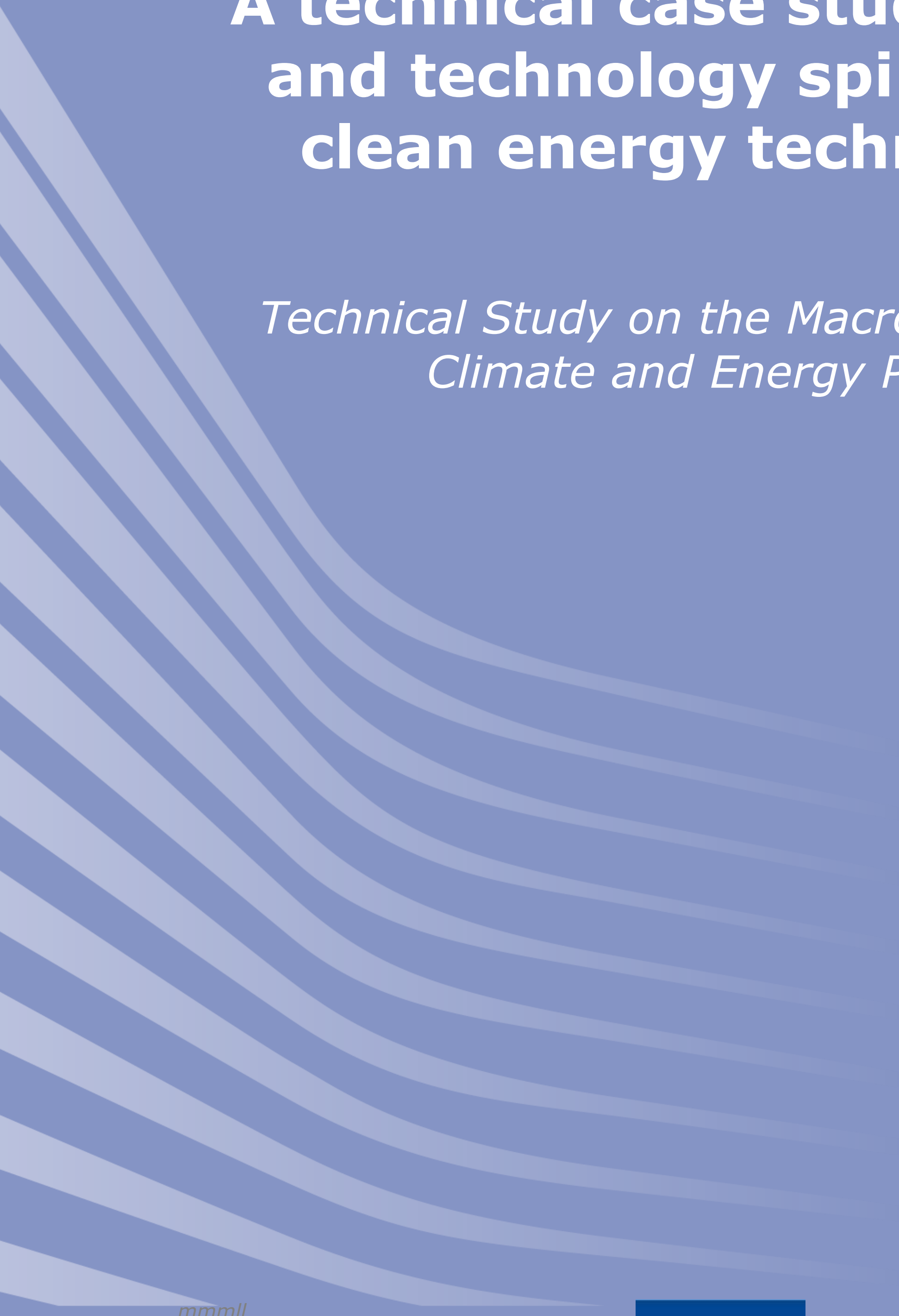
European
Commission

A technical case study on R&D and technology spillovers of clean energy technologies

Technical Study on the Macroeconomics of Climate and Energy Policies



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Part I Summary

The objective of this report is to elaborate on current and expected comparative advantages of EU industries that produce low-carbon emitting products and to estimate whether there could be benefits for the EU economy from initiating ambitious adoption and development of clean energy technologies at a much faster pace than other countries. The industries considered in the study are photovoltaics, wind turbines, electric vehicles, biofuels, insulating materials, batteries and advanced heating and cooking appliances.

