination of generic macroeconomic research questions.

Figure 0-44 shows that the model provides further differentiation regarding agents than standard macroeconomic models. Households exert different roles, as employee, consumer and investor. Firms on the other hand may be consumer good firms (with roles as employer, producer, investor and debtor) or investment good firms (acting as producers). Finally, the model explicitly represents the European Central Bank (setting monetary policy), private banks (which provide credit) and the government (acting as policy maker). These agents interact in 5 different markets for labour, consumer goods, finance (bonds), capital goods and credit.

Each of the agent roles, markets and associated dynamics are governed by heuristics based on microeconomic foundations. For several of these decisions Eurace@Unibi applies logit models, allowing individuals to maximize their objective function according to variables common to the model but also according to individual stochastic characteristics.

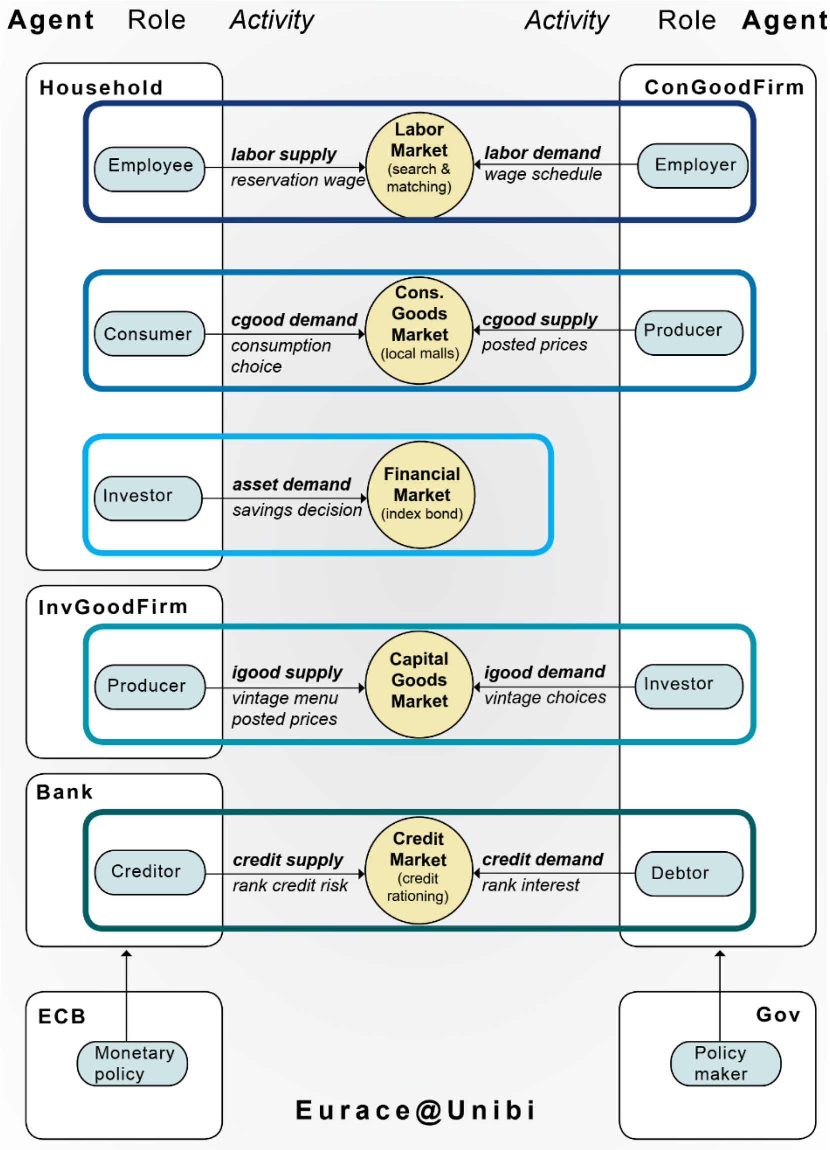
Agents decisions take place on a time scale with yearly, monthly, weekly and daily frequencies. Decision making is asynchronous, based on calendar or agent-subjective times that are allocated randomly at the start of the simulation but updated endogenously.

[37] All figures in this annex are sourced from the model manuals and studies referenced in each model fiche.

The model developers assert this captures the decentralized and asynchronous nature of economic agents' decision making.

With this representation of the economy the model includes for example different vintages of capital goods, adoption dynamics for these goods, worker skill levels, a banking system for receiving deposits from households and firms and distributing credit, monetary policy, and bankruptcy.

Figure 0-44 Overview of the Eurace@Unibi model agents, roles and markets



Box 0-3 Representation of the energy system in an alternative Eurace model

Eurace@Unibi does not contain a representation of the energy system. In an extension of the Eurace model[38] (which led to the Eurace@Unibi model), the energy sector is modelled through the inclusion of a fossil-fuel power producer (importing oil for electricity generation) and a renewable power producer (using capital goods for electricity generation, representing e.g. wind turbines and solar PV panels). Electricity is an input for the production of consumption goods, modelled as an input non-substitutable by either capital or labour.

The government provides a feed-in tariff for renewable electricity production, whose actual level is determined endogenously in the model according to electricity demand by consumption good producers. However, there is no endogenous technical change in the model for either renewable or conventional electricity generation technologies.

Representation of innovation aspects

The standard version of the model represents the productivity of workers and capital goods. Capital goods have different vintages and associated productivities, with the technological frontier improving over time driven by a stochastic innovation process. To drive this process the capital good producer reinvests part of its revenue in R&D and hires the necessary workers for research and development. All economy workers have different levels in a finite number of general skills and in addition acquire job-specific skills when hired which are required to use the advantages of the capital. Consumption good producers adopt capital goods of different vintages by comparing their expected returns given the skills of the producers current workforce, while capital good producers price these capital goods according to these expected returns.

Eurace@Unibi has an eco-technology extension,[39] differentiating technology between conventional and green types. The extension models price competition among two capital good firms, each representing a different technology type. Workers develop skills specific to each type which affect the productivity of consumption good firms, which may employ vintages of both types. Learning is conditional on the learning potential, characterized by the gap between the employee skill level and the firm's vintages. Learning spills over partially to the other technology type.

Capital goods producers reinvest part of their revenues in R&D to increase the probability of innovation, creating endogenous technical change. This leads to competition and different innovation rates for conventional and capital goods. As when green technologies enter the market only conventional ones are present, there are barriers to its diffusion due to lower technical performance and skill level of workers.

Diffusion is modelled as in the main Eurace@Unibi model, where the absorptive capacity of a firm is understood as the specific technology capabilities that determine its perception and ability to commercially adopt technological novelties. Consumption good producers

---

[38] Ponta et al., 2018. An Agent-based Stock-flow Consistent Model of the Sustainable Transition in the Energy Sector. Ecological Economics 145.

[39] Hötte (2019) How to accelerate green technology diffusion? An agent-based approach to directed technical change with coevolving absorptive capacity. Universität Bielefeld Working Papers in Economics and Management; 01-2019.

take adoption decisions based on the relative expected profitability dependent on the firms' technology type-specific capabilities. Additionally, new vintages improve the production costs of all vintages, leading to inter-vintage spillovers. To model policy interventions, the extension can represent environmental taxes on material inputs, investment subsidies for green capital goods or support to consumption of green goods.

Results of the extension indicate the existence of positive feedback for learning in green technologies.

Knowledge barriers and path dependence in technology adoption are also identified, which if strong enough may impede or reverse the adoption of green technologies. Path dependence is modelled as accumulated diffusion barriers and is translated into inferior technical performance of supplied green capital and type-specific know-how of adopters. The suitability of different government policies is related to the prevalent barriers (green technology competitivity, worker or firm-level knowledge).

Relationship of the energy system and growth in an alternative Eurace model

The objective of the EURACE@Unibi model extension developed by Ponta et al. is to analyse the trade-off between the fiscal costs of supporting the transition to a renewable electricity system and the economic benefits of reducing fossil fuel imports in the long-term. Growth and the fossil and renewable energy production, which are modelled as individual agents, have multiple channels of interaction, as described next.

Energy as a production factor: The first mechanism through which the electricity sector affects growth concerns the inputs to the production function of the consumer goods sector Y_{cg} = f(electricity, investment goods, wages). Electricity input is non-substitutable for capital or labour, with constant efficiency of use for all firms, and may be provided by fossil or renewable electricity producers alike.

Inputs to electricity production: Renewable electricity producers use only the accumulated investments in capital goods as an input, with no degradation of capital stocks (for example, no degradation of PV panels). Fossil electricity producers use oil (whose imports negatively impacts the domestic economy) as the single production input factor. Fossil electricity production has decreasing returns to scale, to replicate increasing marginal costs of fossil electricity supply. Hence, for increasing electricity demand, renewable electricity has an advantage as it has constant returns to scale.

Financing and taxation: The government taxes capital and consumer goods producers, banks, households and fossil electricity production. These tax revenues finance government expenditures, among which are the feed-in tariffs paid to renewable electricity producers. Commercial banks provide mortgages to households, which invest in renewable electricity production capacity, and loans to consumer goods producers. Fossil electricity producers pay dividends to households.

Main interaction mechanisms between energy and growth: Hence, in the EURACE@Unibi extension, government-financed feed-in tariffs lead to the deployment of renewable energy. The fiscal burden to finance these feed-in tariffs negatively impacts consumption by households, but in contrast favours capital investments in renewable energy. The additional investments in renewable energy increase employment in the capital goods sector, while the negative impact in consumption leads to reduced employment in the consumer goods sector. In the model, this dynamic is clearly observed only at the highest feed-in tariff levels, and leads to a slight net positive impact on total employment. Reduced consumption by households is explained by the higher cost of consumer goods. These higher costs are a result of reduced production capacity of consumer goods due the higher wages which result from the overall higher employment level of the economy, and which reduce employment in the sector.

The model also allows to identify whether the accumulation of capital goods in the renewable energy sector leads to reduced capital stocks in the consumer goods sector (i.e. whether there is any crowding-out of investments). The model finds no evidence of significant crowding-out of investments in the consumer goods sector, despite the hike in the central bank's interest rate being observable.

Also, high feed-in tariffs affect the government budget through both government expenditures to support renewable energy and changes in the government revenues due to the net effect on growth of the energy transition. At moderate feed-in tariff levels the effect is positive (reducing government deficit), with high support levels increasing the public deficit. Support to renewables also indirectly affects the interest rate set by the Central Bank, as higher consumption good prices lead to interest rate increases to counter inflation, as the Bank follows a dual Taylor mandate (addressing inflation and unemployment).

Moreover, the model allows to assess the impact of support to renewables on the reduced imports of fossil fuels. It indicates that the cost of support to renewables is higher than the avoided import costs, for all feed-in tariff levels. Hence, while the model does not allow for the decoupling of energy consumption and growth, it does allow for the decoupling of growth and fossil fuel consumption (and thus of emissions).

Finally, on the one hand renewable electricity producers have no operational costs (and thus are the preferential supplier), while on the other hand fossil electricity producers have no fixed costs. Hence there is no under-utilization of electricity production assets in the model, except in a case where renewable energy penetration would become so large that it would be able to supply the entire electricity demand.

These model dynamics allow to identify an optimal feed-in tariff which allows for the deployment of renewable energy without being so high that it disproportionately affects household consumption and investments by the consumer goods sector. This occurs at moderate levels of support, which lead to higher growth than either absent or excessive support to renewable energy. This higher growth occurs even though the support cost to renewables exceeds the avoided fossil fuel import expenditures.

8.2. Computable general equilibrium model: GEM-E3-FIT

Model Name	GEM-E3-FIT
Model extensive name	NA
Main developer	E3-Modelling
Modelling paradigm	General Equilibrium
Geographical coverage	46 countries/regions
Geographical resolution	All G20 countries, EU28 member states individually and the rest of the world countries aggregated to form global totals
Temporal coverage	From 2011 to 2050. Currently being extended to 2100.
Temporal resolution	Annual from 2011 to 2020 and five year step from 2020 to 2050.
Represented innovation aspects	Human capital (country specific index) Learning-by-doing (sectoral and country specific) Learning-by-research (through private R&D) Learning-by-research (through public R&D) Spillovers
Link	http://e3modelling.gr/modelling-tools/gem-e3/
Documentation	http://e3modelling.gr/wp-content/uploads/2018/10/GEM-E3_manual_2017.pdf

Brief model description

The GEM-E3-FIT model is a multi-regional, multi-sectoral[40], recursive dynamic computable general equilibrium (CGE) model which provides details on the macro-economy and its interaction with the environment and the energy system. GEM-E3-FIT allows for a consistent comparative analysis of policy scenarios. The model incorporates micro-economic mechanisms and institutional features within a consistent macroeconomic framework and avoids the representation of behaviour in reduced form. Particularly valuable are the insights the model provides regarding the distributional aspects of long-term structural adjustments. The GEM-E3-FIT model is extensively used as a tool of policy analysis and impact assessments.

The advanced features of the model regard the explicit representation of the financial sector, the advanced semi-endogenous representation of technical change and technology spillovers, the bottom up representation of the transport sector and the discrete representation of biofuels. In addition the model features different options for market regimes (perfect or imperfect competition), discrete representation of power producing technologies, semi-endogenous learning by doing effects, equilibrium unemployment, option to introduce energy efficiency standards, formulates emission permits for GHG and atmospheric pollutants. The environmental module includes flexibility instruments allowing for a variety of options when simulating emission abatement policies, including: different allocation schemes (grandfathering, auctioning, etc.), exogenous allowance bubble, various systems of exemptions, various systems for revenue recycling, and others.

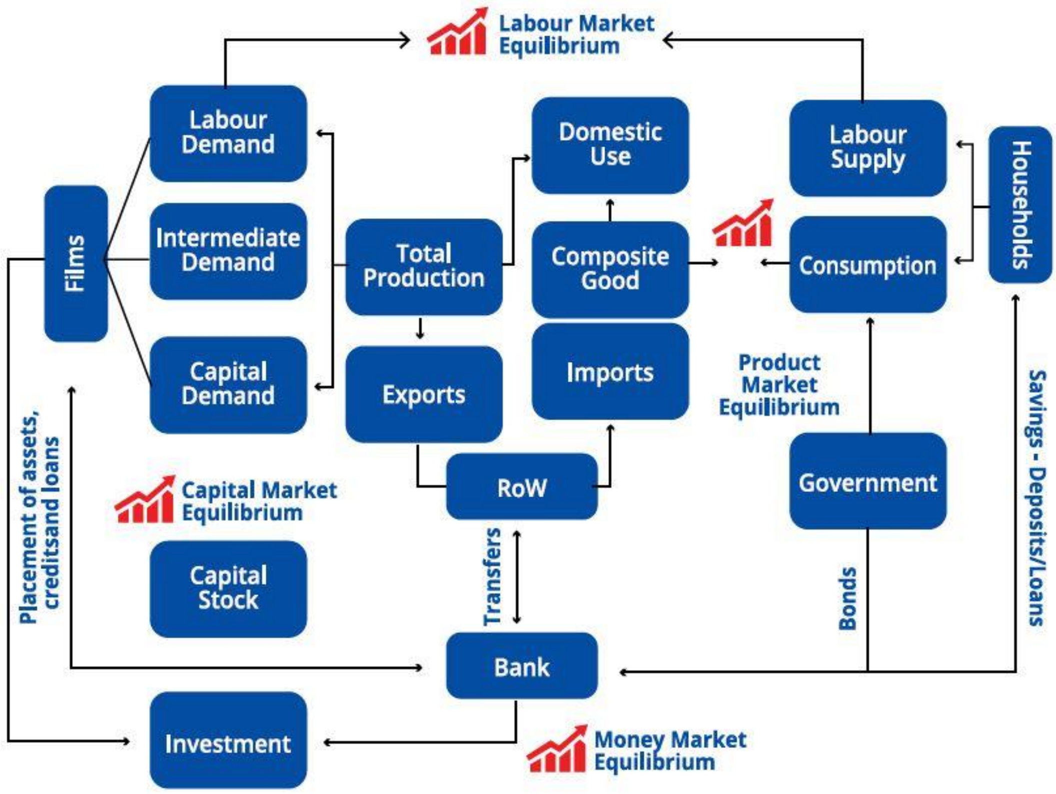
The model is dynamic, recursive over time, driven by accumulation of capital and equipment. Technology progress is explicitly represented in the production function, either exogenous or endogenous, depending on R&D expenditure by private and public sector and considering spillovers effects.

