Macroeconomic representation of the clean energy transition

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1. Introduction

The European Commission has put forward a set of measures to facilitate the clean energy transition and to support the creation of the Energy Union. The energy transition is expected to make the EU energy sector even more stable and competitive and at the same time act as a key driver of EU-wide sustainable economic growth. Energy is an essential element of economic growth both directly (all economic processes require energy) and indirectly (energy availability at low cost and the use of different energy types drive innovations and promote efficiency). As 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 finance for firms and households, and new business models for the delivery of energy and mobility services as well as changes in consumer lifestyles and behaviour.

The low-carbon transition and the realisation of the Energy Union facilitate the invention and production of new technologies that can create a new ecosystem of processes that may strongly impact economic growth through trade, innovation, productivity and knowledge spillovers. The transition will involve substantial innovation to lower the cost for and develop 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 Utilisation and Storage technologies (CCUS). In addition, the development of supporting network infrastructures for various energy carriers and flexibility options, including through the coupling of electricity, gas and heat systems, is required. In other sectors (e.g. in buildings) the transition may not involve much technological innovation, but is likely to involve policy innovation to establish the regulatory framework and incentives for action.

The available literature on the interactions between energy and economy is vast, including qualitative studies, data-driven and econometric analyses and forward-looking model-based assessments. However, the literature is inconclusive on how exactly the clean energy transition would impact economic growth, innovation and competitiveness. At the same time the EC adopts ambitious energy and climate targets for 2030 and 2050, as demonstrated by the Clean Energy package, the new EU Green deal and the Long-term Strategy towards climate neutrality by mid-century. The transition to a low– or zero-carbon economy would have far-reaching implications for Europe's competitiveness, related to energy and resource dependence and technological leadership. With this policy context in mind, it is crucial to improve our understanding of how clean energy transition and the enabling policies would affect firm productivity, economic growth, industrial competitiveness and the society. The overall objective of the task is to identify the channels and mechanisms through which energy historically has contributed to economic growth, to analyse the current trends in the energy-growth-innovation nexus, to examine the substitutability between energy and capital and trade impacts and further improve existing state-of-the-art models to represent the new findings on energy and innovation-induced economic growth. The findings of this analysis will be used to improve current modelling tools (E3ME and GEM-E3-FIT) so as to ensure that the empirically observed channels through which energy contributes to growth are taken into account. This policy brief presents a summary of the main results of the analysis and the resulting policy recommendations.

2. Energy as a factor of economic growth

2.1. How energy influences the determinants of economic growth?

Economic growth is essential for countries to make progress towards sustainable development goals. Literature has identified various determinants of growth both on the supply side (natural resources, capital goods, human resources and technology, institutions and governance) and on the demand side (public expenditure, efficiency, private spending). The evidence regarding the contribution of these factors to growth is not consistent across studies and partly depends on the stage of development of each country. Energy impacts economic growth and its determinants through various channels, both directly and indirectly: The energy sector directly creates Gross Value Added and jobs, energy investment may stimulate growth, energy availability can induce innovation, while energy is an essential input to production of firms as it affects the utilization of other production factors (capital, labour) that depend on the provision of energy. Through several channels, energy can be a determinant of innovation itself which can increase productivity and trigger further economic growth.

Energy is a primary input of production in the energy-intensive industry, and thus it has a direct impact on the industrial competitiveness, together with other factors, including openness to trade, relative production costs, and environmental regulation. Energy efficiency is seen as a way to reduce the environmental footprint of energy use while maintaining the corresponding outputs that energy services provide. However, the rebound effects question the assertion that increased energy efficiency entails reduced energy consumption.

Through several channels, energy may influence innovation dynamics, and thus increase productivity and trigger economic growth. The availability of adequate energy supplies is a precondition for scientific knowledge development and for an effective R&D sector, while energy prices and ambitious energy and climate polices can enhance technical change and low-carbon innovation (“induced innovation”). Access to energy services is fundamental to fulfilling basic human needs as well as to fuelling economic growth and social development. The provision of low-cost and reliable energy services can affect productivity, health, and education. Through these factors, improvements in energy services can increase the availability and quality of educational services and enhance human capital, which can be a driving force of economic growth. Energy is also crucial for the general improvement of human health, allowing access to advanced medical equipment, vaccination, and medication.

Climate change will have a profound effect on economic growth, as weather-related extremes, sea-level rise and water scarcity reduce the availability of commodities essential for growth. Climate change mitigation has significant impacts on the energy sector, that has to be restructured towards a low-emission paradigm with additional investment towards energy efficiency, low- and zero-carbon technologies and enabling infrastructure. The demand and supply of energy are also affected by climate change mainly through temperature-induced factors.

International trade is positively related to energy consumption, but the literature is inconclusive on the direction of causality. Trade liberalization enhances economic growth and boosts energy demand. Economic growth is also influenced by infrastructure, including transportation, ICT, energy and water. Infrastructure is required for the supply of certain energy carriers, i.e. electricity grids, gas pipelines, smart grids, while it also affects other determinants of growth by triggering investment, promoting human capital and reducing transaction costs. Energy quality1 is positively related to economic growth, as the shift to a higher quality fuels, such as electricity, reduces the amount of energy required to produce a given economic output. As the economies move through different stages of development, they tend to use energy forms of improved quality.

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	• Various types of interaction between renewable energy consumption, climate change and economic growth	
	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

2.2. Exploring the causality between energy and growth

Energy as an economic activity accounts for about 8% of global GDP but it is an essential resource for production and consumption. Depending on an economy's pattern of growth and stage of development, the economic system may become more or less energy intensive over time. The question as to whether and how energy drives economic growth has been heavily studied across countries and economic sectors, but the existing literature is inconclusive as to whether energy causes economic growth or vice versa. This raises important concerns to EU and national policy makers, as the implementation of ambitious energy efficiency policies leading to reduced energy consumption should not hamper economic growth. So, the link between energy use and gross value added is further examined using advanced, multi-method econometric analysis[2] (both time series and panel data), and focusing at the sectoral

[1] In economics, energy quality refers to the relative economic usefulness of different fuels and electricity per heat equivalent (Stern, 2011)

[2] For instance, to investigate causality, Granger causality (1987), Toda-Yamamoto (1995) and cointegration tests are applied for time-series data. Pedroni (1999) and Kao (1999) methods are used for panel data.

level (which has not been heavily studied) using the comprehensive WIOD database. Our findings are consistent with the neutrality hypothesis for most countries and sectors, i.e. there is no causality between energy use and economic growth. In the cases (countries and sectors) in which a cointegration relationship exists between energy and GVA, there is a greater tendency for the Growth hypothesis (energy drives GDP growth) to be accepted. The econometric analysis in most sectors supports the neutrality hypothesis; however, the sectors that highly depend on energy (i.e. refineries, electricity, gas and water supply and rubber and plastics) support the growth hypothesis.