The market for these clean energy products is highly competitive and fast growing driven by innovation dynamics, technological advancements and by energy and climate policies and regulations. In 2015 the size of the global market is estimated to be approximately 250 bn € and is currently dominated by the PV and Wind turbines manufacturing which together account for more than 50% of total sales. Figure 1 presents the regional share in global sales for each clean energy technology.

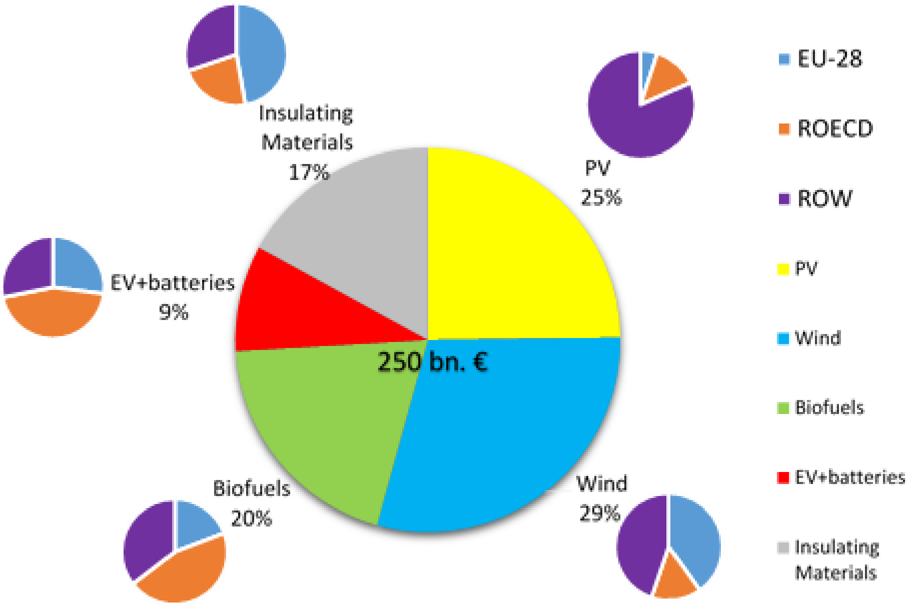


Figure 1: Global market of clean energy products (2015)

The EU holds significant shares in all clean energy markets apart from the solar PV manufacturing; the latter has undergone a rapid transformation in recent years with a fast erosion of the Japanese dominance and EU manufacturing and the emergence of China as the dominant player in the global market, largely due to the massive Chinese exports to the EU-28.