[40] The model covers 51 sectors linked through endogenous bilateral trade flows

The GEM-E3-FIT model adopts a financial closure where money supply can be endogenous. The model has a detailed representation of all inter institutional transactions (by member state) of each institutional sector. The inclusion of the financial module allows the complete accounting of revenues and expenditures of each agent and hence allows for a precise derivation of their surplus or deficit position. The basic idea of the financial module is that the demand for finance is driven by agents in deficit that seek to receive a loan from domestic or/and international capital markets and the supply of finance is driven by profit maximising agents (in surplus) that own a portfolio of financial products with different returns and risks. This loan accumulates to debt and has to be repaid in a specified time period at a market clearing interest rate. The interest rate is a function of demand, supply of finance and of the debt sustainability index of the borrower.

Figure 0-44 shows a graphical representation of the GEM-E3-FIT model. Its scope is general in two terms: it includes all simultaneously interrelated markets and represents the system at the appropriate level with respect to geography, the sub-system (energy, environment, economy) and the dynamic mechanisms of agent’s behaviour. It formulates separately the supply or demand behaviour of the economic agents which are considered to optimise individually their objective while market derived prices guarantee global equilibrium, allowing the consistent evaluation of distributional effects of policies. It considers explicitly the market clearing mechanism and the related price formation in the energy, environment and economy markets: prices are computed by the model as a result of supply and demand interactions in the markets and different market clearing mechanisms, in addition to perfect competition, are allowed. The model formulates production technologies in an endogenous manner allowing for price-driven derivation of all intermediate consumption and the services from capital and labour.

Figure 0-45 Overview of the GEM-E3-FIT model, roles and markets



Representation of the energy system

Energy system representation in the GEM-E3-FIT model includes: bottom-up representation of power generation, energy efficiency, transport electrification, household energy use, biomass modelling, depletable energy sources module, energy taxes and subsidies.

Power generation

The model has a detailed representation of power generation, including renewables, nuclear and CCS. The model allows for three different representations of power generation depending on the context of the use of the model. These options are: (i) an integrated bottom-up representation of the power generation by using a calibrated shares form production function, (ii) a detailed satellite energy model (the BUPG[41] (Bottom-Up Power Generation model)) that is soft linked with GEM-E3-FIT through an iterative process, and (iii) a soft-link with the PRIMES model for the EU countries and with POLES for the non-EU countries. The first option allows for a fully integration of the power sector model that allows GEM-E3-FIT to be autonomous and perform quick runs but it lacks features of the power sector operation such as the differentiation between base and peak load technologies etc. The second option allows a detailed representation of the power sector (for each country represented in the model) while retaining complexity to minimum

[41] The BUPG model is a bottom up model that focuses on the power generation system and is based on the blueprints of the PRIMES model. It is extended so as to cover also the non-EU countries/regions that fully match the GEM-E3-FIT regional representation.

levels. The soft – link between the two models is performed through an iterative process where the input in the GEM-E3-FIT model is the capacity investments in power generation technologies (output of the BUPG model) and the input to the BUPG model is the electricity demand by sector (output of the GEM-E3-FIT model). By applying no more than three iterations, a convergence of the output of the two models is achieved. A similar soft-link methodological approach is used as a third option by linking the output of the PRIMES and POLES energy models with the GEM-E3-FIT model. This option is used when the full modelling of the energy system is required at its highest detail. The methodology for the soft-link approach is described in Capros et al. (2013), Fragkos et al. (2018) and Vrontisi et.al (2019) among others.

Energy efficiency

GEM-E3-FIT includes an endogenous specification of energy-efficiency improvements. There are five distinct mechanisms explicitly specified in the model in order to simulate energy efficiency improvements: (i) substitution between fuels towards more efficient options (e.g. electricity penetration in the transport sector substituting for oil), (ii) substitution between energy and non-energy inputs (e.g. substitution of energy with capital, labour and materials, deployment of advanced energy efficient equipment with higher capital costs and lower fuel costs relative to conventional equipment), (iii) lower energy demand due to a decline in economic production and consumption resulting from the imposition of strong carbon pricing, (iv) firms and households perform energy efficiency improving investments, and (v) R&D investments directed to improve the productivity of the energy and electricity bundle.

Transport

The representation of transport use by households is a critical component for the accurate assessment of the costs of energy and climate change policies. In GEM-E3-FIT households decide how many passenger kilometres (pkm) they undertake following an LES demand function. The overall mobility level depends on the aggregate consumption of households and on the total cost of mobility. Then, households decide between public transport and the use of private vehicles (passenger cars or motorcycles) according to a CES function. In the third stage of the decision mechanism, households decide how many passenger kilometres they will undertake using old and new private vehicles. There is a connection between the vehicle vintage and car utilization rates, which depend on the type of vehicle and operating costs. In the final stage of the problem, the three types of private vehicles identified in GEM-E3-FIT (conventional, electric and plug-in hybrids) compete with each other. The shares by technology of new vehicles are determined using the Weibull demand function. In this specification, the choice of vehicle technology depends on: (i) the total cost of purchasing and using new vehicles, (ii) an index of availability and acceptability of the specific technology, (iii) the sensitivity of substitution between technologies with respect to cost differentials, and (iv) the additional cost of using electric and plug-in hybrid vehicles. This cost is introduced to represent the additional infrastructure requirements and the more limited autonomy of electric cars compared to conventional ones.

Households

Energy demand in the households sector has been divided into two distinct categories of consumption: (i) heating and cooking (including space heating, water heating, cooking, air conditioning), and (ii) electric appliances (including dish washing, drying, lighting, refrigeration, TV and other electric appliances in households).

The specification adopted in the GEME3-FIT model links the purchase of durable goods by households with the use of specific non-durable goods (fossil fuels and electricity).

Consumer's decision to purchase durable goods (heating and cooking appliances, electric appliances, private vehicles) depends both on the cost of buying the energy-related equipment and on the cost of using the equipment (O&M and fuel costs). The operation of appliances is determined by the demand for the linked durable good (which are differentiated into conventional and advanced appliances). The specification implies that the imposition of climate policies (or energy efficiency policies) changes the allocation of households' income away from energy-intensive appliances.

Biomass

The model identifies biomass, ethanol and bio-diesel together with their corresponding energy feedstocks as separate production sectors. Demand for bio-energy commodities is explicitly introduced as option in the sub-models by sector of production and of households. Bio-fuels is also an option as a blending possibility in producing liquid fuels by the refinery sector in which case the blended fuel is sold to transport sectors and to households. Land is a limitation factor (resource in the production function with limited maximum potential) in agriculture and in both sub-sectors. Prices of bio-energy commodities are endogenous based on costs.

Depletable Resources

The price of energy resources (e.g. oil, gas) become endogenous at world or regional scales, as a function of the rate of extraction from proven reserves and the rate of discovery of new reserves. The reserves are introduced as a separate production factor into the CES of energy producing sectors, separately from capital. Reserves, as capital, show a decreasing return to scale pattern, however influenced by technology progress and new discoveries. In the presence of climate change policies, abatement costs increase as a result of lower fossil fuel prices related to lower demand. An additional option for the model is to link it with the world energy system stochastic PROMETHEUS model. This is a one-way link from the PROMETHEUS to GEM-E3-FIT where the international price of crude-oil endogensouly computed by PROMETHEUS is introduced in the GEM-E3- model.

Representation of innovation aspects

Technical change, expressed as productivity improvement by production factor and/or as total factor productivity in certain sectors is endogenous deriving from spending in R&D. The potential of productivity improvement is based on learning curves. The R&D supply sector is represented as a separate activity (R&D services) providing services to firms and government (public R&D) which are demanders for R&D. R&D expenditures are split into public R&D and corporate R&D.

Investments in R&D imply cost reduction in technologies, through total factor productivity gains, especially those being at early stages of development and commercial uptake. The enabler of shifting towards higher demand for R&D which in turn enables productivity gains in the production of technologies is based on pricing. For example increasing costs of using fossil fuels imply substitutions towards clean fuels and technologies but also higher spending on R&D to mitigate costs. The increased R&D in turn enables productivity gains along the learning potential curves.

Regional total factor productivity is determined by the accumulated production and R&D stock and also influenced by the knowledge stock in other regions due to technological transfers and spillover effects. As a basic assumption of the model, both the stock of R&D and the stock of production in one region influence total factor productivity improvements in the rest of the world regions (with a time lag). Technology spillover rates differ per technology but are equal across the regions identified in the model.

A recent modelling feature that allows households to endogenously decide upon the optimal schooling-education years is introduced. Skills representation are extended to five skill levels based on the GTAP classification and are linked to the decision of households on education. The households decision on education affects: i) labour productivity, ii) the ability of a firm to generate patents and iii) to the ability of a firm replicating patents.

The households' decision for education changes the shares of each skill type labour to total labour force, and thus will affect the average productivity of workers. In addition it affects the capacity of absorbing knowledge spillovers. This enters into the model by increasing the total factor productivity of the sector.

8.3. Hybrid computable general equilibrium model: IMACLIM-R

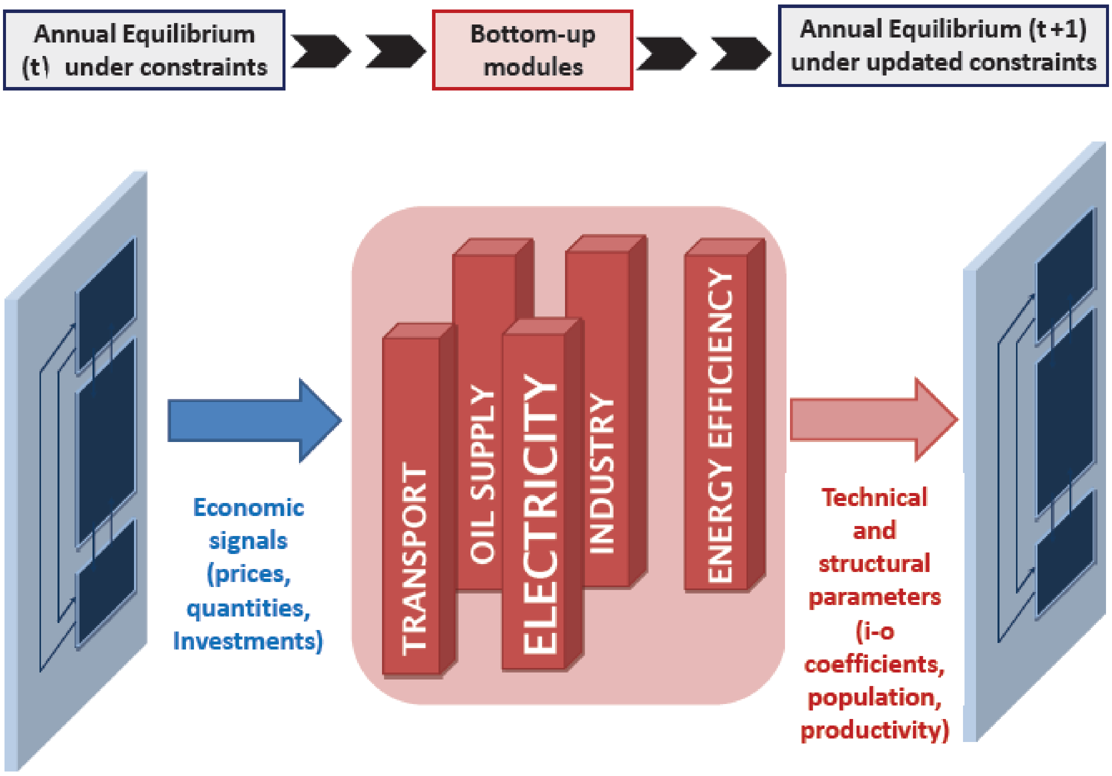
Model Name	IMACLIM-R
Model extensive name	NA
Main developer	CIRED (International Research Center on Environment and Development)
Modelling paradigm	Hybrid computable general equilibrium
Geographical coverage	Global
Geographical resolution	12 regions: USA, Canada, Europe, OECD Pacific, Former Soviet Union, China, India, Brazil, Middle East, Africa, rest of Asia, rest of Latin America
Temporal coverage	2001-2010
Temporal resolution	Yearly
Represented innovation aspects	**Learning effects**: Learning-by-doing for electricity and liquid fuels **Demand pull:** Price-induced energy efficiency improvements **Vintages** and constraints to vintage adoption
Link	http://www.rgte.centre-cired.fr/IMACLIM/Description-des-modeles-IMACLIM/IMACLIM-R/article/IMACLIM-R?lang=en
Documentation	https://wiki.ucl.ac.uk/display/ADVIAM/IMACLIM

Brief model description

IMACLIM-R is a hybrid recursive general equilibrium macroeconomic model with 12 regions and 12 economic sectors. The model comprises a dual representation of economic flows in monetary terms and in physical quantities, which allows for the explicit representation of economic, technical and material aspects of the represented sectors.

IMACLIM-R's static equilibrium module computes the economy equilibrium at year t, providing economic signals to dynamic modules which simulate the reaction of the technical systems and provide the technical and structural parameters which serve to compute the economic equilibrium in year t+1 (Figure 0-46).

Figure 0-46 Recursive linkage of the model's macroeconomic and energy system modules



The model has dynamic modules for supply (primary energy, energy transformation, non-energy sectors) and demand (demography, mobility, housing, consumption goods), which do not necessarily follow the CGE paradigm.

Demand in the macroeconomic model for each good is determined from household consumption, government consumption, and investment and intermediate uses from other domestic or foreign production sectors. Household maximize excess utility (after the satisfaction of basic needs) from the consumption of mobility and housing services as well as agriculture, industry and other services, subject to disposable income and a travel-time budgetary constraints.

Producers in the macroeconomic module decide only on the utilization rate of available capacity given fixed input-output coefficients, while this capacity and coefficients determined in the sector-specific dynamic modules. Utilization of the available capacity is determined in order to balance supply and demand, with decreasing static returns to utilization applied through the sectoral wages of the labour production factor.

Trade in non-energy products is modelled through Armington elasticities. On the other hand energy products are perfectly substitutable which allows to computable traded physical quantities, but a market sharing formula is applied to avoid dominance by the cheapest exporter.