The econometric analysis raises important policy-related issues, as energy efficiency policies (especially in sectors highly dependent on energy) should be carefully designed

in order to alleviate the potential negative impacts on the sectors' GVA. In other sectors, the neutrality hypothesis supports the implementation of policies targeting energy savings without hampering GVA growth.

2.3. Findings from Empirical Estimates on substitution possibilities

The substitution possibilities between energy and Capital-Labour (KL) bundle are heavily studied in the literature. The study empirically estimates Energy-KL substitution possibilities in a large spectrum of countries and sectors using the most recent, state-of-the-art econometric methods (including time series analysis with and without structural breaks, linear and non-linear cointegration relationships and panel data techniques). Both time series and panel data analysis strongly support the weak substitutability between energy and gross value added in most sectors and countries. The statistical analysis identifies the existence of structural breaks, which indicate that the change in the substitutability between energy and value added is most likely driven by other factors than just changes in their prices. A change in the level of the energy intensity to gross value added occurs as a shift at a point in time.

e Whave used econometric models that allow to differentiate between the short-run and long-run elasticity of substitution of energy and gross value added. The estimates based on these models do not provide statistical evidence that the long run elasticity can be considered as greater than the short run elasticity, contrary perhaps to what might have been expected. The elasticity of substitution between energy and gross value added remains stable across time (in most cases). An indicative value of elasticities of substitution between energy and value added is around 0.5 for most economic activities. In some cases, the elasticity of substitution is higher in periods that there is a decrease in the relative ratio of prices between energy and gross value added.

The empirical estimations point to the large impact of "structural breaks" indicating that the energy-KL substitutability is not driven mostly by price-related factors, but by factors related to policy interventions or investment in new technologies (especially in heavy industries with long investment cycles). This highlights the key role of policy makers and investors in the clean energy transition. By implementing ambitious and well-designed policy measures related to energy efficiency, policy makers may increase the speed of capital-energy substitution and foster economic growth. In addition, the increased substitution can be triggered by investment in new technological options and processes, e.g. using high quality fuels (electricity or gas) instead of solids.

2.4. Learning of energy technologies

In the area of technological development research, the learning curve theory refers to the assumption of an power-law correlation between the unit cost and the cumulative production of a specific technology. Empirical findings confirm that learning effects in the form of learning-by-research or learning-by-doing are apparent in all energy-related technologies. However, the relevance of learning-by-research and learning-by-doing, and the relative importance of public vs. private sector involvement in R&D, vary greatly across technologies, depending on: how mature the technology is, what industry the technology is predominantly associated with, and the geographical coverage of analysis.

Our review suggests that learning-by-doing rates decrease with the development of certain technologies and thus different rates could apply for the period to 2030 compared with the longer run. Photovoltaics, onshore and offshore wind turbines, biomass and biofuels, and electric vehicles and batteries are the technologies that are expected to experience slower (although in some cases, still relatively high) learning rates for the period 2030-2050 than over 2015-2030. The learning rates of energy technologies can be influenced by a variety of factors, which can be grouped under two broad categories: *time* and *industry specificities.* The following table presents the suggested learning-by-doing rates to use for the modelling of cost development of clean energy technologies over time.

Recommended learning-by-doing rates to use for the selected clean energy technologies

Clean energy technology	Recommended learning rate to use for the years 2015-2030	Recommended learning rate to use for the years 2031-2050
PV	20%	17%
Wind turbines - Onshore	7%	5%
Wind turbines – Offshore	11%	9%
Biomass and biofuels	7.8%	5%
Electric vehicles and batteries	18%	15%
Hydrogen production by electrolysis	7%	7%
Hydroelectricity	1.4%	1%
Synthetic fuels (power to X)	13%	13%
DAC (Direct Air Capture)	6%	6%
Biomass CCS and traditional CCS	7%	5%
Conventional technologies	3%	3%
Selected other sectors	18%	18%

Note: Learning rates are defined per doubling of cumulative output (learning-by-doing). Conventional technologies cover natural gas and nuclear. Selected other sectors cover chemicals and electronic goods.

Source: Reviewed by Cambridge Econometrics, 2019.

The literature is much sparer for learning-by-research rates, which simulate the rate of decrease in unit costs for every doubling of research and development investment stock for clean energy technologies. For the most part, the reported learning-by-research rates are as high as the learning-by-doing rates for the same technology and in some cases higher. Although the two-factor learning curve model is likely to offer greater accuracy and a more explicit representation of R&D-driven technological advances, its applicability is often limited by data availability. Modelling problems may also stem from the uncertainty associated with R&D processes (high risks regarding their outcomes). The learning curve models cannot capture the potential to develop new products through disruptive innovation, the learning process of which is often not traceable and/or the associated learning curve is most likely non-linear. Early stage technologies are often characterized by higher learning rates, but at the same time they are surrounded by higher uncertainties about the future evolution of costs, thereby increasing the risk of making no profit on the R&D investment.

While the public and the private sectors have different motivations in investing in clean energy R&D processes, technology firms are expected to be more successful in countries where intense R&D is undertaken by both businesses and the government. Private R&D typically yields patents that can derive substantial royalty revenues, thus providing the innovator with the prospect of sustained early-mover advantages. This is much less true in the case of public R&D, where the R&D benefits are much more diffuse, and mostly accrue to the users of the arising products and technological innovations. From a conventional innovation cycle point of view, private R&D is closer to commercialisation stage of technological development, suggesting that private R&D spending will show a larger reduction in unit cost per euro spent than public R&D spending.

Spillover effects play a crucial role in technological learning and development, as they increase the stock of knowledge in the recipient industries and regions in the same way as if they had undertaken the R&D themselves. This in turn contributes to raising productivity, improving quality of products and strengthening trade competitiveness. Spillovers can in principle occur through trade and direct investment links, in which trading partners or subsidiaries acquire knowledge from the source industry-region, or through technological similarities and cultural or institutional proximity. The extent to which the benefits of R&D in one industry and region are transmitted to other industries and regions (knowledge diffusion) are captured through spillover matrices. Based on detailed statistical analysis on patent citations, the strongest linkages are found within countries (a large share of citations were of sources from the same country). The US is an important citer of patents from other regions and an importance source of citations by other regions. This reflects its overall size, its advanced technological state, and its well-developed system of patenting. Together Japan and the US account for more than half of the weighted patent citation shares.

The statistical analysis shows clear evidence of spillover clustering among certain regions. The EU15 countries cite each other heavily, but there are weaker links with and between the rest of the EU countries. There is also clustering among Asian countries showing the impact of geographical/cultural proximity on knowledge dissemination. We also find that citations across countries are mostly symmetric – the spillover effect generally seems to be two-way. With regard to cross-sector spillover effects, again the most important linkages are within-sector. Clustering of sectors is less visible than it is for countries, but there are some examples of clustering, notably among industries covering activities of electronics manufacturing (mechanical engineering, electronics, electronic engineering and instruments).