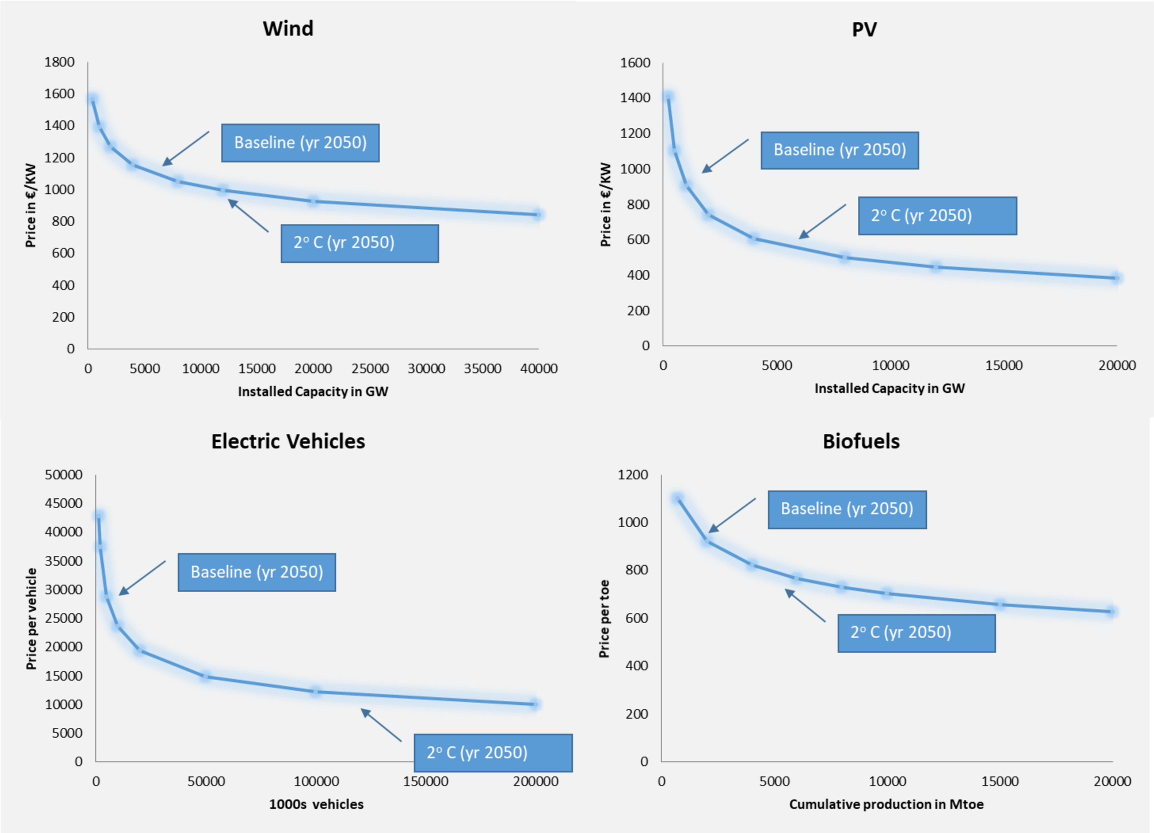
The EU is a global leader in wind turbine manufacturing where it holds the largest market share (about 40% in 2015). EU manufacturers continue to meet local EU demand and at the same time export wind turbines to non-EU economies. High transportation costs and the increasing size of projects (especially for offshore installations) are expected to lead to company mergers and new partnerships globally. The large share of EU companies in global exports shows that transportation costs and non-EU competitors are not yet a significant barrier to EU Wind manufacturers.

Electric vehicle sales are concentrated in three main markets, namely China, USA and Europe, which jointly accounted for about 87% of global market in 2015. The electric vehicles market is still young but grows at a very fast pace together with the advancements in batteries. European manufacturers are competitive in supplying electric and plug-in hybrid vehicles but in the manufacturing of Lithium-ion batteries the EU still lags behind Japan and S. Korea.

With respect to the biofuels market the EU is the world's largest biodiesel producer representing 45% of global production in 2015, while USA leads the global bioethanol market with a global share of 59%.

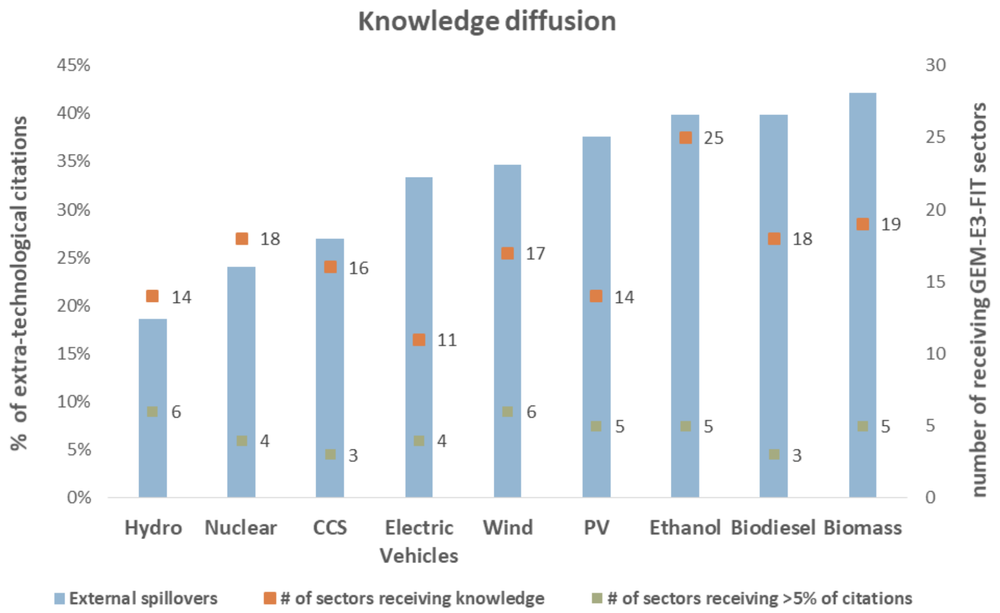
The market for clean energy products is expected to increase strongly driven by ambitious climate and energy policies, security of supply concerns and reductions in technology costs. Cost reductions are particularly important for the expansion of technologies with limited product differentiation such as wind and solar PV and less for electric cars where behavioural and policy coordination aspects are also critical (including technology adoption by individual consumers and timely development of battery recharging infrastructure). The cost reductions that can be achieved through economies of scale and learning by research are presented in Figure 2.