Representation of the energy system

Energy demand is modelled for the residential, commercial, industrial, transport and other sectors. IMACLIM-R pays particular attention to the modelling of transportation. The energy supply dynamic modules comprise primary energy and energy transformation.

Primary energy sectors represented are coal, gas and oil. The model represents oil supply, demand and price formation dynamics including oligopolistic supply and behavioural considerations for demand. Natural gas and coal supply is more simplified, with resource constraints for natural gas, coupling of natural gas prices to oil and use of elasticities to determine coal prices.

Energy conversion includes electricity and liquid fuels. IMACLIM-R models 13 electricity generation technologies characterized by specific capital and O&M costs (fixed and variable), energy efficiency and discount rate. The electricity module includes investment decisions with imperfect foresight using demand and supply expectations driving a projection of the future load demand curve. Actual power dispatch is based on the segmented load duration curve, setting the technical characteristics for the following period. Auto-consumption and transport losses of the power sector are modelled through an input-output coefficient.

Liquid fuels are separated in oil-based, biofuels (bioethanol and biodiesel) and coal-to-liquids. Biofuel supply is modelled through exogenous supply curves and he model includes a limit on the annual supply growth. Coal-to-liquids on the other hand has unlimited supply, although it is still limited by the beliefs of producers in profitability (depending on oil prices) and on an exogenous constraint on the supply growth).

Representation of innovation aspects

IMACLIM-R represents technical change in a variety of ways, first by including inertia and path-dependencies by representing technology vintages and placing constraints on the maximum growth of specific vintages, for example for the power sector or liquid fuels.

Second, learning-by-doing implemented through learning curves is modelled for electricity generation (varying between 5% and 25%) and private vehicles. Electricity generation technologies with endogenous learning include supercritical pulverized coal (w/o CCS), integrated coal gasification (w/o CCS), CCGT with CCS, wind (onshore and offshore), solar (CSP, central PV and rooftop PV) and integrated biomass gasification with combined cycled (w/o CCS).[42]

Third, each of the model's productive sectors (industry, construction, services, agriculture) include energy efficiency improvements induced by the price index, allowing for the rebound effect. In each sector the leading region's energy efficiency will follow the price index (thus allowing also decreases in energy efficiency) with the conversion of less-efficient regions to the leader. Energy efficiency increases are unbiased for fossil or low-carbon energy technologies, and thus substitution of fossil for low-carbon sources is driven by relative prices rather than efficiency improvements.

Relationship between the energy system and growth

The energy system in IMACLIM-R affects growth through a number of mechanisms acting particularly in the energy demand of households, energy as a production factor and innovation in energy technologies, as described next.

Energy demand: The energy services demand of households is addressed indirectly through their demand for mobility and housing services, which determine their energy

[42] Bibas et al. (2014) Potential and limitations of bioenergy for low carbon transitions. Climatic Change Volume 123, issue 3-4.

consumption. This energy consumption is considered in the household budget constraint together with the expenditures in non-energy goods and services. Households have a travel-time budget constraint which limit their consumption of mobility services, and investments in transport infrastructure and adoption of more efficient transport technologies alleviates this constraint. The representation of biofuel and synthetic fuel supply as well as the choice between various vehicle technologies and associated efficiencies determines the consumption of mobility services and associated energy demand by households, and may form a virtuous cycle of increased adoption and efficiency of low-carbon transport technologies.

Energy as a production factor: Energy is used by the commercial, industrial, agricultural and construction sectors as well as by households. Energy demand in non-energy production sectors is driven by price-induced energy efficiency improvements (described below) and by choices between production technologies at each capacity vintage, responding to the relative prices of the technologies and energy carriers (influenced by the carbon price). Also, saturation in the consumption of industrial and agricultural goods is modelled. These mechanisms may lead to a structural change in the economy, with reduced energy demand, dematerialization and substitution of energy carriers.

Innovation in energy technologies: Innovation in specific energy technologies and vehicles (learning-by-doing) as well as price-induced endogenous energy efficiency improvements in non-energy sectors are some of the main endogenous engines of growth in IMACLIM-R. The price induced energy efficiency improvements in non-energy productive sectors take place first in the most energy efficient region, with lagging regions catching up. These improvements are partly free and partly financed by increased firms mark-up rates, impacting mostly new capital goods.

Financing: In the model, household saving rates are set exogenously, and savings then distributed globally among regions and sectors. Therefore, the capital pool is limited and there exists the possibility of crowding-out of investments.

Main interaction mechanisms between energy and growth: Structural changes in the demand for energy carriers caused by consumer preferences and production capacity investment choices of non-energy sectors are a main dynamic allowing the decoupling of growth and energy demand in IMACLIM-R, in response to the relative prices of the energy carriers and technologies. These are affected by innovation due to learning-by-doing in energy supply technologies and vehicles, and in price-induced energy efficiency. Given saving rates and thus available finance is exogenous, the model imposes the crowding out of investments between the energy and non-energy sectors.

IMACLIM-R may also represent first mover advantages in energy efficiency as well as the costs of such initiative. The speed of diffusion of energy efficiency improvements from the leader to followers also affects the impact on growth of energy policies. On the other hand, increased investment needs in electricity generation technologies due to the detailed representation of the sector and rigidity in their installed capacity affects growth negatively.

Hence, while in IMACLIM-R relative prices and sectoral productivities may lead to higher growth due to a structural change of the economy, consumer preferences and energy efficiency improvements, underutilized or insufficient production capacities in the energy as well as non-energy sectors may lead to lower growth.

8.4. Dynamic I/O simulation model GINFORS

Model Name	GINFORS
Model extensive name	Global INterindustry FORecasting System
Main developer	GWS (Gesellschaft für Wirtschaftliche Strukturforschung)
Modelling paradigm	Dynamic I/O simulation
Geographical coverage	Global
Geographical resolution	38 countries and rest of the world
Temporal coverage	Yearly
Temporal resolution	To 2050
Represented innovation aspects	**Learning effects:** One- or two-factor learning curves for global and cost components, with national cost component for system integration, grid connection and macroeconomic factors
Link	https://www.gws-os.com/de/index.php/global-developments-and-resources/models/model-details/ginfors.html
Documentation	http://papers.gws-os.com/gws-paper13-5.pdf

Brief model description

GINFORS is a dynamic Input-Output simulation model cantered on the world Input-Output database, and counting with four modules for the economy, bilateral trade, energy-emissions and resource use. Generally, GINFORS aims to model the decision making of agents with bounded rationality in imperfect markets.

The economy module for each region models 35 sectors and 59 products, balancing demand and supply, including mark-up costs. On the supply side, each sector is a certain aggregation of the 59 products of the model. The aggregation is conducted by a time series of supply matrices, with input coefficients of the matrices modelled as price-dependent variables and GINFORS also modelling the capital stock and the necessary labour input for the sector. Intermediate demand is given implicitly from the input demand of the different sectors, while final demand is sub-divided between private consumption, public consumption, gross fixed capital formation, inventory investments and exports. Private consumption for each product group is defined from real disposable income per capita and relative prices, with energy product final consumption being define in the energy module.

The bilateral trade module takes as inputs the export prices and import values of the 59 product groups. The import shares for intermediate and final goods are defined separately based on the relative export prices for each good, with exchange rates determined by the inflation in the different regions.

Representation of the energy system

In the energy and emissions module of GINFORS, primary energy is converted into secondary energy in the electricity, gas and water supply, and coke and refined petroleum sectors.

Final energy demand of a sector is determined by a two-step approach. First energy intensity of a sector regarding three purposes (heating, mobility and electricity) is determined by the specific aggregated energy price for these needs in relation to the basic price of the industry (determined in the economy module). Energy for heating (including industry process heat) is aggregated from different fossil fuels and waste while mobility aggregates (bio)diesel, (bio)gasoline and electricity. Second, the shares for the energy carriers for each industry and purpose (heating, mobility and electricity) are determined from the relative prices of the inputs.

Final energy demand of households is divided in the purposes of heating, mobility and household appliances. First demand for each purpose is defined from specific parameters, e.g. capital stock of the real estate sector for housing, or real disposable income for mobility and household appliances. Second, the shares of each energy carriers are determined from their relative prices. This energy demand quantity is feed into the economy model to determine the shares of the different energy carriers in the intermediate and final energy demand.

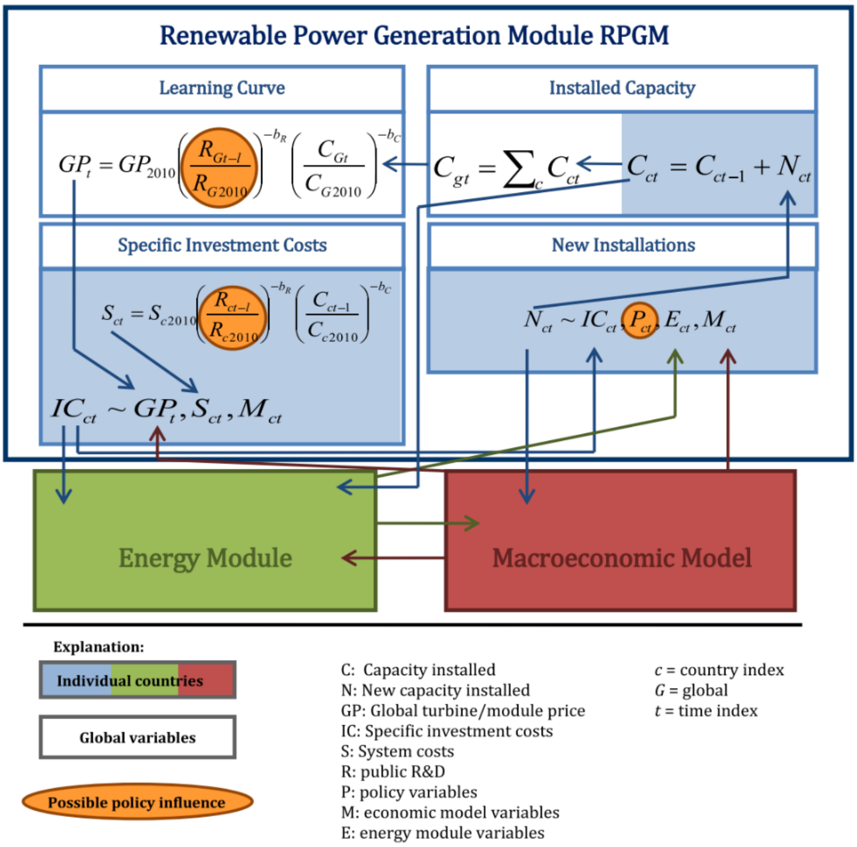
Competition between technologies for electricity generation is modelled (except for nuclear and the aggregate renewables, given energy & climate policies). Shares for specific renewable technologies (biogas, hydro, geothermal, photovoltaic, solar thermal heat, solar thermal electricity and wind) depend on unit costs (except hydro). Fossil shares fill the gap with the shares being defined from relative prices of coal, gas and oil.

Representation of innovation aspects

The renewable power generation module (RPGM)[43] is an extension to GINFORS which aims to introduce endogenous technical change.

[43] Wiebe et al. (2016) Endogenous technical change and the policy mix in renewable power generation. Renewable and Sustainable Energy Reviews 60.

Figure 0-47 Structure of the renewable power generation module for GINFORS



RPGM models the installed capacity and costs of wind and solar PV, separately. Global technology costs are determined using a learning curve with either one factor (global installed capacity) or two factor (global installed capacity and government R&D spending with a lag). Costs for each country depend on the global technology costs added by a national cost component representing the three drivers of system costs, connection to grid and macroeconomic factors (e.g. wages). One or two factor learning curves can also be applied to the national cost component. Technology costs influence the installed capacity together with policy measures, energy module variables (e.g. electricity demand) and macroeconomic factors (e.g. workforce qualification, investment climate).

Hence, as seen RPGM uses several parameters from both GINFORS's economy and energy modules. Furthermore, RPGM defines the renewable power cost and installed capacity to the energy module, while the changes in the composition of electricity generation technologies affects the input structure of the sector, which needs to be considered in the economic model.

Relationship between the energy system and growth

As GINFORS addresses the energy supply and demand throughout the I/O structure, the energy system impacts grow through the general model dynamics rather than in a specific point in the model, with multiple channels of interaction as described next.

Energy demand and energy as a production factor: Energy supply represents important economic sectors in GINFORS, being used as intermediate production input and consumed by households. Overall sectoral energy supply is determined by the sectoral activity and prices (except for electricity), while shares of each carrier in sectoral and household demand is generally determined by relative energy carrier prices. As assets in energy sectors and elsewhere are not necessarily fully utilized, this is a factor which would allow the economy to growth above a baseline.

Main interaction mechanisms between energy and growth: Energy and climate policies have to be set exogenously in GINFORS in order to observe the impact (changes from the baseline) of the energy sector on the economy and emissions. In the CECILIA2050 project[44] a first exogenous effect is central to the economy growth: investments in renewables, networks and building energy efficiency. Investments triggers economic growth through the circular flow of income, partially compensated by increases in capital costs which reduce growth (partial crowding-out). Reduced material use increases the productivity of firms at the end of the supply chain, while reducing economic activity in sectors upstream.

GINFORS also calculates material extraction of different resources including various biomass types, coal, oil and gas, but the material use does not impact growth. Nonetheless, a second important exogenous trend in CECILIA2050 is the reduced material use (dematerialisation) of the economy. The net effect of this dematerialisation depends on the geographical extent: when dematerialisation occurs globally, other more material-intensive regions benefit, negatively impacting the EU economy. The positive investment effect predominates in the short-term, while the negative dematerialisation effect is strongest in the long-term.

[44] GWS, 2014. CECILIA2050 Macroeconomic routes to 2050

8.5. Macro-econometric model: E3ME

Model Acronym	E3ME
Model extensive name	
Main developer	Cambridge Econometrics
Modelling paradigm	Macro-econometric
Geographical coverage	Global
Geographical resolution	61 countries / global regions All G20, all EU28, other countries aggregated to form global totals.
Temporal coverage	Solution to 2050, currently being extended to 2100
Temporal resolution	Yearly
Represented innovation aspects	**Learning effects:** Learning-by-doing through learning curves **Increasing returns** to adoption in FTT modules **Spillovers**: Technology indices affecting output capacity, trade, prices, labour and non-FTT sectors driven by capital and knowledge stock
Link	www.e3me.com
Documentation	https://www.e3me.com/wp-content/uploads/2019/04/E3ME-Technical-Manual-v6.1.pdf

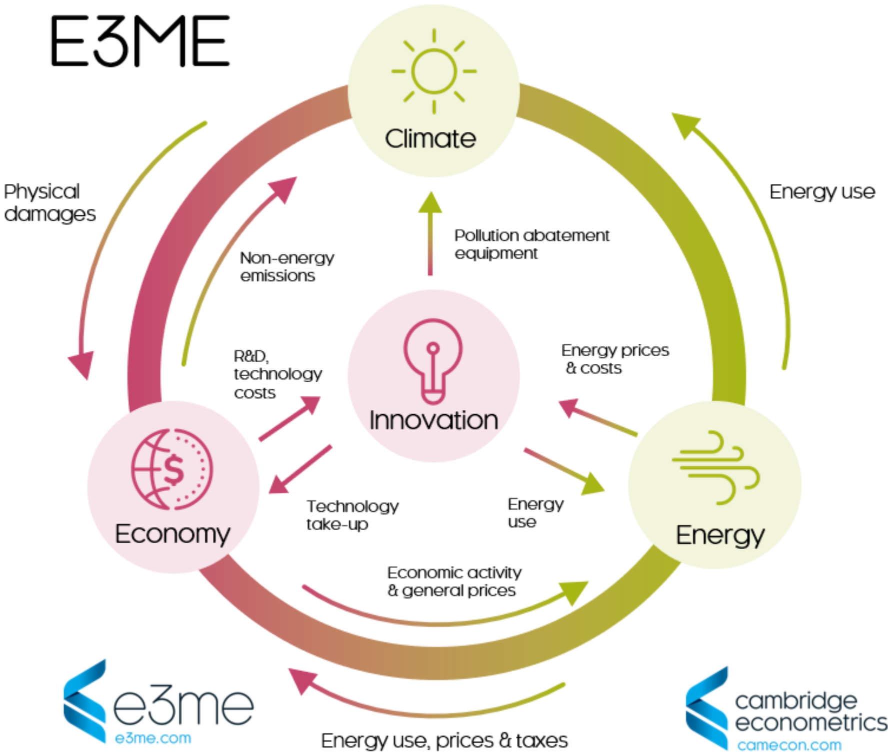
Brief model description[45]

E3ME is a macro-econometric model designed to assess global policy challenges widely used for policy assessment, forecasting and research purposes. E3ME is based on the system of national accounts, with also links to energy demand and environmental emissions, and a representation of the labour market. This is complemented by bottom-up technology diffusion models (i.e. Future Technology Transformation Models, FTT) for the power, transport, household heating and steel sectors. E3ME (and the FTT models) project forward annually up to 2050 through time-step (recursive) path-dependent simulations. The schematic below shows how the key model linkages for assessing climate and energy policy.