The evidence suggests that EU and national policy makers should adopt ambitious innovation-promoting policies and integrate them carefully in the EU Green deal and other energy/climate policy packages. Investing in clean energy research and innovation pays off, as it reduces technology costs and increases productivity growth resulting in a more competitive European economy. The development of coherent policy packages tailored to the specific needs of a country or clean energy technology can boost growth; these packages may target clean energy innovation, knowledge flows and spillovers, creation of clean markets, education and the development of the required labour skills.

3. Energy technology transitions

The low-carbon energy transition requires a major wave of technological and social innovations while its impacts on economic activity occur through several interlinked channels. One viewpoint on the energy transition considers that the change from cheap fossil energy sources to renewable energy sources reduces GDP and welfare: transition policies force firms and households to make second-best choices with regional and distributional adverse impacts. However, the high cost of the energy transition is unlikely to be the whole story. 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 effects. Third, clean energy R&D efforts have cross-sectoral and international spillover effects which reduce the cost of the transition and may give (or not) first-mover advantages to certain countries. Fourth, climate policies stimulate higher investments and relocation of resources that can also boost economic growth.

To define the contribution of innovation aspects in the technology transition and assess the energy-growth linkages, six case studies on energy technology transitions are developed. The studies have been selected according to their importance to clean energy transition and industrial priorities of the EU, especially in view of the EC Green deal, the EU Innovation fund and the 2050 Long-Term Strategy. The case studies cover a number of value chains, focused on current (solar PV, lithium-ion batteries) and future energy technology transitions (hydrogen fuel cells, carbon capture and storage), but include also a historical energy technology transition (combined cycle gas turbines-CCGT) 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 case studies chosen illustrate technology development at different stages. In particular, two distinct outcomes for historical energy transitions can be identified: successful innovations, which established a significant market in the recent past (i.e. CCGTs, solar PV, lithium-ion batteries) and less successful technologies, which have not achieved substantial market penetration despite technological maturity (i.e. fuel cells and CCS). 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.

Summary of the case studies in technology transitions

Case	Cost reductions		Competitiveness	Sectoral interactions	
	Past	Future	Present[3]	Past	Future
Combined cycle gas turbines	**Strong reduction** in 1980-2000 **Moderate reduction** after 2008	**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 (2017-2030)** EV: 50%, Stationary: 80%	**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 • Transport infrastructure (**refuelling stations**) • Transport decarbonization (**EVs but also rail, maritime**) • Industry decarbonization (power and feedstocks) **Energy system integration** Cheap electricity supply from **renewable power**
CCS	**Costs still high barrier and vary significantly** No comparable cost reduction available due to maturity.	**Moderate reduction** Decrease 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** 38-60% reductions 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**

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[3] 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

The idea of the supply-side-driven innovation constitutes the supply push argument. Diffusion of innovation takes place once the emerging technology or process is spread in the market following the “invention-innovation-diffusion model”. This implies that advances in the underlying scientific base determine the pace and direction of innovation activity, and thus stimulating innovation requires the increase of new inventions, which arise through allocating more resources into R&D. According to the demand (or market) pull hypothesis, firms innovate in order to maximize their profit, thus turning the market and not the scientific base as the prime mover of innovation. As a result, the public policies should favour the creation of market space for new technologies to emerge. From the demand-pull perspective **market niches** play an important role, providing initial demand for maturing products and services, which cannot compete in mainstream markets, but can be interesting for targeted applications and early adopters.

In all technology transitions, policy and a combination of supply push and demand-pull drivers[4] have played an important role. While a combination of both driver types seems to be optimal, supply push measures (i.e. R&D support) are more effective to support new technologies at early development stages, whereas demand pull measures are better suited for technologies closer to market readiness. Economic drivers are central to enable significant market growth of clean energy technologies, as the latter are faced with competition from alternative options for the supply of energy and mobility services. When economic drivers are not enough to create sufficient demand pull, technical drivers such as energy security or niche applications (space application for fuel cells and solar PV) may play an important role. Environmental drivers (such as climate action and air pollution) play a central role in all energy technology transitions examined. Finally, social drivers for demand pull of new energy technologies are less observed in case studies, but they may impact technology adoption in the first phases of development.

Policy is a central driver of innovation, acting to provide both supply push and demand pull. Public R&D support is central in the initial phase of technology transitions, 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 for technologies with large potential growth complemented with demand-pull through investment or production support to the supply chain.

R&D efforts are conducted both by academia and industry, at different intensities per technology and phase. The lead private actors conducting the R&D efforts differ per case, e.g. in CCGTs R&D has been led by industrial conglomerates, while for autonomous vehicles disruptors such as electric car manufacturers (e.g. Tesla) are pivotal. Innovation can arise at different speeds and different forms with incremental innovation having a large contribution to clean energy technologies. All successful technologies transitions analysed (solar PV, lithium-ion batteries, CCGTs) took a long time to become established, while even radical innovations take time to establish themselves. Given the long time required for technology transitions and the inherent energy system inertia, there are large time lags between innovation and technology adoption even when technologies are successfully upscaled and commercially deployed.

Among energy technologies, several innovation characteristics are identified in different degrees and forms, such as increasing returns, learning effects and both purposeful and unintentional knowledge diffusion. The energy technology studies identify the following central aspects in technology transitions closely related to applied policy-making:

- **Drivers of innovation**: Supply push policies should be differentiated by technology as well as public and private R&D efforts and include inter-sectoral interactions.

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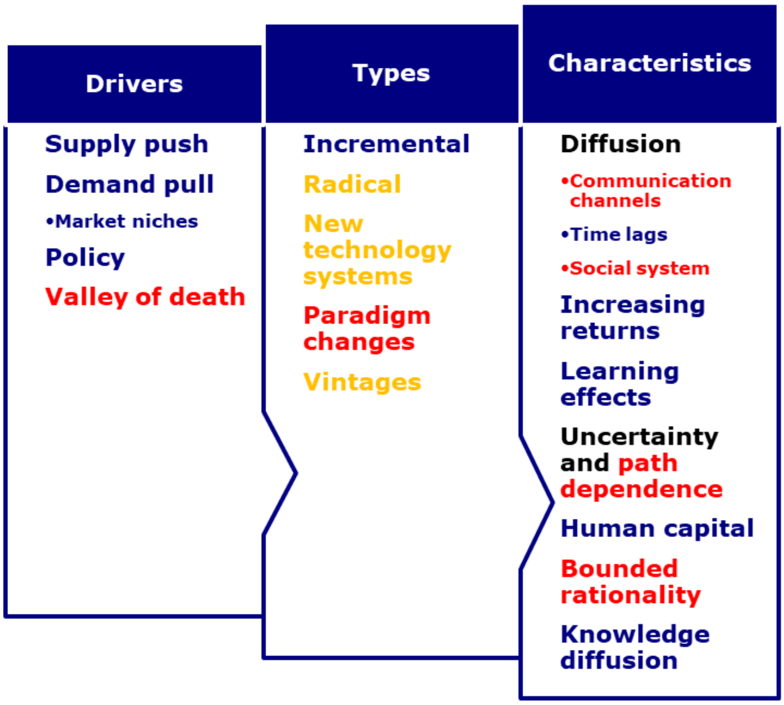
[4] Drivers may include economic, environmental, technical and social drivers.