Figure 2: Cost reduction potential of clean energy technologies



The cost reductions achieved through economies of scale clearly depend on the size of the market and benefit only the region/country that undertakes the production. On the other hand, cost reductions achieved through intense R&I impact the whole industry (with a time lag depending on the patent protection and speed of spillovers absorption). As described in Keller (2004), technological progress which in general is positively linked with economic growth, is difficult to measure directly. R&D expenditure has been widely used as an input-based indicator of innovation (Albino et al 2014), while patents are also widely used as output-based indicators. Generation of patents does not only have a direct positive effect on the industry that produces them, but also impacts positively other industries through knowledge spillovers. These spillovers benefit the country and industry that receives them, increases the income of innovator through royalties and reduces the monopoly rents of the innovator. Based on the most recent patent-citation statistics, collected and analysed for the purposes of this study, the technology with the highest spillovers is biofuels (Figure 3).

Figure 3: Knowledge spillovers for clean energy technologies



In order to evaluate the potential First Mover Advantage (FMA) of the EU, the GEM-E3-FIT and E3ME models are used. The GEM-E3-FIT is a CGE macroeconomic model that incudes explicitly the financial sector, while E3ME is a macro-econometric model. The scenarios simulated with both models are i) **EU alone** where the EU decarbonises its energy system delivering an 80% GHG emission reduction in 2050 from 1990. Non – EU countries adopt reference climate and energy policies to 2050, ii) **First mover advantage** scenario where the EU starts from 2020 to adopt ambitious energy and climate policies and non-EU countries follow only after 2030 and iii) **Delay action scenario** where all countries adopt ambitious emission reduction policies after 2030. Both the FMA and Delay scenarios deliver the same carbon budget globally, while the EU carbon budget (in the 2015-2050 period) is assumed to be the same in all scenarios examined.

Profits from the EU’s early action regarding the development of clean energy technologies depend on the size of the market and the potential for market penetration that can be achieved. It is found that under specific conditions a first mover advantage for the EU exists but it is small and diminishes over time. The EU FMA advantage is roughly 0.06% of EU cumulative GDP (2020-2050) compared to the EU Alone scenario and it is mainly driven from exports of electric vehicles. The FMA advantage when compared to a delayed action scenario is 0.6% of cumulative EU GDP over the 2020-2050 period. The delayed action scenario ranks last in terms of GDP performance among the different scenarios examined. This is due to the economy and energy restructuring required in such a short term globally. This restructuring is achieved at a high cost as technology maturity of RES and electric vehicles fails to achieve full potential. Capital requirements are much greater relative to the other scenarios, where investment plans and R&D expenditures span over a longer time period.

The conditions that need to be met for the EU to establish a first mover advantage in clean energy industries are:

- Clean energy technologies have a potential of cost reduction if developed at a large scale, as a result of R&D and economies of scale

- The European internal market is sufficiently large and unified to allow for achieving a large part of the learning potential for clean energy technologies
- The Rest of world needs to follow ambitious energy and climate action with a sufficiently large time lag (at least 10 years). Clean energy technologies are massively deployed in non-EU regions allowing the EU to reap export benefits from its leading climate action.
- Establishment of integrated vertical supply chains for the manufacturing of clean energy technologies in order to exploit in full the potential for economic growth and net job creation (e.g. wind turbine manufacturers in EU)
- The speed and magnitude of technology, innovation and knowledge diffusion to non-EU regions and sectors (cross-sectoral spillovers) needs to be balanced. A slow technology diffusion will extend the lifetime of the EU first mover advantage, but will impact negatively the GDP of the EU through the overall slowdown of global economic growth as advanced technology is not shared.