For each economy, economic policies are set exogenously (including tax rates, growth in government expenditures, interest rates and exchange rates). The linkages between the different modules and variables within each module are determined by 33 sets of stochastic equations disaggregated by regions and sectors, including the components of GDP (consumption, investment, international trade), prices, energy demand and materials demand. The parameters for the equation sets are determined from historical time series, thus providing an empirical grounding to the behavioral relationships of the sectors.

The parameters for the economic equation sets are estimated econometrically from historical time series, thus providing an empirical grounding to the behavioural relationships of the sectors. This approach cannot be applied to the parameters of the bottom-up FTT models because typically the time series are insufficiently long; in these cases parameters are calibrated using the available historical data.

[45] This section is partially based on von Linde et al., 2019. MONROE project - Technical description of the R&I module of the E3ME model.



Representation of the energy system

E3ME includes the bottom-up Future Technology Transformations (FTT) energy sub-models of power generation, steel, road transport and household heating. For other sectors, top-down econometric equations of energy demand are used. For all sectors, energy consumption is disaggregated by fuel type, with specific emissions factors per fuel.

Representation of innovation aspects

Innovation is represented in E3ME in three different ways.

First, each FTT energy model includes a set of explicitly defined technologies. FTT uses a decision-making core for investors wanting to build new electrical capacity, facing several options. The decision-making core takes place by pairwise levelized cost (LCOE) comparisons, conceptually equivalent to a binary logit model, parameterised by measured technology cost distributions. Costs include reductions originating from learning curves. The diffusion of technology follows a set of coupled non-linear differential equations, sometimes called ‘Lotka-Volterra’ or ‘replicator dynamics’, which represent the better ability of larger or well-established industries to capture the market, and the life expectancy of technologies. Due to learning-by-doing and increasing returns to adoption, it results in path-dependent technology scenarios that arise from electricity sector policies.

Second, the non-energy sectors feature sets of technology indices that were recently updated as part of the Horizon 2020 Monroe project. The technology indices are based on accumulated capital (i.e. capital stock) and R&D (knowledge stock). They feed into the econometric equations for capacity, from which the model derives its source of endogenous growth. They also feed into the model’s equations for trade, prices and the labour market. Finally, they feed into the energy equations that are used for the non-FTT sectors.

The third representation of technology is through exogenous specific implementation for particular scenarios. Here, the scenario is designed around the characteristics of the technology that is being assessed. Possible inputs include changes in input-output coefficients, labour intensity or prices. The model results assess the potential benefits and costs of increased uptake rates for the technology.

8.6. Macro-econometric model: NEMESIS

Model Name	**NEMESIS**
Model extensive name	New Econometric Model of Evaluation by Sectoral Interdependency and Supply
Main developer	ERASME
Modelling paradigm	Macro-econometric
Geographical coverage	Global
Geographical resolution	EU27 less Bulgaria and Cyprus USA, Japan and rest of the world
Temporal coverage	Present - 2050
Temporal resolution	Yearly
Represented innovation aspects	**Vintage** ex-ante investment decisions **Spillovers**: national, foreign and public R&D spillovers **Time lags** for spillovers **Spillovers** for ICT **Human capital**: Other intangible spillovers **Human capital**: Absorptive capacity **Learning effects**: Fishing out and knowledge depletion
Link	http://www.erasme-team.eu/modele-economique-econometrie-nemesis-vp14.html
Documentation	http://www.erasme-team.eu/files/Manual_Part_I.pdf http://www.erasme-team.eu/files/Manual_Part_II.pdf

Brief model description

The NEMESIS model is an econometric model with detailed representation of economic sectors for the EU27 Member States and more simplified models for non-EU regions. Each Member State model comprises a core economic model which interacts with three other modules on energy-environment, agriculture and land use. Therefore, NEMESIS is hybrid in the sense that this modular approach allows for the representation of both top-down forces and bottom-up ones for the three models represented.[46]

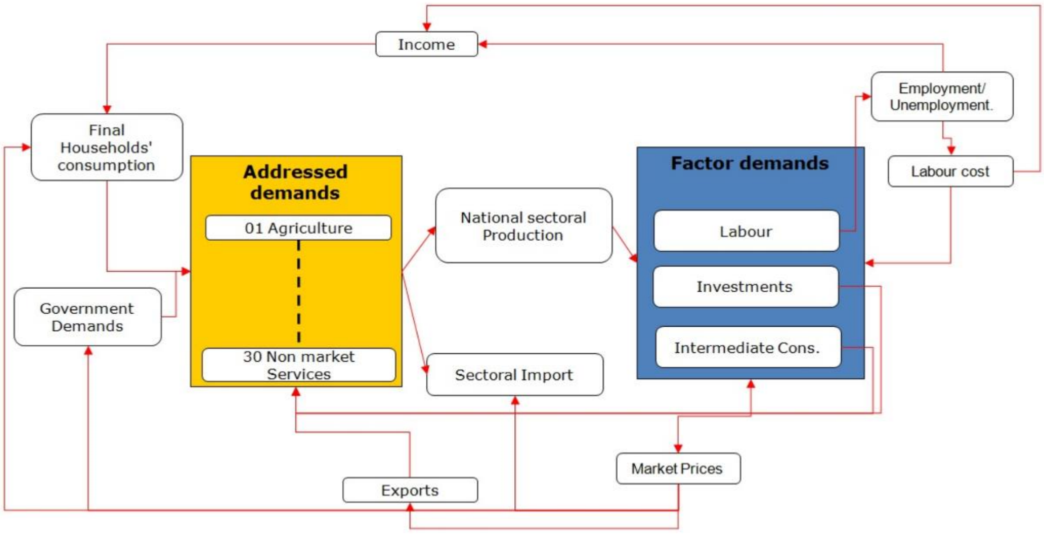
Besides the exchange of goods and services between sectors and countries, NEMESIS highlights the interdependencies between the sectors as represented by externalities, both positive (spillovers of sectoral R&D investments) and negative (emission of pollutants by specific sectors).

NEMESIS represents the supply side with 30+ production sectors, with multiple ones e.g. for transportation (4), energy (6), capital goods (5) and private services (5). The model uses constant elasticity of substitution (CES) production functions for most sectors with 5 production factors: capital, unskilled labor, skilled labor, energy and intermediate consumption. On the demand side, the aggregate consumption of representative households depends on current income, which on its turns is related to disposable income, wealth, interest rates and inflation. Up to 27 durable and non-durable good and products consumption sub-functions serve to determine the aggregated consumption. Aggregate demand of the government is on the other hand determined by education, health, defence and other expenditures. Trade is separated between intra-EU and with the rest of the world.

[46] Capros et al. (2014) Description of models and scenarios used to assess European decarbonisation pathways. Energy Strategy Reviews 2.

These interdependencies are exchanges of goods and services on markets but also of external effects, as positive technological spillovers and negative environmental externalities

Figure 0-48 Overview of the NEMESIS model

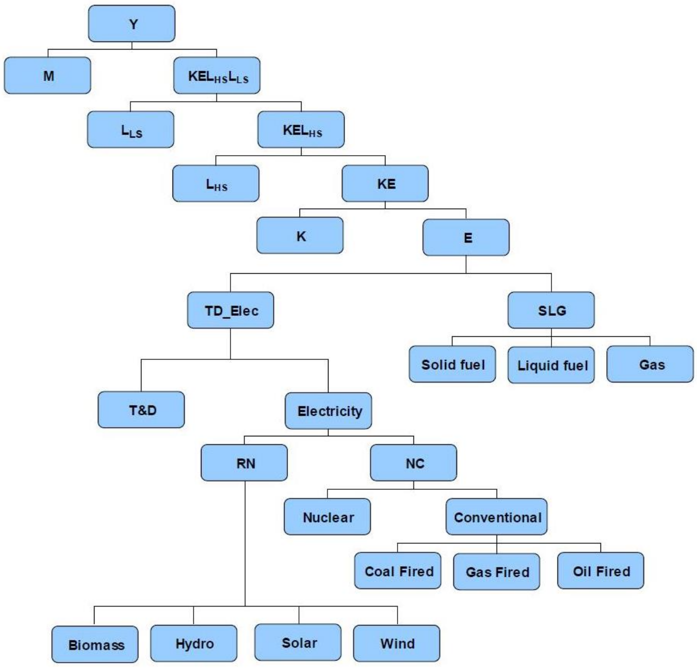


Representation of the energy system

The representation of the energy production factor in NEMESIS uses a nested CES function combining electricity and a SLG (solid fuel, oil and gas) bundle in the first level, with these fuels constituting the SLG bundle in the second level. The elasticities of substitution for the CES function in each level are specific to each economic sector.

However, the electricity generation sector is modelled with a more complex nested CES function, as illustrated in Figure 0-49. The sector consumes part of the electricity it generates through transmission and distribution losses. The elasticities are calibrated to allow substitution between renewables, conventional fuels and between renewable and conventional electricity, but not between conventional electricity technologies or between electricity generation and transmission & distribution.

Figure 0-49 Production structure of the electricity generation sector



Representation of innovation aspects

In its different versions NEMESIS has represented innovation through 3 different approaches: first representing the stock of knowledge and its impact on innovation and economic performance, second through embodying endogenous technical change in production functions, and third by expanding the latter approach with the inclusion of investments in ICT and other intangibles.

Representation of the stock of knowledge and its impacts on innovation

Nemesis represents the stock of knowledge for each sector, which is on one hand increased by sectoral R&D expenditures and spillovers, while being depleted due to aging of knowledge on the other hand. Spillovers arise from the stock of knowledge in other sectors (national, public and foreign) determined through knowledge flow matrices based on patent analysis.

The stock of knowledge leads to process and product innovation. Process innovation affects the global productivity of factors in the production functions reducing product price and increasing demand. Product innovation impacts the quality of the products as measured in the efficiency per volume of the product, leading to an increased product demand. Thus NEMESIS leads to growth both trough increases in the productivity of factors (biased technical change) and in product quality (technology neutral change).

Endogenous technical change embodied in production functions

This approach models asset vintages, each with different productivity levels. For this, the model uses nested CES production functions with five factors (capital, low- and high-skilled labour, energy and materials) for all sectors, except electricity generation.

As before, NEMESIS differentiates between product innovation (improving product quality) and process innovation (improving the productivity of the five production factors). A representative firm per sector makes R&D investment decisions regarding vintages for the five production factors, which translate into a fixed ex-post productivity per factor for the next period. The representative firm may also invest in R&D to improve the final quality of the product, as measured in efficiency units. The investment in R&D for the final product and the five production factors leads to six different possible sources of endogenous technical change in NEMESIS, one technology neutral and the other 5 biased.

Innovation for final products and production factors is dependent of the respective innovation stock. The innovation stock depends on R&D investments, which are adjusted by the innovation productivity. The latter is influenced positively by the sector knowledge stock, and negatively by the research difficulty which results from past successful innovations. The sector knowledge stock is determined by past intra-sectoral R&D efforts by national and foreign firms (intra-sectoral spillovers), by past R&D efforts in other sectors, and by R&D externalities from R&D efforts in public laboratories, both national and foreign. Spillovers from private R&D efforts are lagged by one year, while public R&D efforts are lagged by 3 years following indications in the literature of longer maturation.

Investments in ICT technologies and the intangibles of training and software

The third approach to representing innovation in NEMESIS highlights the impact of investments not only on R&D of general purpose technologies such as bio- or nano-technologies, but also investments in ICT and intangibles such as training, software, intellectual property or managerial skills.

In this model version CES production functions of sector representative firms combines the compound production input with a flow of innovation services. These innovation services on their hand are provided with a CES technology combining the innovation components of R&D investments, of ICT technology investments, and of investments in other intangibles (software and training).

The innovation components' function depends especially on the knowledge stock of the innovation asset (R&D, ICT or other intangibles) and of the sector absorptive capacity. The national sectoral knowledge stock is spread from a global stock. This global stock for each innovation asset is the sum of the decayed past global knowledge stock, the present investments in the respective asset and the lagged public investment in the asset (e.g. R&D). The absorptive capacity is a function of the sectoral investment rate in the innovation asset.

Relationship between the energy system with growth

The production function of the electricity generation sector is modelled in more detail than other sectors in the NEMESIS model, but still addressed within the general representation of the economy. The energy sector has multiple channels of interaction with the economy, as described next.

Energy as a production factor: the production in most of the NEMESIS' economic sectors is defined by a nested CES function with five inputs, with energy and capital forming the lowest-level bundle. The elasticities of substitution of this main production function are calibrated with energy and capital exhibiting high substitutability. As the model differentiates between ex-ante and ex-post production functions, this substitutability between capital and energy takes place especially ex-ante through the adoption of new vintages. Hence, while theoretically in the long-run there should be an equilibrium between demand and potential production, rigidities may lead to sub-optimal results.

Within the energy bundle, while elasticity of substitution between electricity and the bundle of solid fuels, oil and gas is considered relatively high (0.5), the elasticity within the bundle ranges from 0.1 to 0.5 depending on the sector. Within electricity supply (for the electricity generation sector), elasticity of substitution between renewables is high, and lower for and within the bundle of fossil and nuclear technologies.

Innovation in energy technologies: The endogenous sectoral investments in R&D can be unbiased or directed at one of the five input factors, including energy. Therefore, the model can assess the decoupling of growth from energy consumption through R&D investments in the other production factors. Spillover arises from both international and domestic private and public R&D.