Demand pull policies should reflect multiple drivers whose importance varies according to the technology and phase of development.

- **Policy** plays a key role in all technological transitions and should be reflected in analysis through supply push and demand pull mechanisms but also other factors, such as infrastructure development and knowledge transfer.
- **Incremental innovation** is highlighted in the case studies, allowing for continuous improvements of processes and products. In the energy sector, even radical innovations take a long time to reach significant deployment levels, because assets in the sector have a long lifetime and high cost improvements need to be achieved.
- **Increasing returns** are observed in some case studies, arising from economies of scale in the supply chain and learning-by-doing.
- **Learning effects** play an important role in innovation, both due to learning-by-doing and learning-by-searching. The regional and sectoral interactions vary per technology, and thus the analysis should consider whether global, regional or (inter) sectoral scopes apply.
- **Path dependence** in technology innovation is not clearly identified and does not explain failures in the innovation strategies of certain countries. Innovation is enabled or hampered by a number of aspects such as policies, human capital and increasing returns, so specific countries are repeatedly at the forefront of innovation. The increasing capital intensity and long lifetimes of energy technologies may lead to path dependence in innovation.
- **Human capital** (and its international and intersectoral mobility) is an important factor not only for labour productivity but also for R&D efforts and knowledge diffusion and absorption (i.e. fuel cell development in Japan).
- **Knowledge diffusion** occurs within or across countries or sectors through various channels, such as within public/private partnerships and technology replication. Knowledge diffusion can take the form of purposeful knowledge transfer or spillovers and played a central role in development of CCGTs using aerospace technology or of solar PV with electronics technology.

The case studies highlight that the role of energy as an economic activity influences technical change at the national level. The influence of energy as an input to production processes is less evident, as energy technologies (except for CCGTs) have not yet been able to significantly drive energy prices down globally.

Relevant innovation aspects identified in the case studies



The interaction of energy and technical change is apparent in the analysis of the demand pull drivers, highlighted by the role of the competition between energy technologies (for electricity supply or transport services) that fosters innovation. Given the importance of knowledge diffusion, energy technologies may further promote growth by maturing national research networks, providing new forms of spillovers to other sectors, as e.g. autonomous vehicles are related to EVs, while fuel cells are a central piece in the future hydrogen economy. Climate change is major demand-pull driver, as clean technologies may support mitigation by decarbonizing the economy, and increasing the resilience of the energy system. Energy technology trade and investments may lead or support bilateral and multilateral trade openness, as manifested by direct foreign investment in China (due to potential market and economies of scale in PV and batteries) and company acquisitions or technology purchasing and licensing by Canada and China for fuel cells.

Infrastructure affects the viability and deployment of energy technologies (e.g. battery recharging or hydrogen refuelling), while evidence suggests that certain technologies can reduce the dependence on electricity networks (off-grid solar PV) or increase the electricity system flexibility (fuel cells, batteries). The function of modern energy infrastructures impact growth through reducing transaction costs and improving trade and human capital. Environmental drivers also play a crucial role in clean energy innovation; for example, the target to reduce air pollution in China and S. Korea is the major driver for the deployment of solar PV and low-carbon mobility (fuel cells and battery EVs).

Policy plays a key role in technological transitions both through supply push and demand pull mechanisms, but also other factors, such as infrastructure development (as for fuel cell and battery electric vehicles) and knowledge transfer (for example in technological innovation systems in Japan). Increased public and private expenditure on clean energy R&D would accelerate technological learning, reducing the cost burden of the low-carbon transition to consumers and businesses and supporting activity growth. These policies should be complemented with policies facilitating innovation, development of human capital and diffusion of knowledge.

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

In the face of climate change, the relationship between economic activity and energy use is receiving increasing attention. Economic activity has been one of the main drivers of greenhouse gas emissions, and their mitigation, which requires reductions in fossil fuel energy use, would have profound macroeconomic consequences. Central to the discourse of climate change mitigation is the role of technological change that will allow for reductions in energy use and cleaner energy production.

There exist a number of approaches and models to describe the macroeconomy and its interlinkages with the energy system and technological change. These approaches can be broadly classified into two main paradigms: the equilibrium (optimisation) and the non-equilibrium (simulation) schools[5]. The paradigms are based on fundamentally different assumptions and descriptions of the macroeconomic system. The neoclassical school of thought gave rise to the equilibrium paradigm, while the non-equilibrium paradigm is associated with the Schumpeterian and Keynesian schools. All schools of economic thought concur that technical change is an important element of economic growth, but differ regarding the incentives that are thought to motivate actors to innovate and regarding the channels through which innovation impacts growth. So, the challenge in both modelling paradigms is to consistently incorporate technical change and its effects on economic growth.

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. Technical change and innovation are also central in the Schumpeterian theory that focuses on the role of entrepreneurs and their innovative ventures as the driving forces of economic development. In the 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 most important innovation aspects can be represented endogenously in models through a number of techniques, while approaches such as the design and quantification of alternative scenarios may capture the pervasive impact of innovations (both incremental and radical innovations). Policy plays a key role in technological transitions and should be reflected in the models through supply push and demand pull mechanisms but also other factors, such as infrastructure development and knowledge transfer. Incremental innovation is commonly represented in applied modelling through the use of learning-by-doing and learning-by-research curves, simulating cost and performance improvements of technologies driven by increased cumulative production and R&D expenditure. Models should strive for a balanced representation of increasing (and decreasing) returns of innovation reflecting the underlying causes and their regional and sectoral scope. The regional and sectoral interactions vary per technology, and thus the models should also consider whether global, regional or (inter)sectoral scopes apply for specific technologies. Human capital is an important factor influencing both labour productivity and knowledge diffusion; models should address the impact of human capital considering both general and sectoral skill levels as well as the role of education and training in developing new labour skills required for the clean energy transition. Knowledge diffusion occurs both within and across countries and sectors through various channels, i.e. technology replication and public/private/academia

[5] The optimization/equilibrium modelling paradigm involves Computable General Equilibrium models, optimal growth models, DSGE and partial equilibrium models. The simulation/non-equilibrium paradigm involves macro-econometric models, systems dynamics approaches (stock-flow and diffusion models) and agent-based modelling approaches.

partnerships. Given the complexity, macro-economic models strive to find an efficient compromise for representing the various channels of knowledge diffusion and the influence of policy.