The macro results are robust regarding the assumptions on R&D expenditure and its impact on total factor productivity. Sensitivity analysis showed that when learning by research rate is halved from the central scenario values, the benefit of the first mover advantage is reduced by 0.05% of GDP (Table 1).

Table 1: Macroeconomic impacts of alternative settings regarding EU energy, climate and R&D policy (GEM-E3-FIT)

cumulative change 2020 - 2050 from reference scenario, in %		***GDP***	***Investment***	***Private consumption***	***Net exports (trillion € 05) Clean Energy Technologies***	***Employment in Clean Energy Technologies***
No Spillovers	***EU Alone***	*-0.06*	*0.73*	*-1.56*	*0.12*	*8.34*
	Delay	*-0.62*	*0.08*	*-2.34*	*0.72*	*9.14*
	EU - FMA	*-0.03*	*0.84*	*-1.60*	*0.86*	*11.14*
Full Spillovers	***EU - Alone***	*-0.10*	*0.75*	*-1.53*	*0.10*	*8.29*
	Delay	*-0.62*	*0.12*	*-2.29*	*0.70*	*9.14*
	EU - FMA	*-0.04*	*0.90*	*-1.54*	*0.81*	*11.06*
Low R & D	***EU - Alone***	*-0.11*	*0.74*	*-1.56*	*0.01*	*7.62*
	Delay	*-0.63*	*0.09*	*-2.32*	*0.71*	*9.46*
	EU - FMA	*-0.06*	*0.85*	*-1.58*	*0.61*	*10.99*
absorbion of Spillovers	***EU - Alone***	*-0.08*	*0.74*	*-1.55*	*0.11*	*8.32*
	Delay	*-0.62*	*0.10*	*-2.31*	*0.71*	*9.14*
	EU - FMA	*-0.03*	*0.87*	*-1.57*	*0.84*	*11.10*
absorbion of Spillovers	***EU - Alone***	*-0.08*	*0.74*	*-1.54*	*0.11*	*8.31*
	Delay	*-0.62*	*0.10*	*-2.31*	*0.71*	*9.15*
	EU - FMA	*-0.04*	*0.87*	*-1.56*	*0.84*	*11.10*

Source: GEM-E3-FIT

The technology spillovers impact the EU economy through two main channels: i) Negative impact through the reduction of first mover advantage and ii) Positive impact through stimulating world demand for EU products (the adoption of EU patents enable non-EU manufacturers to produce carbon free technologies at low cost and hence adjust better to a low carbon energy system). Sensitivity analysis on the spillovers showed that increasing spillover rates has a positive impact on EU GDP by increasing demand for non-clean energy products and a negative impact on GDP by reducing the demand for clean energy products. EU GDP impacts for the different scenarios examined are presented in Table 1.

The findings of E3ME regarding the potential for EU First Mover Advantage are consistent with those of GEM-E3-FIT. In particular, E3ME results show that there is the potential for a small FMA in the period immediately after 2030 (around 0.1% of GDP) but that this effect dissipates quickly and there are no lasting impacts.

Table 2: Macroeconomic impacts of alternative scenarios regarding EU energy, climate and R&D policy (E3ME)

cumulative change 2020 - 2050 from reference scenario, in %		**GDP**	**Investment**	**Private consumption**	**Net exports (trillion € 05) Clean Energy Technologies**	**Employment in Clean Energy Technologies**
Full Spillovers	**EU - Alone**	*1.0*	*2.1*	*0.8*	*0.17*	*0.2*
	Delay	*1.2*	*2.0*	*1.0*	*0.21*	*0.3*
	EU - FMA	*1.4*	*2.3*	*1.1*	*0.22*	*0.4*

Source: E3ME

Part II Introduction

Whether the EU clean energy technology[1] manufacturers can expand their market share and act as a locomotive for growth for the rest of the EU economy, either through their structural importance and integration in the economy or through driving technology innovations, depends on a multitude of factors. This case study focuses on the importance of economies of scale, learning by research and knowledge spillovers of clean energy technologies for the European economic and employment growth.