Main interaction mechanisms between energy and growth: In NEMESIS, decoupling of energy and growth thus occurs first through the increased use of capital given its high substitutability. Within the different energy inputs, electricity and the bundle of coal, oil and gas have high elasticity of substitution, but the substitutability between renewables, nuclear and fossil sources is more limited. Decoupling can be furthermore strongly favoured by R&D investments in non-energy production factors which might be enhanced by international, intersectoral spillovers, while the ability of regions to gain a competitive advantage through private and public investments will depend on the strength of these spillovers. As interest rates (which influence aggregate consumption) are determined exogenously, there is no possible crowding-out of sectoral investments due to higher capital costs.

8.7. Integrated assessment model: IMAGE

Model Name	IMAGE
Model extensive name	NA
Main developer	PBL (Netherlands Environmental Assessment Agency)
Modelling paradigm	Integrated assessment model
Geographical coverage	Global
Geographical resolution	26 regions
Temporal coverage	2005-2010
Temporal resolution	Yearly/5 years
Represented innovation aspects	**Learning effects**: Learning-by-doing for fossil fuels, renewables, nuclear, hydrogen and energy conservation cost curves **Demand pull**: price-induced energy conservation **Diffusion**: Technology adoption for specific sectors
Link	https://models.pbl.nl/image/
Documentation	https://models.pbl.nl/image/index.php/Welcome_to_IMAGE_3.0_Documentation

Brief model description

IMAGE is an integrated assessment framework comprising models for the agricultural and energy sectors, besides the representation of the earth system (land, atmosphere and oceans).

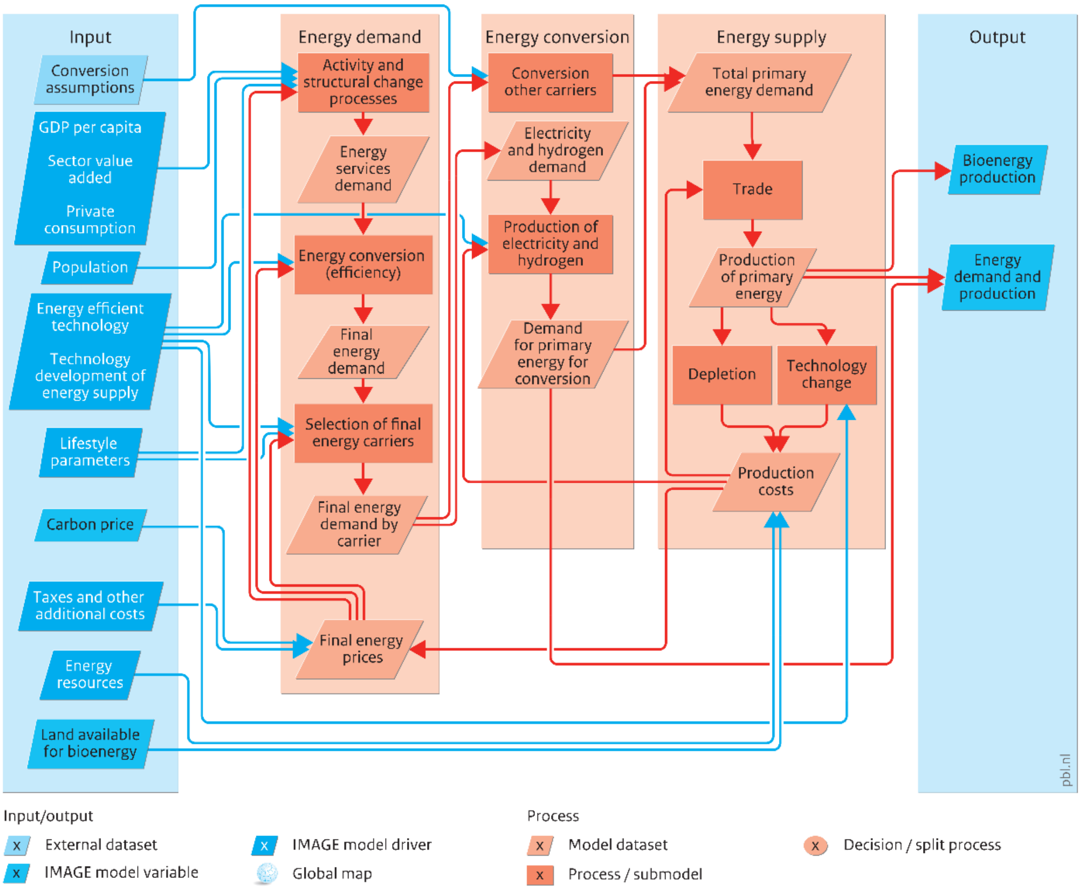
Key inputs of the model comprise population, economic development, lifestyle, policies and technical change (except in the energy sector where it is endogenous). Therefore, IMAGE is not a macroeconomic model with endogenous growth. Private consumption, capital and labour supply, and sectoral value added defined from sources and models such as from the World Bank, GTAP or sector-specific ones.

Representation of the energy system

IMAGE's TIMER module (IMage Energy Regional model) is an energy system simulation model representing 12 primary energy carriers in 26 regions, with three basic components: energy demand, conversion and supply (

Figure 0-50).

Figure 0-50 TIMER, the energy demand and supply model in IMAGE 3.0



Energy demand in TIMER is represented with more detail (residential, heavy industry and transport) or less, being more generic for some sectors (service, light industry). Energy demand in the generic representation form depends on sectoral activity, structure of the energy demand, autonomous and price-induced energy efficiency improvements, and the end-use efficiency of each energy carrier.

The residential energy demand representation uses different functions and parameters for space and water heating, cooking appliances and lighting, with price-induced energy efficiency improvements only for appliances. Heavy industry energy demand is calculated for cement and steel making, with the representation of different technologies and their adoption, whose selection constitutes the price-induced efficiency improvements. Finally, transport energy demand is separated between passenger and freight, considering modes of transport and for the passenger transport the money and time budgets. For both transport sectors, price-induced energy efficiency is driven by selection between transport modes.

TIMER details the energy conversion to electricity and hydrogen more than other carriers. The model first defines the capacity investments in each carrier, and then the operational strategy. TIMER includes wind, solar, nuclear and 20 types of fossil and bioenergy power plants, plus 11 types of hydrogen production technologies. Investment decisions consider capital, O&M fuel and other costs (e.g. CO_2 storage) and only hydropower investments exogenously defined. For wind and solar PV, electricity curtailment, backup capacity and spinning reserve constitute the additional costs. The operational strategy first determines the dispatch of PV, wind and hydro, then peak load and finally base load.

Energy supply in TIMER highlights the dynamics of resource depletion, trade and technical change (the latter is described in the next section). Depletion depends on either cumulative production (for exhaustible resources) or annual production (for renewables) with a supply cost curve to represent increasing costs.

Representation of innovation aspects

TIMER uses learning curves for the capital output ratio of coal, oil and gas supply and for the investment cost of wind, solar PV, bioenergy, nuclear and hydrogen technologies, as well as for the rate of decline for the energy conservation cost curves (i.e. learning for energy efficiency). Hence, costs for all energy technologies are determined in the supply module of TIMER rather than in the conversion module.

Following the literature, learning rates for renewables are set higher than for other technologies. The global installed capacities are considered, with the option to isolate certain regions depending on scenario, in which case learning for that region would progress more slowly.

Endogenous energy efficiency improvements occur either through learning or through technology selection. Learning determines the decline in energy conservation cost curves, which affects energy demand for the sectors with a generic representation (service, light industry) through price-induced increases in energy efficiency. Price-induced energy efficiency improvements in the sectors with a detailed demand representation occurs through the selection of competing technologies, e.g. in heavy industry or passenger transport.

Relationship between the energy system with growth

The energy sector is modelled in a separate module in the IMAGE model, with some channels of interaction between the economy and the energy sector as described next.

Energy resource endowments: Depletion of fossil or renewable resources leads to decreasing economies of scale in the model. Based on exogenous economic output as is the case of IMAGE, this would increase the size of the energy sector to the detriment of non-energy sectors.

Innovation in energy technologies: the depletion of fossil or renewable resources is compensated (partially or entirely) by learning curves for fossil, renewable, nuclear and hydrogen technologies, as well as by energy efficiency. As the learning rates for renewables are higher than conventional resources, these may naturally develop a higher participation in energy supply for higher (exogenous) growth rates.

Main interaction mechanisms between energy and growth: As indicated, in IMAGE, GDP per capita is set exogenously based on World Bank projections. Therefore, in the model, growth impacts the energy system, rather than the other way. Potential decoupling between energy consumption and economic growth is possible due to price-induced energy efficiency and structural change in the energy supply, while substitution of fossil energy sources with renewable ones may further contribute to decoupling growth from emissions.

The capital supply does not affect the deployment of the different energy technologies, and thus there is no crowding-out due to increasing capital costs. Nonetheless, as IMAGE places a focus on the dynamics of recursive investment and operation of energy supply assets, high-marginal cost assets such as combined cycle gas turbines or plants with CCS technology may be underutilized.

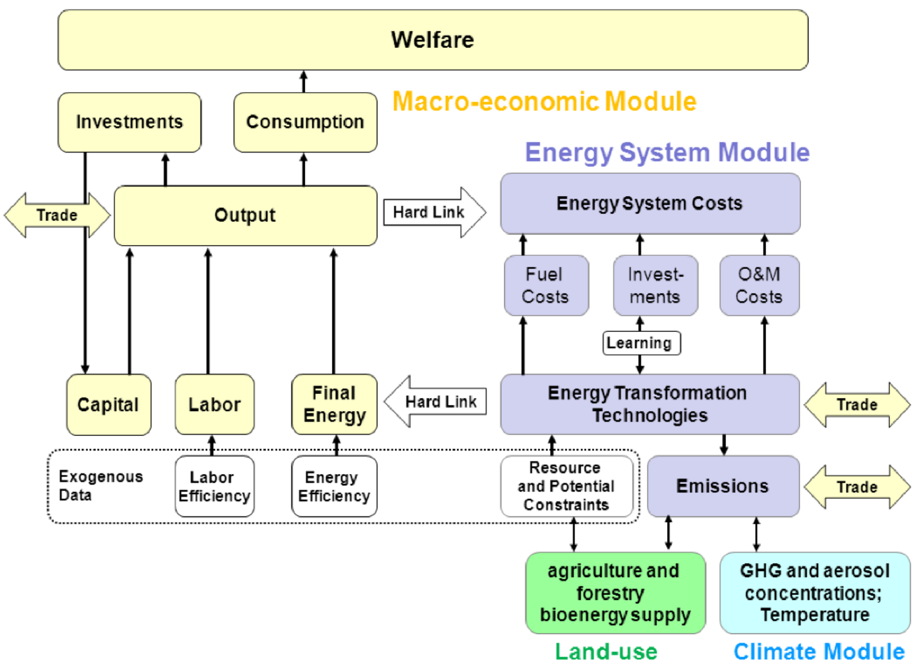
8.8. Integrated assessment model: REMIND

Model Name	**REMIND**
Model extensive name	Regional Model of Investments and Development
Main developer	Potsdam Institute for Climate Impact Research
Modelling paradigm	Ramsey optimal growth
Geographical coverage	Global
Geographical resolution	11 regions: EU, China, India, Japan, United States of America, Russia, Latin America, sub-Saharan Africa without South Africa, Middle East/North Africa/Central Asia, other Asia, Rest of the World
Temporal coverage	2005-2100
Temporal resolution	5/10/20 years
Represented innovation aspects	**Learning by doing**: Learning-by-doing **Decreasing returns**: Fast deployment mark-up costs
Link	https://www.pik-potsdam.de/research/transformation-pathways/models/remind/remind
Documentation	https://www.iamcdocumentation.eu/index.php/Model_Documentation_-_REMIND

Brief model description

REMIND is an integrated assessment model with a Ramsey-type optimal growth macroeconomic module with intertemporal welfare maximization, as well as energy system, land use and climate modules as presented in Figure 0-46. Welfare may be maximized either at the global level (Pareto optimal solution with internalization of all regional externalities), or at the regional level (Nash equilibrium without interregional internalization).

Figure 0-51 Overview of REMIND



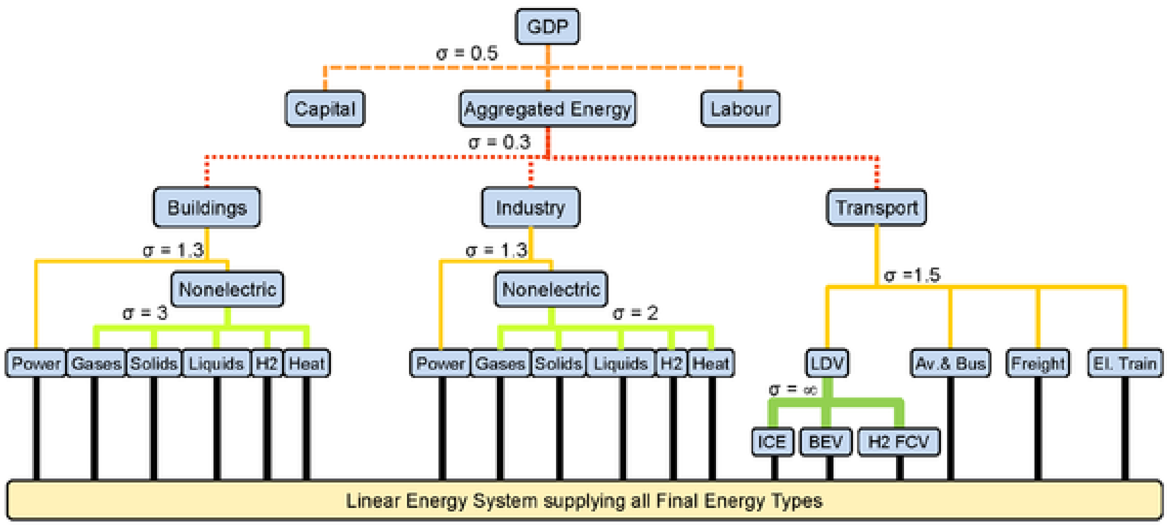
In the macroeconomic module of REMIND each region is modelled as a representative household with an intertemporal utility based on the discounted per-capita consumption. As shown in Figure 0-52 regional production uses a nested CES function with three inputs at 1st level: capital, labour and energy (only the latter being disaggregated and described below), with low elasticity of substitution (σ = 0.5). A macroeconomic budget constraint guarantees the balance of production, imports, exports, consumption, investments and energy expenditures.

REMIND allows for the trade of the economy composite good, primary energy carriers as well as emission permits, in a common global market subject to product-specific trade costs. REMIND also allows for discounted intertemporal trade of goods within a region while total trade across time and regions must be balanced, leading to interregional and intertemporal equilibrium.

Representation of the energy system

Energy is the only production factor to be disaggregated as show in Figure 0-52. Economic activity determines demand via the production function; energy system costs (investments, fuel costs, operation and maintenance) are included in macro-economic budget constraint. Interregional and intertemporal trade is allowed for coal, gas, oil, biomass, uranium and emission permits. Trade of renewables and secondary carriers is not allowed, although the model supports bilateral electricity trade as an additional feature.

Figure 0-52 Production structure of REMIND 1.7



Technology choice in the energy system is modelled via linear substitution between competing technologies for secondary energy production, with supply curves for exhaustible resources (cumulative extraction cost curves) as well as renewables (differentiated by capacity factors). The biomass potential is separated into three feedstocks and may be coupled with the land use model. The non-biomass renewable energy resource potential is differentiated per region and max available production at different capacity factors.