The models reviewed represent a number of different approaches (i.e. agent-based, CGE models, macro-econometric and Integrated Assessment Models), many of which are hybrid. The models commonly 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, with nuances per model. The energy system representation differs among models with regard to sector, policy and country representation and the level of detail incorporated in the modelling. Following the quest towards a more detailed representation of the energy system, most models make use of a hybrid approach, incorporating energy systems submodule(s). IAMs have a difficulty in representing economic sectors, while macro-economic models succeed in a detailed representation of the energy and economic sectors.

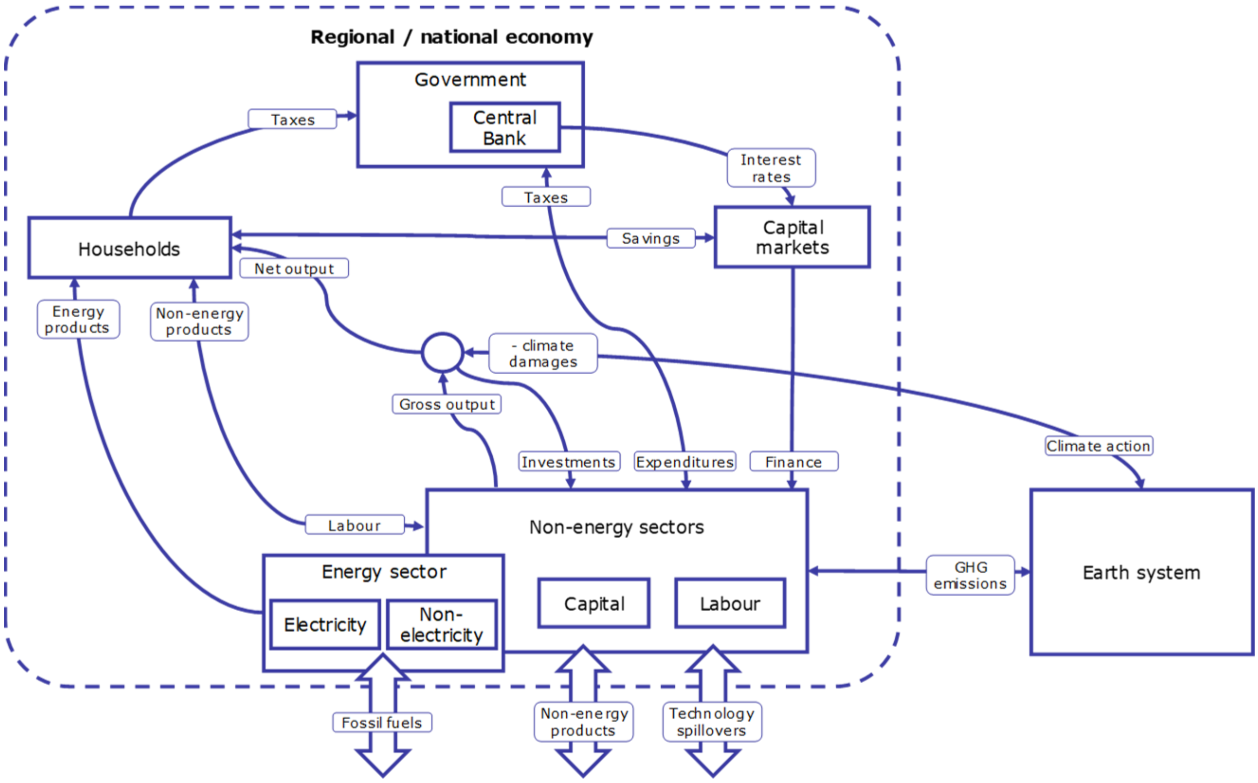
Each modelling paradigm entails certain assumptions regarding the behaviour of the economy, although recent macroeconomic models have made significant advances in addressing identified modelling shortcomings. innovation is a key factor contributing to economy growth, and thus models strive to incorporate an endogenous representation of innovation processes. In general, learning effects (mostly learning-by-doing, but also learning-by-searching) are widely employed in all reviewed models regardless of the economic modelling paradigm followed. In contrast, knowledge diffusion and spillover effects are represented only in a subset of models (namely NEMESIS, GEM-E3-FIT and E3ME). Human capital considerations expressing the capacity of firms and people to absorb knowledge and use new technology were integrated only in the above models.

It is very difficult for models to capture the dynamics of historical technological and social innovations. This difficulty can be addressed through the development of narrative and policy scenarios describing illustrative examples of pervasive technological and social innovation in the energy transition and to represent those scenarios in the applied modelling. The energy transition scenarios 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 economic growth. The transition scenarios evaluate the effect of policies on given technology, energy or environmental outcomes, while learning effects are an important source of endogenous innovation.

Learning effects reduce the cost and induce higher deployment of energy-efficient and clean energy technologies, thus easing mitigation constraints by decreasing the required carbon price. Endogenous technical change in the scenarios increases economic output, or at least has no negative impact, but depends on certain conditions such as the speed of knowledge diffusion. The transition scenarios can also explore the relative strength of supply-push and demand-pull drivers facilitating accelerated innovation and higher uptake of clean energy technologies. Model and scenario-based evidence suggests that policies should be tailored based on the different barriers (supply- or demand-side) that technologies have to overcome, considering the specific regional and sectoral context. 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 captured in the model-based scenarios, which is consistent with the findings from the case studies. This type of learning effect underlines the importance of local know-how for technological development, when learning is (partially) dependent on regional capacities. Human capital and absorptive capacity are also important aspects for technology innovation and economic growth. Lastly, coherent provision of information on model assumptions and results and multi-model inter-comparison projects are important to improve the understanding of the impacts of endogenous technical change on growth and derive robust policy-relevant conclusions and recommendations.

The figure below presents a schematized representation of the main elements of a regional/national economy and its interactions with innovation and the energy system.