In order to assess the potential of clean energy technologies to contribute to EU economic growth, we estimate the potential for production cost reductions through massive production (economies of scale), through learning by research, through learning by waiting (free riding) and through knowledge spillovers. The potential cost reductions estimations are based on learning rates available in the literature and are combined with current market shares, cumulative capacities and R&D spending in order to calibrate the GEM-E3-FIT and E3ME models. Both models are used to quantify the economic implications of EU early action in adopting ambitious energy and climate policies and to assess the potential and conditions under which EU can get a first mover or comparative advantage. First-mover advantage is defined as the benefits that can be realised from acquiring early market share in a nascent market. First-movers entering into a new market undertake risks and bear costs in the short term aiming at reaping profits through monopoly rents in the longer term. A comparative advantage is regarded as the capability of a firm to produce a good of specific characteristics at a lower cost than its competitors. Comparative advantages are driven by factor endowments and technological progress. They enable the market penetration or the increase of current market shares. Comparative advantages can be mainly established through investment in technical progress and human capital whereas first mover advantages is established through timely[2] early action.

Part III of this report provides a literature survey regarding the factors driving comparative advantages with a focus on clean energy technologies and presents the previous findings of E3ME and GEM-E3 models on the potential for the EU to acquire a first mover advantage.

Part IV is dedicated to describing the current status of the global clean energy technologies market. The objective of this section is to set the starting point regarding market shares and competitiveness of the different clean energy technologies and to briefly present the key factors that have led certain industries and countries to be market leaders.

Part V presents regional R&D spending and the link to patents creation and Part VI provides the empirical evidence for the learning by research and by doing curves.

In Part VII the extensive work that has been performed in collecting and reconcilliating data on patents and citations is presented. In this part technology spillovers and how they are included in empirical modelling is also discussed.

In Part VIII the model based analysis on the potential for early action advantage for the EU industry and overall economy is presented.

Part IX discusses modelling caveats and provides suggestions for modelling improvements.

Part X concludes.

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[1] RES equipment, advanced heating and cooking appliances, electric/plug-in hybrid cars, advanced biofuel production

[2] If the first mover establishes a market for a product where demand is not sufficiently developed, i.e. too early, he/she will not be able to make expected profits.

Part III Literature findings on technological leadership and first mover advantages

Countries first adopting and developing a technology innovation are considered as a lead market, the market in which innovation takes place and the demand for the new technology is higher than in other countries of the world. This implies that firms can realise cost and quality advantages and technological leadership, as seen from such examples like the wind industry of Denmark. Technological innovation is associated with several interacting factors, including technological deployment, specialised human capital, public and private R&D expenditures, spillover effects between industries, sectors and countries and experience in specialised high-tech technology production. The potential of countries to become market leaders in a specific technology primarily depends on the factors discussed below, taking also stock from the work of Beise and Rennings (2005):

- Price and quality competitiveness: Competition is not only driven by price differentials but also by quality differentiation. This is especially the case for knowledge-intensive goods and services.
- Export dynamics: Innovations of a country should not only serve domestic demand but also be suitable for exports. Established export capacities of a country can enhance trade of new innovations.
- Learning, innovation and absorption potential: the ability of a country to perform technological learning and to absorb knowledge as well as its overall innovation dynamics
- Domestic demand: A country which has an innovation-oriented demand and firmly supports new technologies can become a lead market
- Institutional framework: Innovation-friendly regulation and subsidies for R&D investments

Many studies identify technological leadership[3] as the core source of first-mover advantage (Lieberman and Montgomery (1988)). The technological leadership provides a cost advantage to the early entrant in a market as long as the learning can be maintained proprietary for a sufficient time period (Spence, 1981).Hence, key to sustaining technological leadership is technology and knowledge diffusion. The latter may be highly beneficial for aggregate growth but may diminish the first-mover advantages of an industry over time. This is highlighted in Bosetti et al (2008) where results show that international knowledge spillovers tend to increase free-riding incentives and decrease the expenditure for investment in energy-related R&D. This can be particularly the case for high income countries where international knowledge flows crowd out domestic R&D efforts.

Assessments on the potential first mover advantage of the EU have been previously conducted by the models (or their earlier versions) contributing to this report.