The energy system module optimizes energy supply for all final energy types given investment, fixed and variable O&M, fuel and emission costs. Over 50 conversion technologies are available for 6 secondary energy carriers (electricity, gases, liquids, hydrogen, solids and heat), with full substitutability of technologies supplying any given final energy type. Only power-to-hydrogen and the reverse technology convert between secondary energy carriers. Technology parameters include data for all cost types, conversion efficiency, capacity factor, technical lifetime and learning-by-doing (detailed below).

Variable renewables require a tailored mix of short- to long-term storage technologies, with an increasing market share for a technology demanding higher storage needs due to rising balancing challenges. Grid requirements follow a similar approach to storage, increasing with higher market shares for a grid technology. Grid and storage needs are regionalized and thus lower for regions with high potential for a certain technology.

Representation of innovation aspects

REMIND's energy system module includes learning rates of investment costs for wind (12%), solar PV (20%), solar CSP (9%) battery and fuel cell electric vehicles (10%), and storage for variable renewables (10%). These learning rates are reduced as installed capacity grows for costs to converge asymptotically to cost floors, and the model may internalize interregional spillovers or not depending, on the cooperation between regions – that is, regions may benefit entirely or only partially of innovation in other regions. Energy efficiency improvements are determined exogenously by calibration to the baseline final energy trajectories. Additional efficiency improvements induced by policy are represented via substitution of aggregate energy with additional capital on the top level of the CES production function.

Furthermore, the model represents conversion technology vintages and uses capacity stocks for full vintage tracking. Cost mark-ups for fast growing technologies are implemented to provide a more realistic rate of deployment, and early retirements of technologies that are not competitive anymore are allowed (at a maximum rate of 4% per year).

Given the intertemporal optimization, REMIND considers cost reductions and adoption rates achievable through the learning rates and capacity stock constraints from the beginning of the simulation period.

Relationship between the energy system with growth

The energy sector is modelled separately from the rest of the economy in the REMIND model, with multiple channels of interaction as described next.

Energy as a production factor: At the highest level, the CES production function *Y = CES(aggregated energy, capital, labour)* of REMIND allows for limited substitution between energy and the other inputs. In the 2nd-level function *aggregated energy = CES(buildings, industry, transport)*, substitutability between these energy-consuming sectors is even lower. In contrast, within each of these three sectors there is much more flexibility in the substitution between electric and non-electric energy inputs.

Innovation in energy technologies: Within the energy systems module, the exogenous energy efficiency improvements and the endogenous learning for specific technologies will positively impact growth. However, the flexibility needs due to the deployment of renewable energy technologies and cost mark-ups for fast growing technologies have a negative impact on their cost, and hence the economy. The effects of interregional spillovers modelled in REMIND are limited, so regions may retain the benefits of their investment in energy technologies, in the case of non-cooperation.

Factors impacting gross output: gross output is reduced due to climate damages as represented by a multiplying damage factor, as well other factors including the energy system costs. As the energy system is a major emitter, the deployment of low-carbon energy technologies and energy efficiency improvements will reduce climate damages and positively impact growth.

Energy resource endowments: Increasing exploitation of energy resources leads to rising costs in REMIND given the regional extraction cost curves for fossil fuels and uranium, and the renewable energy potentials graded by capacity factor. Moreover, biomass availability is gradually restricted, especially for first-generation and lignocellulosic bioenergy technologies.

Main interaction mechanisms between energy and growth: In REMIND, some decoupling of the economy from energy consumption is possible, while decoupling from emissions is more readily achievable, through energy efficiency (exogenous) and technological learning for renewable electricity sources, electric vehicles and electricity storage, which increases their competitiveness vis-à-vis fossil energy-based technologies. However, the benefits of lower investment costs for renewable energy can be partially affected by lower capacity factors as deployment increases. In the case that interregional spillovers are modelled, their effect is limited, so that economies will benefit most from cost reductions driven by their investments in energy technologies. As financial markets are not modelled, there is no crowding-out possible between different energy technologies. However, underutilization and even decommissioning of energy assets is possible.

8.9. Integrated assessment model: WITCH

Model Name	***WITCH***
Model extensive name	World Induced Technical Change Hybrid
Main developer	RFF-CMCC European Institute on Economics and the Environment (EIEE) Fondazione Eni Enrico Mattei Centro Euro-Mediterraneo sui Cambiamenti Climatici
Modelling paradigm	Optimal growth
Geographical coverage	Global
Geographical resolution	13 regions
Temporal coverage	2005-2150
Temporal resolution	5 years
Represented innovation channels	**Increasing returns:** learning curves with knowledge stock and installed capacity **Learning-by-researching**: knowledge stock accruing from R&D investments **Decreasing returns:** Fast deployment cost mark-ups **Knowledge diffusion:** R&D spillovers **Human capital**: absorptive capacity
Link	https://www.witchmodel.org
Documentation	https://www.witchmodel.org/documentation/

Brief model description

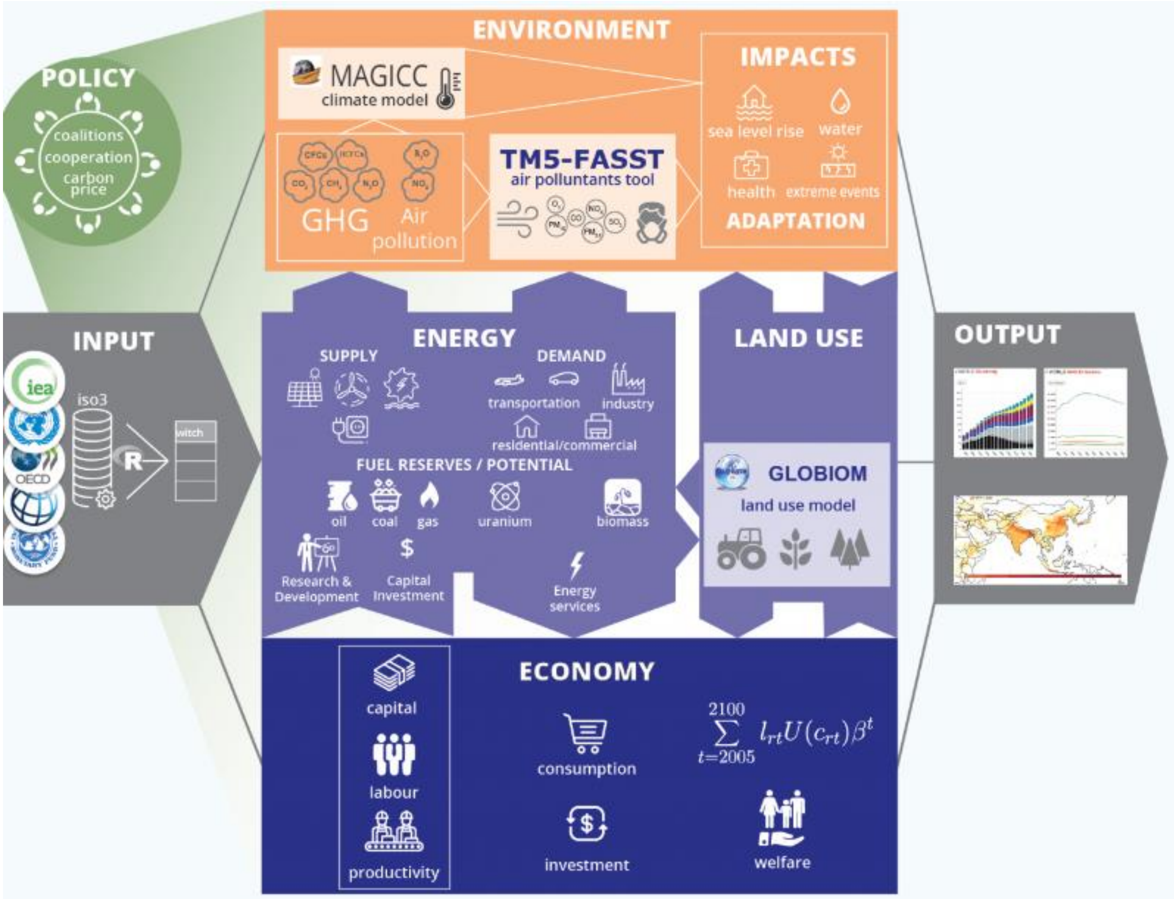
WITCH is an integrated assessment model based on inter-temporal growth optimization which captures the long term economic growth dynamics and the impact of climate change on output. A compact representation of the energy sector is fully integrated with the rest of the economy such that energy investments and resources are optimized, along with the other macroeconomic variables.

In WITCH each of the 13 regions *a priori* solve their respective optimization program by default, although any set of cooperating regions can be modelled as a coalition. Each region or coalition adopts an optimal mitigation and adaptation strategy (which maximizes the total welfare of its members) in light of externally set constraints on emissions, concentrations or temperature. A distinctive feature of WITCH is the ability to assess the optimal response to climate policies with all degrees of cooperation by appropriately defining the coalition structure. Two special cases of coalitions are predefined (but others can be modelled):

- **No cooperation:** each region maximises its welfare (default setting);
- **Full cooperation:** a grand coalition containing all world regions.

In full cooperation all externalities are internalized and therefore it can be seen as a first-best solution. The Nash equilibrium (no cooperation) instead can be seen as a second-best solution. Regional/coalition strategies are based on investment profiles that are developed based on a maximization process where the welfare of each region is chosen strategically and simultaneously accordingly to other regions. The regions interact through the greenhouse gas emissions, the dependence on exhaustible natural resources, the trade of oil and carbon permits, and technological R&D spillovers.

Figure 0-53 Overall representation of the WITCH model



Representation of the energy system

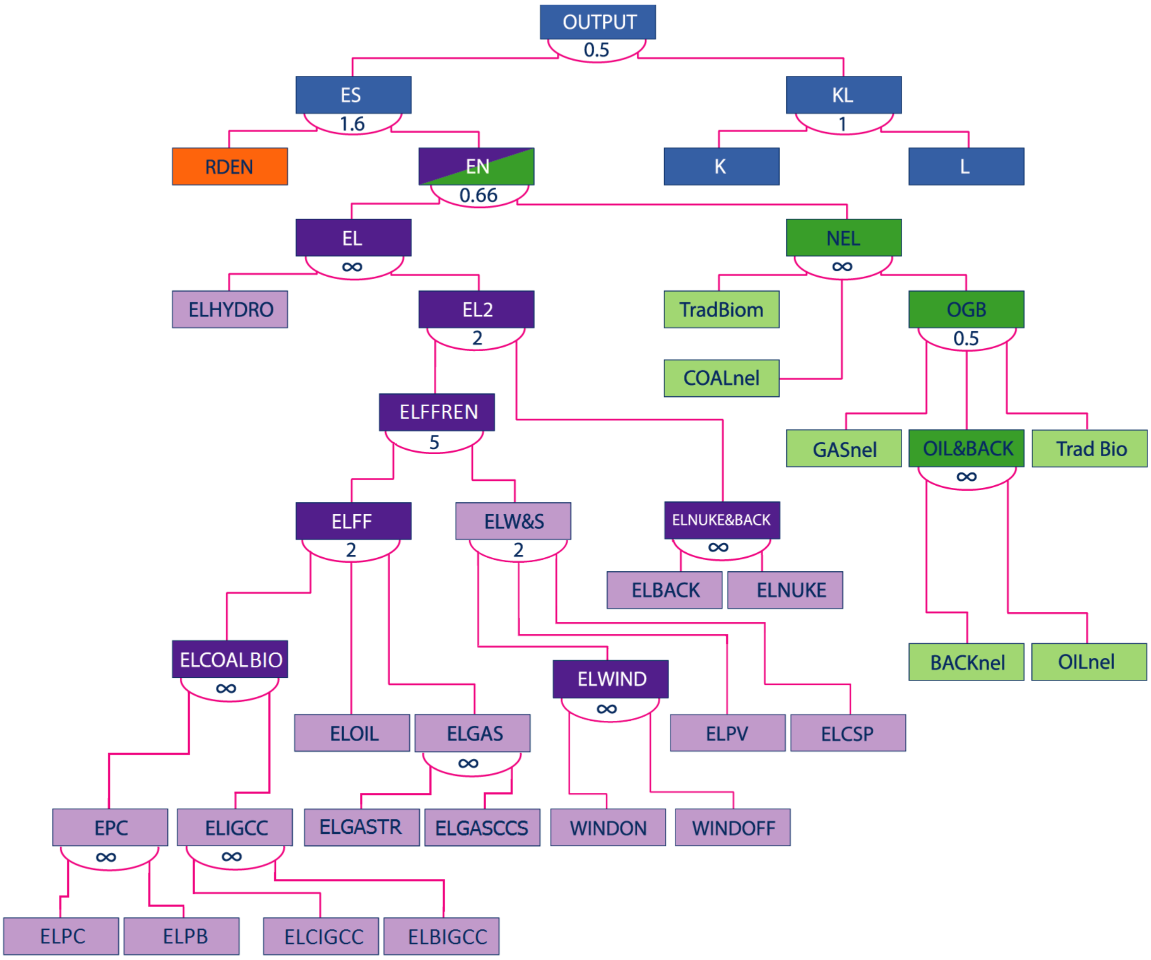
The energy sector is described by a production function that aggregates different factors at various levels and with associated elasticities of substitution. Figure 0-54 shows the constant elasticity of substitution (CES) production function of WITCH, where the first level separates between the electricity and non-electricity input factors. For each technology, the main features are the yearly utilisation factors, fuel efficiencies, investment and operation & maintenance costs, and capital depreciation.

Electricity technology comprise both fossil fuel-based (natural gas combined cycle, integrated gasification combined cycle with Carbon Capture and Storage, fuel oil and pulverised coal) and carbon-neutral ones (hydropower, nuclear, solar and wind), including two backstop technologies. These backstop technologies represent incipient technologies which are not yet in the commercialization stage. The cost of electricity generation is endogenous and combines capital costs, O&M expenditure, and the costs for fuels, as well as waste management costs for nuclear. Capital accumulation for solar, wind and the backstop technologies lead to cost reductions implemented through learning curves as described below.

Several power system integration aspects are considered in WITCH. The model implements a simple flexibility constraint rule requiring a minimum power system flexibility given supply technologies which require flexibility (e.g. wind, solar) and others which provide flexibility (such as combined cycle gas, hydro and storage). Additionally, a capacity constraint is implemented where firm capacity is required to be 1.5-2 times higher than the yearly average load (varying per region), with the firm capacity of variable technologies being reduced. Finally, investments in the electrical grid are considered through a required grid capital, adjusted for wind and solar far from shore or load centres as well as for the integration of variable renewables in general.

Energy consumption in the non-electric sector is based on traditional fuels (traditional biomass, oil, gas and coal) and bio-fuels. This sector comprises transportation, industrial, and residential and commercial energy use.

Figure 0-54 CES Production Function of WITCH



Representation of innovation channels

One of the main features of the WITCH model is the characterisation of endogenous technical change. Both innovation and diffusion are modelled. Dedicated R&D investments in the energy efficiency sector are distinguished from investments in innovation of low carbon technologies in both the electric and non-electric sectors (batteries and the two backstop technologies).