Figure: Schematic interaction of the economy, innovation and energy system



5. Impacts of trade on output and employment

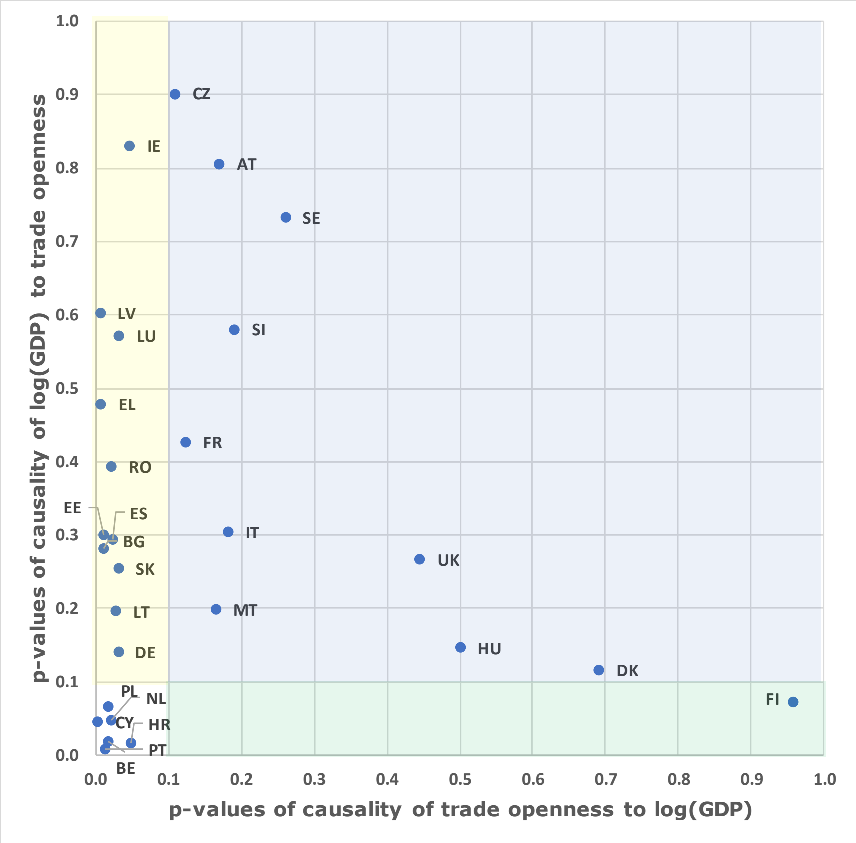
During recent decades, the nature of trade has changed significantly, calling for revised methods in economic assessment. International trade increases the efficiency of production both through the dedication of resources to their most productive use and through the use of efficient products to the production process of other products.

5.1. Exploring the causality between trade and growth

In the last decades, many theories have been developed to explain trade transactions, while a multitude of studies focus on the identification of causality between trade and growth. The literature and the empirical findings on how trade integration affects economic growth are inconclusive, and the findings depend on the stage of development of a country or a sector. Using advanced econometric techniques and the comprehensive Eurostat dataset, we conduct an econometric analysis to examine the causality between trade openness and economic growth. The trade openness is computed as the ratio of the sum of exports and imports to GDP and economic growth as the GDP growth rate.

The figure below presents a graphical representation of the p-values at a 10% level of significance in order to identify the causality between trade openness and GDP growth. The light blue area corresponds to no-causality between the two variables, the light yellow area corresponds to unidirectional causality from trade openness to GDP growth, the light green area to the unidirectional causality from GDP growth to trade openness, and the white area the bi-directional causality. In most countries, evidence suggests that trade openness causes GDP growth, while in several the causality is bi-directional and only in one country GDP growth is found to cause trade openness.

Figure: Causality test of trade openness and GDP growth rate



Important policy relevant conclusions can be derived from these findings as trade openness is found to have significant impacts on GDP growth. Trade-supporting policies should thus be carefully designed and implemented, and policy makers should ensure that ambitious energy and climate policies promote (or do not impact negatively) trade openness of EU economies, in order not to cause negative impacts on economic growth. Policies protecting trade-exposed industries from industrial leakage should ensure consistency with economic growth, while the potential for EU industries to reap first mover benefits from early climate action should be fully explored, as these would increase EU exports and boost economic growth.

5.2. Trade substitutability

The Armington assumption, which refers to the imperfect substitutability of products according to the place of production, has become a standard assumption used in macro-economic models. Despite the popularity of the use of Armington elasticities, very few empirical estimations have been published. To fill the gap, we performed extensive time series analysis using advanced econometric techniques to estimate the Armington elasticities between domestic and imported goods at a very disaggregated sectoral and regional level (following the disaggregation of the WIOD database).

The econometric model used for the estimation of Armington elasticities was selected with the objective to extend the international trade module of GEM-E3-FIT and to feed up the module with reasonable estimates of these elasticities. The representation of global supply chains in GEM-E3-FIT is improved by explicitly representing bilateral trade in intermediate goods. The improved modelling also benefits from the new econometric estimates of Armington elasticities which increases the realism of the trade module.

The estimated Armington elasticities differ substantially across sectors and countries which supports the new approach used to improve the modelling of international trade in GEM-E3-FIT. The estimated weighted Armington elasticities lie in the interval [1-4] for most countries and sectors. In some limited cases, high values of Armington elasticities have been estimated, especially in sectors like chemical products and non-metallic minerals. High values of Armington elasticity are estimated in countries with low share of demand for domestically produced goods to total demand.

5.3. Global value chains on clean energy technologies (electric cars)

In 2018, almost 2 million electric cars were sold globally, up from around 1 million sales in 2017 illustrating the trend of rapidly increasing EV stocks worldwide, with China, EU, Norway and the US accounting for more than 90% of the global market. The main cost component of electric vehicles is the battery pack which makes up from 35 to 50% of the costs of a new vehicle. The relatively high cost of battery packs is one of the main reasons for the higher selling price of electric vehicles relative to ICEs. The future evolution of the battery cost will have significant impact on the EV competitiveness.

Electric vehicles are currently in the early market adoption stage, with strong annual growth in sales that is expected to continue in the next decade (to a great extent because of regulatory incentives). The effect of economies of scale, learning curves and innovative technologies is pushing the price of vehicles downwards; the price of lithium-ion battery pack has decreased by 85% in the period 2010-2018, while it is expected to

further decline, from today's cost of 180-200 € per kWh of storage capacity to 50-100 €/kWh in 2030[6]. The Figure below includes a summary of several recent cost estimates. The price of other components, such as powertrain parts and power electronics, is also expected to decrease but not to a such degree. This would mean that by the mid-2020s, the price of a new electric vehicle would match the price of standard ICE vehicle[7].

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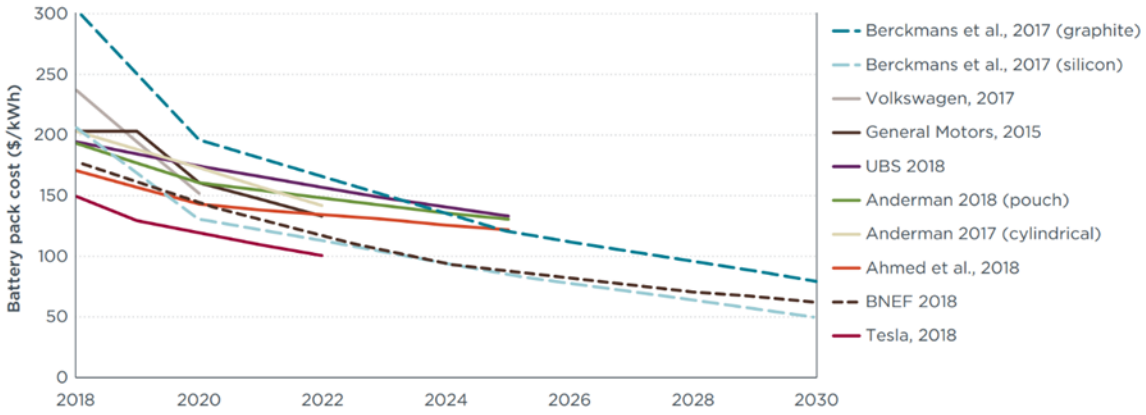
[6] Li-ion batteries for mobility and stationary storage applications; https://theicct.org/sites/default/files/publications/EV_cost_2020_2030_20190401.pdf; https://steps.ucdavis.edu/wp-content/uploads/2018/02/FRIES-MICHAEL-An-Overview-of-Costs-for-Vehicle-Components-Fuels-Greenhouse-Gas-Emissions-and-Total-Cost-of-Ownership-Update-2017-.pdf; https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/