In Pollitt et al (2015) E3ME model has been used to assess the impact of a European early climate action with the rest of the world following later. Explicit assumptions about market shares that were captured by EU companies are included in the analysis. The scenarios are highly ambitious and should be interpreted as the development of a completely new product that captures a large proportion of global market share rather than an incremental improvement that offers a marginally better product. In the paper, an increase in ambition for 2020 (25% GHG reduction rather than 20%) is included, along with the 80% reduction by 2050. The emission reductions are assumed to be

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[3] Technological leadership can provide advantages associated with the 'two factor learning' curve (costs are assumed to decline with cumulative output) and with the success in R&D (product or process technology advances are associated with R&D expenditures).

made through a carbon pricing mechanism with no revenue recycling (implying efficient emission reduction mechanisms but an overall cost to GDP).

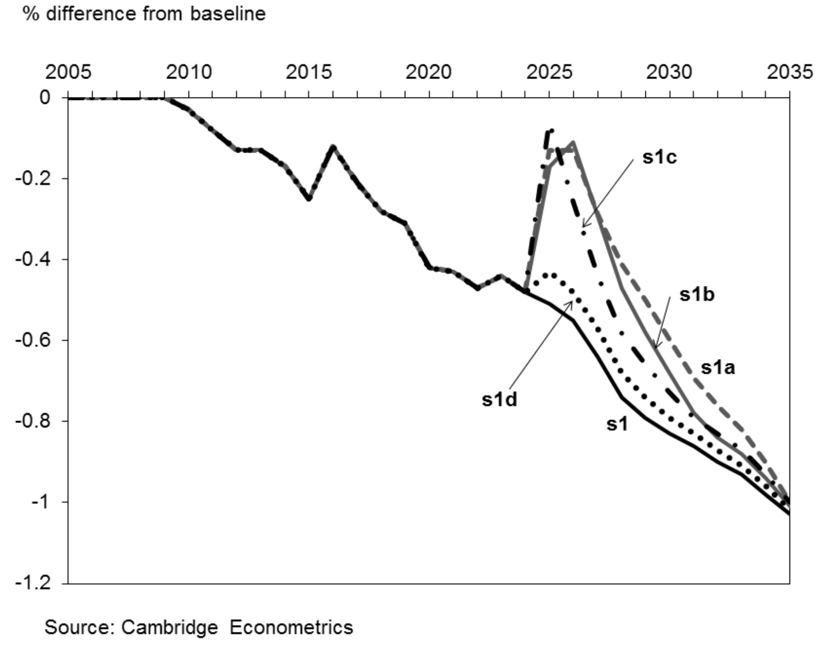
In Scenario 1 (S1) there was no FMA, but the variants assumed that EU production captured market share as follows:

Scenario	Summary description
S1a	EU enhanced policy with FMA in all renewables (25% market share)
S1b	EU enhanced policy with FMA in wind and solar technologies (100% market share)
S1c	EU enhanced policy with FMA in all renewables (50% market share)
S1d	EU enhanced policy with FMA in motor vehicles (1% market share)

S1d is based on an assumption that electric vehicles are produced in the EU but still make a relatively small share of total vehicle sales. In all cases it is assumed that the FMA is most beneficial in 2025 when other countries start to implement more stringent climate policy, but that the FMA is gradually eroded over time as other countries catch up in terms of technological progress. However, the modelling allows for the possibility that the initial boost to the EU can persist through the endogenous linkages that are outlined above.

The results of the analysis are shown in Figure 4. The cost to the EU of more ambitious climate policy is around 1% of GDP by 2035. In the short run, a large proportion of this cost could be reclaimed through benefits related to FMA, but the modelling suggests that these benefits could be quite short lived. By 2035, once the initial FMA has been lost there are only very minor positive effects (i.e. all the variants of S1 are close together). The conclusion from the analysis is that there are potential positive impacts from encouraging innovation, particularly innovation relating to FMA, but it must fit into a broader, more long-term plan to encourage technological development.