The stock of accumulated knowledge has a positive impact on returns to investment in R&D of the two backstop technologies, batteries and energy efficiency. The stocks of knowledge are defined for two backstop technologies, and overall energy efficiency improvements. At each point in time, a Cobb-Douglas function per technology perpetuates the stock of knowledge added by a supplement dependent on the domestic innovation efforts and on the international spillovers. The spillovers are modelled based on the absorptive capacity of a region (as represented by the stock of knowledge) and its distance from the technology frontier.

For the two backstop technologies, batteries and energy efficiency the model incorporates two-factor learning curves: investment costs decrease as a result of the accumulation of knowledge (learning-by-researching) and experience (learning-by-doing). In the model, the first is equivalent to the stock of knowledge, and experience is proxied by the global, cumulative installed capacity for the technology. In addition to the two-factor learning curves, one-factor learning curves are also used to describe the cost evolution of solar (PV and CSP) and wind (onshore and offshore) technologies. Here, investment costs decrease according to the progressive technology deployment (global cumulative capacity), without considering the stock of knowledge.

Relationship between the energy system with growth

The energy sector is integrated within the rest of the economy in the WITCH model, with multiple channels of interaction as described next.

Energy services as a production factor: energy is an important input factor determining the gross output GY. As discussed, a CES function $GY = CES(ES, KL)$ represents the optimal combination of energy services with capital and labour, with a 0.5 elasticity of substitution between energy services and the capital and labour bundle, limiting the potential decoupling of production from the consumption of energy services.

The energy services bundle in turn has as input the energy efficiency stock of knowledge and energy products, that is $ES = CES(RDEN, EN)$. WITCH allows for R&D in energy efficiency to increase the energy efficiency knowledge, substituting energy consumption as an input to the energy services production function, as they are relatively complementary (substitution elasticity of 1.6). The energy efficiency stock of knowledge is affected by both domestic R&D investments and spillovers of foreign stock of knowledge. This substitutability of energy efficiency knowledge and energy consumption is calibrated exogenously in order to match expected energy intensity improvement pathways.

Energy resource endowments: the economy may grow through the extraction of oil, coal and gas resources which may be traded globally and provide the main components for the non-electricity energy input in the nested production function. Fossil fuel extraction requires investments in extraction capacity in each region.

Factors impacting gross output: gross output GY is reduced due to the net effect of benefits and damages (Ω) of climate change (global warming represented by temperature T increases). Negative impacts are mitigated by adaptation actions ADA, leading to the net output form of $Y = GY/\Omega(T,ADA)$. Temperature increases are caused due to increased carbon stock from emissions arising from the consumption of fossil fuels. Then, this reduced gross output is further impacted by costs related to the energy system: the costs of consumption of fossil fuels, and the costs of mitigation actions to address climate change.

Moreover, various costs are subtracted from the net output Y to determine final consumption $C = Y - C_{ener} - C_{clim}$. Energy-related costs C_{ener} comprise investments, O&M and R&D in energy technologies, investments in the extraction sector, fossil fuel costs in the extraction and other sectors, and electricity network investments. The cost of climate action C_{clim} includes net costs of mitigation (carbon tax, permits, CCS, deforestation actions) and adaptation.

Main interaction mechanisms between energy and growth: Therefore, in WITCH the economy is supply-driven, with consumption being defined by the gross output, adjusted for the climate impacts and energy-related and climate action costs. The energy efficiency stock of knowledge allows to reduce energy inputs in the production function, and regional economies may develop a lead in energy efficiency, although international energy efficiency knowledge spillovers occur. Moreover, substitution between energy services on the one hand and capital and labour on the other is limited. Investments may enable increased fossil fuel production capacity or increased energy efficiency. Regions may increase output by increased production and trade in fossil fuels, but emissions from fossil fuel consumption affect gross output due to both the impacts of global warming and the costs for climate action. Due to the supply-driven economy, crowding-out will occur between the necessary investments and other costs of energy supply technologies, energy efficiency R&D, fossil fuel extraction and climate action.

9. Annex C: Review of energy transition scenarios

9.1. Scenario: Complementing carbon prices with technology policies

	Complementing carbon prices with technology policies
Organization	Potsdam Institute for Climate Impact Research
Publication	Bertram, C. et al., 2015. Complementing carbon prices with technology policies. Nature Climate Change 5.
Focus	Energy system, energy technologies, policies
Scenario model	REMIND
Number of scenarios	24 scenarios (combinations of 4 carbon pricing and 4 technology dimensions)
Time horizon	2010-2100 (5-year time steps)
Geographical coverage	Global: 11 regions
Sectoral coverage	Single macroeconomic sector (generic consumption good) Detailed energy sector
Energy technologies	More than 70 technologies for energy conversion and distribution
Innovation aspects	**Learning effects**: learning-by-doing **Decreasing returns:** diseconomies of scale by fast deployment mark-up costs
Link	https://doi.org/10.1038/nclimate2514

Brief description

The objective of the study was to understand how weaker-than-optimal carbon pricing schemes and additional technology policies interact, and which combination of carbon pricing and technology policies can best reduce the adverse effects of sub-optimal carbon pricing. The study uses exclusively REMIND, an inter-temporal general equilibrium model of the global economy with a technology rich representation of the energy supply system.

Main relevant assumptions

The macroeconomy is represented based on a Ramsey-type growth model, with a constant rate of pure time preference of 3% and an average rate of increase of global per capita incomes of 3%.

The

Figure 0-55 below provides a short description of all scenarios modelled in the study. Four scenarios focus on the policies related to carbon pricing or capping while the other four are based technology policies. The study then looks at different combinations of the pricing and technology scenarios.

Two types of climate policies are modelled either in the form of limits on greenhouse gas (GHG) emission budgets or as explicit carbon price trajectories that apply to all GHG. Carbon price trajectories under budget policies emerge endogenously from the

model, with a carbon budget of 1500 $GtCO_2$ in the 2000-2100 period. Consumer fuel taxes and subsidies are represented as pre-existing policies impacting energy use. In the default settings, subsidies are assumed to be phased out linearly until the year 2050 and taxes are constant.

Figure 0-55 Description of policy options for construction of scenarios

Table 1 | Description of medium-term policy options considered in the scenarios.

	Name	Scenario	Description
Pricing dimension:	Zero	Zero carbon price	Baseline scenarios with zero carbon price.
	Cap	Sub-optimal carbon pricing implemented as cap-and-trade system	Emission target for 2030: 60.8 $GtCO_2$ globally, in line with extrapolation of lenient interpretation of Copenhagen pledges[4,9].
	Tax	Sub-optimal carbon pricing implemented as carbon tax	Globally uniform carbon tax of US$7.3 per tonne of CO_2 in 2015, increasing at 5% p.a.
	Opt	Immediate optimal carbon pricing with respect to 2 °C target	CO_2 budget of 1,500 $GtCO_2$ for the period 2000–2100 with full flexibility on when and where emissions occur.
Technology dimension:	noT(ech)	No additional technology policy	Only the pricing determines technology choice.
	CM	Coal moratorium	Ban on construction of new freely emitting coal-based transformation capacities for electricity, liquids, gas and H_2.
	LCS	Low-carbon support	Minimum targets for global installation of different renewable electricity generation capacities (wind power, photovoltaics, concentrated solar power), CCS deployment (gas electricity and bio-liquids) and electric vehicles. Excess costs for solar and wind generation are refinanced through electricity price mark-ups to avoid rebound effects.
	C&L	Combined coal moratorium, low-carbon support, tax and subsidy reform	Combination of coal moratorium and low-carbon support plus an accelerated phase-out of final energy subsidies (until 2030 instead of 2050), plus international convergence of transport fuel taxes.

All monetary values are given in constant 2013 prices. The Methods section and the Supplementary Information contain further details on the scenario design.

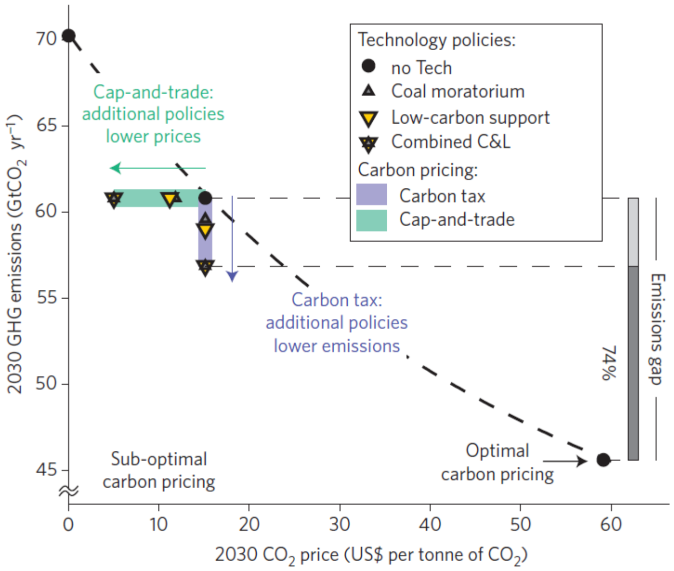
Source: Bertram et al. 2015

Main results

The main conclusion from the study is that additional technology policies help to considerably lower the socio-economic challenges associated with long- and short-term costs, carbon value and energy price increase. The results of combining different policy options with regards to GHG emission reduction by 2030 is summarized in the

Figure 0-56 below. The results show that combining sub-optimal carbon pricing with technology policies results in higher emissions (between 56 and 61 GtCO2) than under the optimal carbon price ($60) policy scenario (around 45 GtCO2). This results can be compared with Acemoglu et al. (2012) which concludes on the efficiency of market-based incentives, and the agent-based analysis of Lamperti et al. (2019) which in contrast highlight these same market-based policies suffer from path dependence and exhibit limited windows of opportunity.

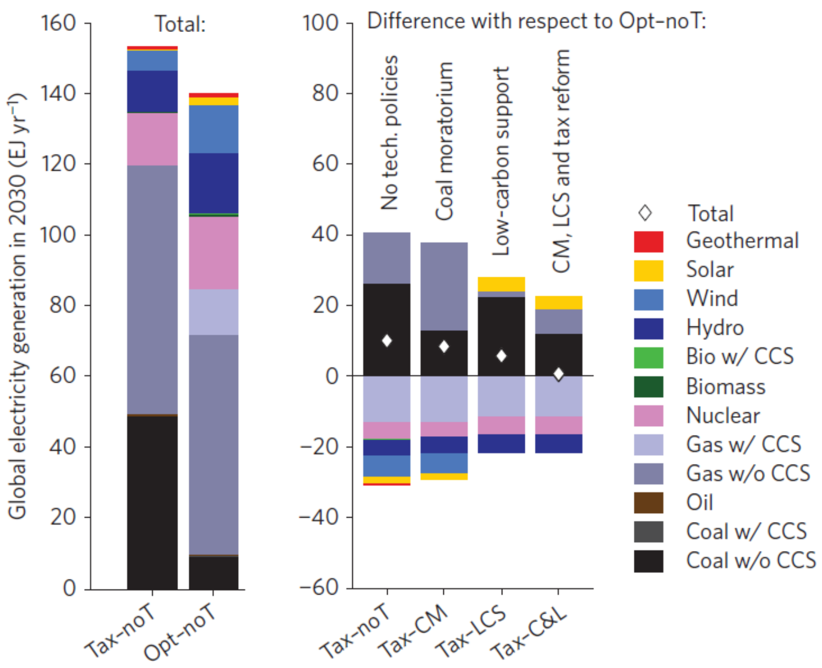
Figure 0-56 Results as a function of carbon prices and total GHG emissions in 2030



Source: Bertram et al. 2015

Under the optimal carbon pricing scenario, the energy mix in power supply shows that decarbonization of the power supply is well underway by 2030. The results also show that the technology policies bring the electricity generation system closer to the optimal configuration with respect to the technology mix and to the overall electricity output. Overall, 2nd best carbon pricing and technology policies approximately halve the cost to achieving the 2 ^{O}C target, from an additional 0.4% to 0.2% to the optimal baseline costs.

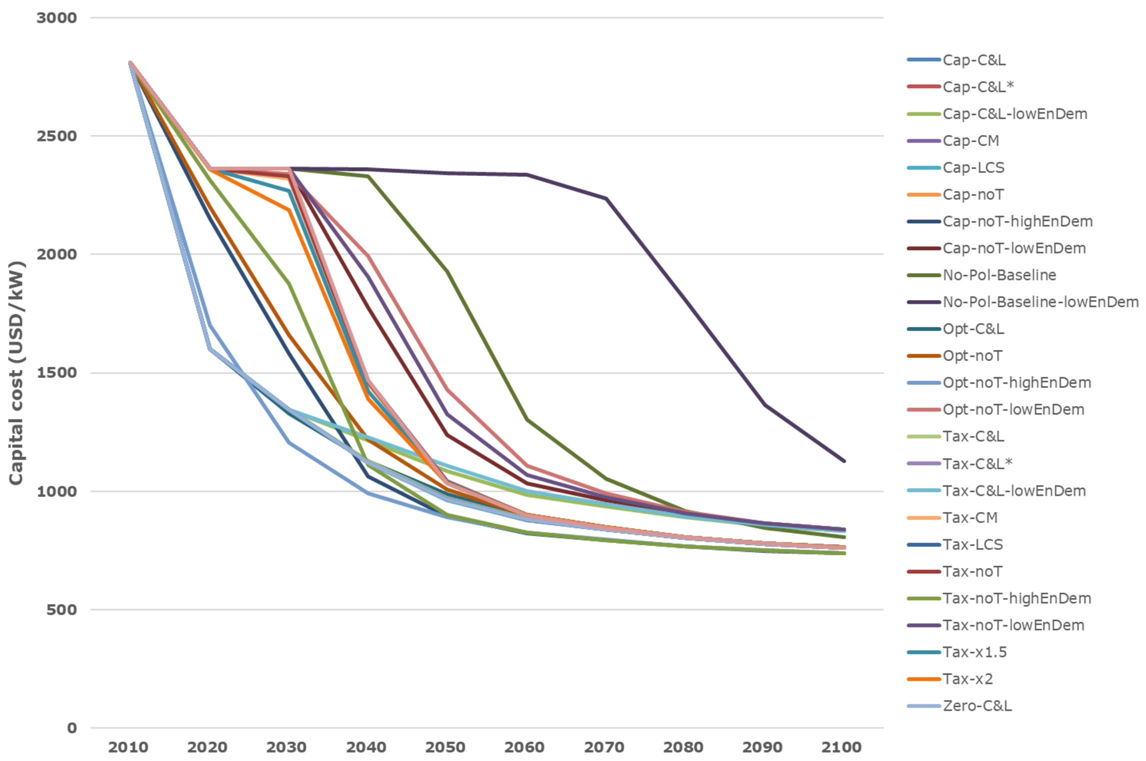
Figure 0-57 Results of global generation by technology by 2030



On the right the differences between the benchmark optimal pricing scenario and different technology scenarios is shown. Source: Bertram et al. 2015

Figure 0-58 shows the evolution of the capital cost of solar PV for the different study scenarios. Here the costs reductions driven by learning-by-doing lead to up to around 6% difference in the capital cost in 2100 for the central energy demand scenarios, due to the different capacity deployments between the scenarios. This interacts with a more than doubling of the installed solar PV capacity between the no policy baseline scenario and the scenario with the most installed capacity (80 versus 38 GW). Moreover, it is possible for certain scenarios to surpass or lag behind others regarding solar PV costs, due to the interaction with other dynamics of the economy or the energy system.