[7] https://about.bnef.com/electric-vehicle-outlook/, https://theicct.org/sites/default/files/publications/EV_cost_2020_2030_20190401.pdf, https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/making-electric-vehicles-profitable

Figure: Summary of battery cost estimates[8]



Due to various reasons, such as supply chain considerations or import tariffs, most of the car manufacturing capacities (including EV manufacturing capacities) are located in the countries or regions where the produced vehicles are to be sold. One of the greatest competitive advantages for EV equipment manufacturers is the sizeable domestic EV market, which allows scaling up the production and distributing various fixed costs. The case of Chinese market however highlights another important factor, which is that the EV demand is still highly dependent on governmental policies, in the form of subsidies for purchase of new electric vehicles. The EV markets thus appear to be too fragmented to induce a truly global competition. A different situation is however emerging in the battery production industry, where competition is intense due to the long-lasting production overcapacity in the world market. Incumbent battery producers in Asia (China, South Korea and Japan) can benefit from this situation, as they hold a competitive advantage in economies of scale or lower labour costs and can thus supply a major share of world markets.

The pressure on lowering the costs of EVs may force the car manufacturers to focus on increasing battery pack customization, towards a process where the automotive industries have a bigger influence on battery manufacturing. As battery packs are rather heavy and have high transportation costs, their production in geographical proximity with the final EV assembly locations brings additional cost advantages. The current situation where the market players in China, Japan and Korea hold together more than 90% share in battery cell production, would probably change in the future driven by strategic capacity investment in other major economies worldwide. Judging by the already announced investments, Europe could, for example, cover its demand by supply from local production by 2023. To offset the advantage of incumbent Asian players, the new market entrants should focus on innovation, such as increased use of digitalization or better factory design, while the diffusion of new battery designs would create new markets. In that sense, Europe holds a competitive advantage, as the European car manufacturers lead the world in R&D expenditure, and in patents of EV technologies.

The manufacture of electric vehicles is globally oriented to domestic markets (with the exception of South Korea) if one considers the EU internal market as a whole. There is limited trade relative to manufacturing levels, and the EU, China and the US supply their own demand to a large extent. In contrast, global battery markets are more integrated, with Japan, South Korea and China presenting significant exports. EU Member States are frequently among the top global exporters and importers of electric vehicles and related components, indicating the high trade openness in the sector. Germany is the largest exporter and importer in the EU. The US, South Korea and Japan are top exporters for all

[8] https://theicct.org/sites/default/files/publications/EV_cost_2020_2030_20190401.pdf

components, while China is a major battery exporter and Norway is the biggest importer of both batteries and electric vehicles. While the US exports a relevant portion of its domestically-produced EVs, Chinese production was exclusively oriented to the national market, which is the largest worldwide. The EU battery manufacturing is limited, so EU's domestic demand is mostly covered by extra-EU battery imports. There is a relationship between trade in EVs and batteries, including cross-relationships between EV manufacturing and battery imports.

The major trade partners for EVs and batteries for the EU are China, South Korea and the United States. Imports of electric vehicles from these countries are not as significant as battery imports, where in addition Japan is a major supplier. The main EU countries in the EV supply chain are Austria, France, Germany, Hungary, the Netherlands, Poland and the UK. These Member States account for around 1 518 million € of value added for the EVs in 2018. France is leading the European EV manufacturing (both in terms of value added and employment), mainly due to the assembly of the best-selling Renault Zoe, whose battery packs are also assembled in the country, with Germany following due to the assembly of EVs (the Volkswagen e-Golf and BWM i3). Poland and Hungary realize mostly the assembly of battery packs.

The European economy can benefit from the expected growth in the electric vehicle markets, especially if policies effectively integrate demand-pull (i.e. measures to boost domestic EV uptake) and supply-push drivers, such as increased R&D spending on EVs and batteries or support to clean energy industries. In case of early climate action coupled with ambitious measures to boost the uptake of EVs by consumers and policies to support clean energy innovation, the European industries can reap competitive, first mover advantages and benefit from increased productivity, competitiveness and exports in international markets.

6. The Economic Impacts of an EU Carbon Border Adjustment Mechanism - Scenarios using E3ME and GEM-E3

The macrosectoral economic models E3ME and GEM-E3 are applied to analyse the economic impact on the EU27+UK of the removal during the 2020s of ETS compensation for EU producers at risk of carbon leakage and the introduction of a carbon border adjustment mechanism (CBAM), intended to ensure a level playing field for EU producers compared with producers based in the rest of the world facing a lower or no carbon price.

Following (Whitmore, 2019), we assume that the CBAM is applied to imports of products of the sectors deemed to be at significant risk of carbon leakage .

The modelling compares the outcomes for economic indicators in

- a 'baseline' projection, in which there is no CBAM and ETS compensation measures remain in place
- a 'CBAM scenario', in which a CBAM is introduced and ETS compensation measures are eliminated

The baseline projection includes policies consistent with 'current EU ambition', interpreted here as EUCO3232.5 (the EU achieving by 2030 a 32% share of renewable energy in gross final energy consumption and a 32.5% energy efficiency target). This baseline achieves a 45% reduction in EU domestic greenhouse gas emissions from 1990 levels by 2030.

The CBAM tax rate covers the manufactured fuels, basic metals, the chemicals, the pulp and paper and the non metallic minerals sectors and is applied on non-EU carbon intensity.

In E3ME, the scale of the CBAM tax is relatively small when averaged and so the impact on the volume of extra-EU imports is small: at most a reduction of just under 0.8% in 2030. In GEM-E3 the imposition of the CBAM tax on imported goods leads to a 3.4% reduction in imports. This response is much higher than that seen in the E3ME results; it reflects slightly higher CBAM rates and a greater responsiveness (presumably higher trade price elasticities). This difference in responsiveness to price changes between the two models is consistent with their macroeconometric (E3ME) and CGE (GEM-E3) features.

7. Conclusions and recommendations

Energy and environmental aspects are increasingly studied and integrated in applied macro-economic models, through the improved representation of the energy system, climate change and clean energy innovation. Innovation may significantly reduce the costs of the energy transition, and thus the direct and indirect impacts of incremental and radical innovations need to be better represented in macroeconomic models. An adequate representation of innovation and its impacts in macroeconomic models will allow analytical support to be provided especially to the dimensions of the Energy Union and EU Green deal of decarbonization of the EU economy and the promotion of research, innovation and industrial competitiveness.

The role of energy and exhaustible resources is gaining importance in the neo-classical and neo-Keynesian schools of economic thought, while technical change is considered as an important element of economic growth. Innovation is driven by supply push and demand pull mechanisms, which are both influenced by policy. In the case of energy technologies, the observed technical changes are often incremental, however radical innovation can also take place. Depending on the degree of disruption, an innovation can give rise to new technology systems and/or paradigm changes.

Energy is highly interconnected with innovation and economic growth, but literature is inconclusive on the exact relationship and direction of causality. Energy as an economic activity accounts for about 8% of global GDP, but energy is an essential resource for production and consumption. Depending on an economy's pattern of growth and stage of development, the economic system may become more or less energy intensive over time. Our findings support the neutrality hypothesis for most countries and sectors, i.e. there is no causality between energy use and economic growth. However, sectors highly depending on energy (i.e. refineries, electricity, and gas supply and rubber and plastics) support the growth hypothesis, i.e. energy drives GVA growth. This raises important policy-related issues, as energy efficiency policies in these sectors should be carefully designed in order to alleviate the potential negative economic impacts. In other sectors, the neutrality hypothesis supports the implementation of policies targeting energy savings without hampering GVA growth.

The substitution possibilities of energy with capital and labour are econometrically estimated with results supporting the weak substitutability between energy and gross value added. The existence of "structural breaks" indicates that substitutability changes is most likely driven by other factors than just changes in their prices. These factors are related to policy interventions and/or investment in new technologies, highlighting the key role of policy makers and investors in the clean energy transition. By implementing ambitious and well-designed policy measures related to energy efficiency, policy makers may increase the speed of capital-energy substitution and foster economic growth. The increased substitution can be triggered by investment in new technological options and processes, e.g. using high quality fuels (electricity or gas) instead of solids.

Learning processes are included in applied models in the form of learning by doing and learning by research curves. The analysis suggest that different learning-by-doing rates could apply for the period to 2030 compared with the longer run. Photovoltaics, wind turbines, biofuels, electric vehicles and batteries are the technologies that are expected to experience slower (although in some cases, still relatively high) learning rates for the period 2030-2050 than over 2015-2030. The reported learning-by-research rates are as high as the learning-by-doing rates for the same technology and in some cases even higher. Knowledge diffusion is a key mechanism spreading the effects of innovation to other countries and sectors. Reflecting its technological leadership and large size, the US is an important citer of patents from other countries and an importance source of citations by other countries. Knowledge diffusion is clustered among certain countries, i.e. the EU countries cite each other heavily showing the impact of geographical and cultural proximity on knowledge dissemination. Clustering of sectors is less obvious than it is for countries, but it exists notably among electronics manufacturing industries (mechanical engineering, electronics, electronic engineering and instruments).

The impacts of trade on output are explored using advanced econometric techniques. The findings highlight that in most countries, trade openness causes GDP growth, while the causality is bi-directional in several countries. Macro-economic models commonly use the Armington assumption that refers to the imperfect substitutability of products according to the place of production. The representation of global supply chains in GEM-E3-FIT is improved by explicitly representing bilateral trade in intermediate goods, which also benefits from the new econometric estimations of Armington elasticities. The latter

differ substantially across sectors and countries (in most cases they lie in the internal [1-4]) which supports the new approach to model global value chains in GEM-E3-FIT.

Investing in research and innovation pays off. A robust outcome of the analysis suggests that R&D spending triggers accumulation of knowledge stock leading to higher productivity growth, reduced costs, resulting in a more competitive European economy. Research and innovation policy needs to be considered carefully within the context of EU's climate change mitigation goals and strategies, supporting energy efficiency and low-carbon energy production without hampering economic growth. Because of strong interactions between R&D investment, knowledge accumulation and human capital, the

simultaneous implementation of well-designed policies targeting innovation, knowledge diffusion, decarbonisation, trade openness and the development of the required labour skills will boost EU competitiveness and growth. The implementation of ambitious policy frameworks targeting decarbonisation and clean energy innovation should take care to avoid negative activity outcomes especially in energy-intensive sectors.

7.1. Suggestions to improve macroeconomic models

As macroeconomic models, both GEM-E3-FIT and E3ME address energy as an economic activity and as an input to production processes. They also include a comprehensive representation of labour and capital markets, the potential for under-utilisation of resources and substitution possibilities between production inputs (capital, labour, energy, materials). The impact of technical change on growth is also included in the models through the integration of learning by doing and learning by research curves for energy technologies. On the other hand, the macro-economic models have a limited representation of the impacts on energy quality & developmental stages, infrastructures and openness to trade.

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

- **Public support to supply push:** implement synergies produced by coordinated policies that promote R&D, production and adoption of low-carbon technologies; endogenous modelling of public R&D defining priorities and allocating resources (e.g. R&D funds) across sectors; represent targeted subsidies that increase the levels of private R&D (that is, leveraging);
- **Learning effects:** use multi-factor learning curves, highlighting learning-by-doing, learning-by-researching (public and private), and/or intersectoral spillovers. Learning curves can be disaggregated to global and regional levels.
- **Radical innovations:** represent backstop technologies/sectors, including the non-economic demand pull drivers (technical, environmental, social) which lead to increasing adoption despite an initial lack of economic competitiveness;

- **Representation of innovation types:** differentiation between incremental and radical innovation; uncertainty analysis determining the success probabilities of innovation efforts, which are much lower for radical innovation;
- **Human capital:** 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;
- **Knowledge diffusion:** represent the relevant channels of knowledge diffusion (e.g. within public/private partnerships, technology licensing and company acquisitions) which can vary per sector; improve proxies used to capture knowledge diffusion such as bilateral imports or patent citation data. Include time lags for interregional spillovers.
- **Incorporate the findings of the econometric analysis,** i.e. on substitution elasticities for production inputs, Armington elasticities and learning by doing rates depending on time or technology cumulative production.

The GEM-E3-FIT and E3ME models can be further improved through novel approaches. For example, the models can represent intersectoral R&D expenditures to push inter-sectoral R&D supply, through investments by industrial conglomerates and cross-sector investments, such as digital technology or oil & gas companies investing in low-carbon technologies. Alternative strategies leveraging the model inputs (such as through the development of scenarios) can provide important policy insights into the macroeconomic impacts of the energy transition. The use of coherently-designed scenarios can be applied especially to explore the impacts of highly uncertain radical innovations that impact multiple sectors through various channels, for example the development of electric, connected and autonomous vehicles. Well-designed scenarios can explore the impacts of coordinated national policies supporting the 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.

The number of recommendations for improved macroeconomic modelling is challenging, requiring the selection of the best approaches to address them, either endogenously in the models or exogenously (through carefully-designed scenarios). The study confirms that to an important extent the GEM-E3-FIT and E3ME models are already capable of providing relevant insights into the macroeconomic impacts of the energy transition, endogenously considering innovation aspects such as supply push and demand pull, human capital and knowledge diffusion.

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