Figure 0-58 Capital cost of new solar PV cells for different REMIND scenarios, 2010-2100



Source: Own elaboration based on Bertram et al. 2015

Main impacts of the representation of energy and innovation on growth

- As REMIND represents the economy through a single sector, the energy sector cannot contribute by being an economic activity in itself.
- Remind provides energy as an input to the production function of the economy composite good, and thus reductions in the cost of energy supply impact economic growth.

- The deployment of low-carbon energy technologies eases emission constraints, decreasing the carbon price and increasing economic output.
- Learning effects reduces the cost of energy supply, including for low-carbon energy technologies, thus increasing output through lower energy inputs and relaxation of emission constraints

9.2. Scenario: Energy efficiency policies and the timing of action

	Complementing carbon prices with technology policies
Organization	CIRED (International Research Center on Environment and Development)
Publication	Bibas, R., Méjean, A;, Hamdi-Cherif, M., 2015. Energy efficiency policies and the timing of action: An assessment of climate mitigation costs. Technological Forecasting & Social Change, 90.
Focus	Price-induced energy efficiency improvements
Scenario model	IMACLIM-R
Number of scenarios	8 scenarios (combining energy efficiency, technology diffusion and climate action)
Time horizon	2010-2100
Geographical coverage	Global: 12 regions
Sectoral coverage	12 sectors (5 energy, 3 transports, construction, industry, agriculture, composite)
Energy technologies	9 electricity technologies
Innovation aspects	**Learning effects**: learning-by-doing for electricity and liquid fuels **Demand pull:** price-induced energy efficiency improvements **Vintages** and constraints to vintage adoption
Link	https://doi.org/10.1016/j.techfore.2014.05.003

Brief description

The objective of this application of the IMACLIM-R is to analyse the impacts of energy efficiency policies on the costs of climate actions limiting the total greenhouse gas emissions up to 2100.

For this the scenario models focuses on endogenous price-induced energy efficiency improvements in the different productive sectors, which are partly free and partly financed by higher mark-ups on the products produced. The only model utilized for these scenarios to 2100 is IMACLIM.

Main relevant assumptions

The representation of the economy in this scenario follows the usual representation of IMACLIM-R with 12 regions and 12 economic sectors. Total emissions to 2100 are capped at 2400 $GtCO_2$. Macroeconomic inputs for the scenarios following the AMPERE project protocol as detailed in Kriegler (2015). The USA is the overall technology leader with a medium TFP growth of 0.8% per year in the long run, while most other regions reach TFPs of 80% or more of the frontier. The assumed global average growth rate is of 2.7% per year in the period. The energy policies of the AMPERE baseline scenario were translated to the IMACLIM model representing an average reduction of the emission intensity after 2020. The final energy consumption for the EU27 peaks at around 21 000 TWh by 2050, decreasing to around 12 500 TWh by 2100. Wind capital costs stabilize after 2020 at slightly above 1450 USD/kWh, while solar PV strong decreases from 7500 in 2020 to 3500 USD/kWh in 2100 (AMPERE, 2014). The main innovation channel of the model is the price-induced energy efficiency improvement which is the focus of the analysed scenarios. Additionally, the model represents learning-by-doing for electricity generation and transportation, and technology vintages as detailed in section X. Retrofitting of existing vintages is limited, for example in some retrofitting of energy efficiency vintages, are induced by price.

Main results

Overall, the model indicates decarbonization policies will result in a GDP loss of -4.4 to 7.0% by 2100 compared to the baseline, using a 4% discount rate. The energy intensity of the economy is reduced by two-thirds in all scenarios, and this results in a halving in energy expenditures for the high efficiency scenario.

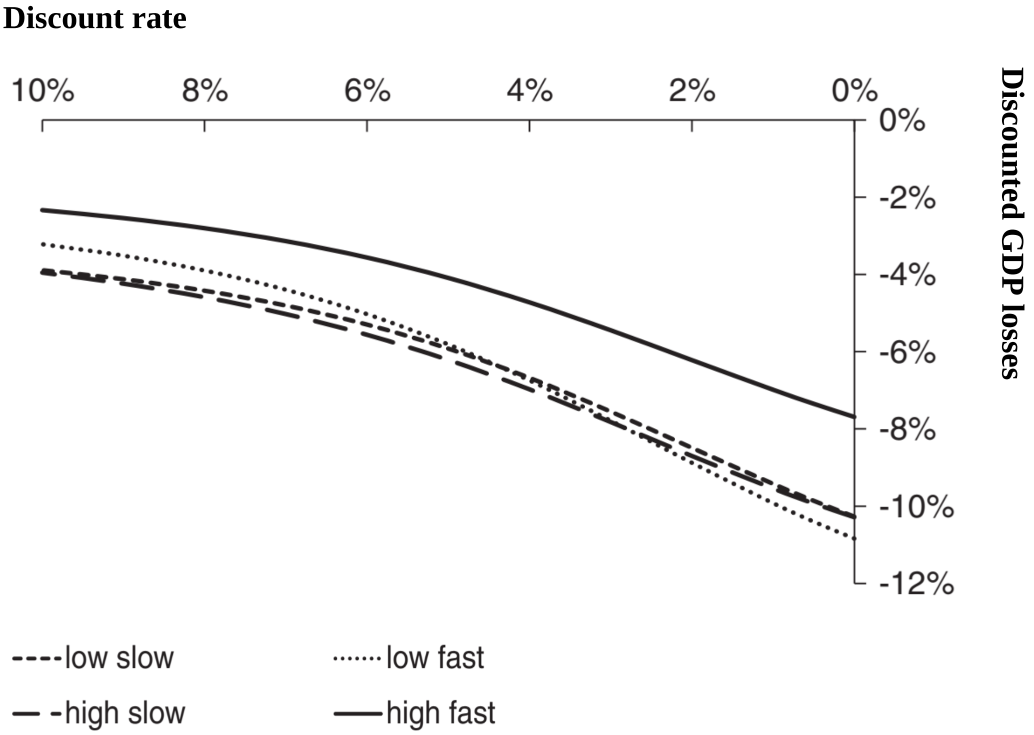
The analysis of the results focuses on the impact of three dimensions:

- **Price-induced energy efficiency improvements** by firms, with either low or high improvements;
- **Diffusion speed** of energy efficiency technologies from the lead to follower regions, with either fast or slow diffusion;
- **Timing of climate action** considering a common emission ceiling, with either early or late action.

The combination of these dimensions leads to 8 scenarios. Due to the constraint in emissions and the general equilibrium macroeconomic nature of IMACLIM-R, the model results in discounted GDP losses for all decarbonization scenarios. High energy efficiency leads to important decreases on the energy intensity of the productive sectors, which in turn reduces the emission constraints on households and transport. Overall, high efficiencies lead to a slight increase in the investment average growth rate (0.1%), due to increased household revenues, output of the productive industries as well as the higher mark-up of these industries required to finance the energy efficiency investments.

Figure 0-59 relates the GDP losses to the discount rate for late climate action, when most of the emission reduction efforts take place after 2040. It is evident that lower discount rates increased the losses due to greater importance of future GDP loss. Furthermore, the model results indicate only one dominant scenario to limit GDP losses due to decarbonization policies: the combination of high price-induced energy efficiency improvements in the lead region with fast diffusion of the energy efficiency technologies to the follower regions. The minimum GDP increase to the other scenarios is between 2.0-2.3% for late climate action and 1.7-2.1% for early climate action, at a 4% discount rate. On the other hand, high energy efficiency improvements by the lead region are ineffective if not accompanied by diffusion to regions with worse energy efficiency.

Figure 0-59 IMACLIM discounted GDP losses for late climate action according to the discount rate



Source: Ribas, R., Méjean, A., Hamdi-Cherif, M., 2015. Energy efficiency policies and the timing of action: An assessment of climate mitigation costs.

Main impacts of the representation of energy and innovation on growth

- As IMACLIM-R represents 5 energy sectors, energy is represented as an economic activity and affects overall output directly.
- Energy is a factor of production in other economic sectors, with energy prices affecting sectoral output. High energy efficiency reduce energy expenditures of industry by more than 3 trillion USD in 2100, reducing the share of energy in total production costs by more than 30% and increasing industrial output by 2-8%.
- Endogenous high energy efficiency improvements lead to up to 2.3% reduction in GDP losses due to climate policies, unambiguously when coupled with fast diffusion to follower regions.
- Energy efficiency improvements lead to marginally higher investment growth rates through households and firm decisions.
- Slow technology diffusion can paradoxically lead to lower GDP losses than with fast diffusion in the case of low energy efficiency improvements and late climate action. This occurs because then low energy efficiency translates into higher carbon prices which drive global adjustments in the transportation and household sectors;
- Generally, the diffusion speed determines the energy intensity in the mid-term, while the energy efficiency improvements of the leader determine the long-term energy intensity.

9.3. Scenario: Accelerating green technology Diffusion

Green Technology Diffusion	
Organization	Bielefeld University
Publication	Hötte (2019) How to accelerate green technology diffusion? An agent-based approach to directed technical change with coevolving absorptive capacity. Universität Bielefeld Working Papers in Economics and Management; 01-2019.
Focus	Diffusion of low-carbon technologies
Scenario model	Eurace@Unibi
Number of scenarios	3 scenarios
Time horizon	N/A
Geographical coverage	Regions in closed economy
Sectoral coverage	Fossil fuel-based power sector Renewable energy sector
Energy technologies	Renewable Energy technologies (generic)
Innovation aspects	**Incremental and radical innovations** **Learning effects:** learning-by-doing and learning-by-searching **Path dependence** **Human capital** and absorptive capacity **Diffusion**
Link	http://www.wiwi.uni-bielefeld.de/lehrbereiche/vwl/etace/Eurace_Unibi/

Brief description

The objectives of the study are to understand how to accelerate the diffusion of climate friendly (green) technologies, and to understand the determinants of diffusion, learning and the coevolution of innovation and heterogeneous absorptive capacity. All scenarios have been generated using solely the Eurace@Unibi model.

To understand the process of innovation diffusion the model focuses on the competition between two types of technologies: green (innovative) and brown (conventional/incumbent). The green technology represents eco-innovation and is understood as any type of innovation across the whole economic system that is environmentally more benign than the incumbent technology. In the model, innovations overcome resource scarcity. The green technology is environmentally neutral and allows adopters to reduce material input costs. Thus, in the long run, the green option is technologically superior.

Main relevant assumptions

As it uses a maquette model, the study does not provide macroeconomic assumptions which can be compared to real-world economies. The representation of the energy system is also simplified, as there are only producers of conventional and green technologies. One important input parameter to the simulations is the exogenous productivity progress parameter of 0.04.

Main results

The study analyses three scenarios:

- Baseline scenario
- Barriers to diffusion scenario

- Policy scenario

In these, green technology is able to penetrate the market based on positive feedback loops from market-induced innovation dynamics and learning-by-doing. Two type of policies are modelled: a) environmental taxes and b) subsidies.

In the **baseline scenario** the entry barriers for green technology is set sufficiently low such that it can outperform the conventional technology, in order to analyse the relationship between path dependence in technological learning and technological superiority. The results indicate that:

Endogenous technical change shifts the technological frontier upwards and dominates the price dynamics of adaptive pricing in response to market demand;

Initial adoption rates of green technology are high, likely due to the lower effective using costs. Nonetheless, in around half of the considered cases the initial diffusion reverses after some time and the share converges to a technological state with roughly 100% utilization of conventional capital;

Divergence between green and conventional technological regimes is reflected in technology utilization, capital prices, skills and technological development. The endogenous nature of technological innovation seems to be an important factor that governs the process of divergence of the two technological regimes;

The results point out to learning effects; in the early phase of technology diffusion (around 10 years) aggregate output is significantly lower. Market clearing at the end of the transition time occurs only in the case of a technological regime shift, but not when the conventional technology remains dominant.

In the **barriers to diffusion scenario** the diffusion barriers are higher compared to the baseline scenario. The results indicate that:

- The supply-side barrier points to a stronger association with the transition dynamics than the demand-sided barrier;
- Age, price and unit costs are positively associated with technological lock-ins. Firms with more productive capital stock are less likely to be early adopters;
- Symmetric barriers are less inhibiting than asymmetric ones, i.e. the combination of skills and physical capital is more decisive than either of these components in isolation.

In the **policy scenario** addressing barriers to diffusion, incentives for green technologies are set. An environmental tax is imposed as a Value Added Tax (VAT) on material inputs. Since brown technologies are less efficient than green ones this makes the use of conventional capital relatively more costly. An investment subsidy reduces the price of green capital goods. The government can also pay a green consumption price support for producing CG in an environmental way. This subsidy is directly paid to firms and is proportional to the share of green capital used in the production.

The two types of subsidies reflect the difference between static and dynamic aspects of technological superiority. The investment subsidy decreases the price for green capital goods immediately and all green technology adopters benefit homogeneously. The price support for green consumption goods, in contrast, relates to the dynamic aspect of technological barriers. In this case, the extent to which firms will benefit depends on the relative extent to which they use green capital, which has a more permanent effect dependent on the vintage structure of the capital stock.

The results of the policy scenario indicate that policies should be tailored based on the type of barriers preventing diffusion:

- Taxes help overcoming disadvantages related to the productivity of the green technologies;
- Subsidies help overcoming barriers related to non-tradable capabilities at the firm level that are needed for the effective utilization of the green technologies;
- If barriers are only a question of lacking experience of adopters in green technology, they can prevent the diffusion of green technology if they undermine the firms' financial capacity to invest.

Main impacts of the representation of energy and innovation on growth

- Conventional and green capital good firms compose an economic sector, thus affecting growth by explicit representation of energy as an economic activity
- Performance and price of energy capital goods affect the productivity of conventional goods
- Human capital is represented through worker skills in conventional and green capital goods, affecting the absorptive capacity of firms
- Endogenous innovation and diffusion of capital goods lead to path dependence where green technologies may be eliminated from the economic system
- Economic output in the phase of introduction of a new technology can be negatively impacted
- Although simplified environmental impacts are calculated they are not fed into the model, thus not differentiating conventional and green technologies from this perspective

GETTING IN TOUCH WITH THE EU

In person

All over the European Union there are hundreds of Europe Direct information centres. You can find the address of the centre nearest you at: https://europa.eu/european-union/contact_en

On the phone or by email

Europe Direct is a service that answers your questions about the European Union. You can contact this service:

– by freephone: 00 800 6 7 8 9 10 11 (certain operators may charge for these calls),

– at the following standard number: +32 22999696, or

– by email via: https://europa.eu/european-union/contact_en

FINDING INFORMATION ABOUT THE EU

Online

Information about the European Union in all the official languages of the EU is available on the Europa website at: https://europa.eu/european-union/index_en

EU publications

You can download or order free and priced EU publications from: https://op.europa.eu/en/publications. Multiple copies of free publications may be obtained by contacting Europe Direct or your local information centre (see https://europa.eu/european-union/contact_en).

EU law and related documents

For access to legal information from the EU, including all EU law since 1952 in all the official language versions, go to EUR-Lex at: http://eur-lex.europa.eu

Open data from the EU

The EU Open Data Portal (http://data.europa.eu/euodp/en) provides access to datasets from the EU. Data can be downloaded and reused for free, for both commercial and non-commercial purposes.

MJ-07-22-268-EN-N

ISBN 978-92-76-52355-0

Publications Office
of the European Union