Figure 4: GDP temporal growth under different FMA scenarios, E3ME; Source: Pollitt et al (2015)

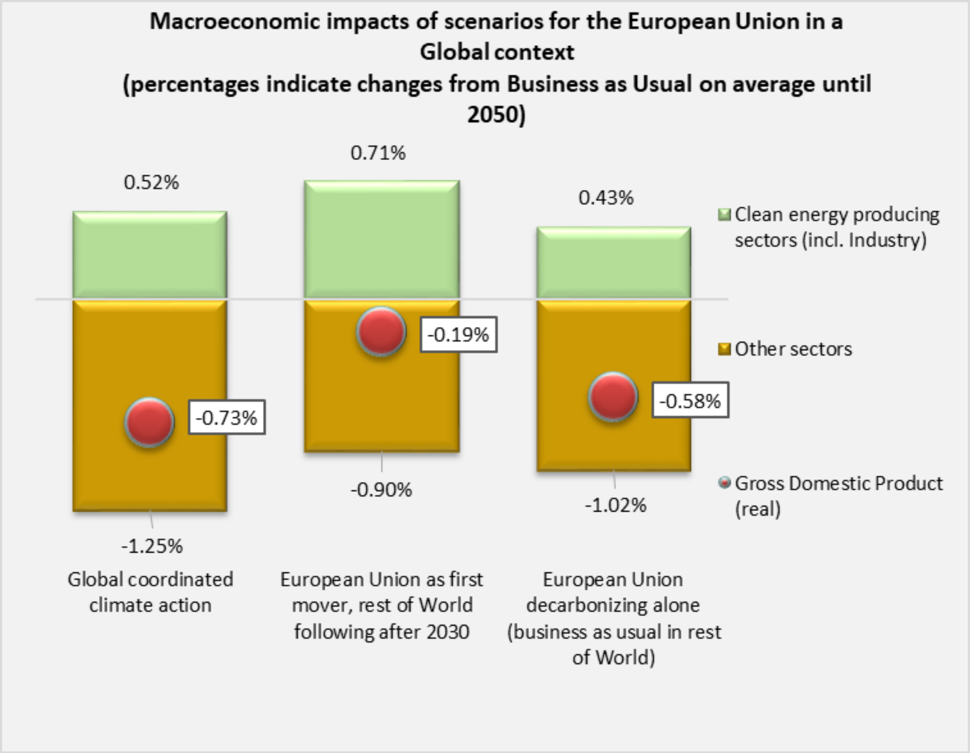


Source: Cambridge Econometrics

In Karkatsoulis et al. (2014) an assessment of the EU early action has been conducted with GEM-E3 model. They find that in case of a unilateral European climate action, the

EU would face negative impacts on GDP while the issue of climate change would remain open. Delaying action until the rest of the world takes action results in an even higher cost for the EU, as the required decarbonisation effort would be stronger and achieved in a shorter time frame. Further results indicate that the EU could benefit from first-mover advantages provided that the world as a whole would eventually implement sufficient climate change mitigation actions. The benefits for the EU are associated with the time frame allowed for the decarbonization of the European economy and with the advantage it can gain in developing clean energy technologies domestically. A longer time frame for decarbonisation will allow the EU economy to undertake the necessary structural changes without putting much pressure on the competitiveness of the EU economy, on factor and capital markets. Early action in clean energy technologies leaves the EU well positioned to address future increased demand for these technologies from the rest of the world.

Figure 5: Macro-economic impacts for the EU (in % cumulative changes from Baseline)



Source: Karkatsoulis et al (2014)

Karkatsoulis et al. (2014) move further to an analysis at a sectorial level. The stronger benefits for the EU are identified for the production of electric vehicles. It is also underlined that the export-related benefits of the EU critically depend on the international technology spillover assumptions. Numerous sensitivity runs with GEM-E3 confirm that technology diffusion can be extremely fast nowadays due to the global opening of trade and capital markets, independently of whether a country performs climate action or not. Karkatsoulis et al. (2014) include stylised scenarios regarding alternative regimes of intellectual property rights revealing an important trade-off: strict intellectual property rights bring economic benefits but also induce global economic losses by preventing other regions to use the advanced clean technologies while they carry out strong climate action. In summary, they find that the net potential gain to EU from undertaking a first mover action can be up to 0.54% of GDP and electric vehicles are the key technology contributing to EU exports. Similarly, Cleff (2016) surveyed the global refrigerator market where the lead producer is Germany, followed by Korea and Italy and found that first mover advantages can be realised in Germany, backed by high European efficiency standards which diffuse after some years to other countries.

Summary

The studies reviewed in this section suggest that acquiring technological leadership is key in establishing a comparative and first mover advantage. Sustaining the market leadership greatly depends on innovation, patenting and property rights framework and on the distance to the technological frontier of competitors. These studies find a first mover advantage for the EU and conclude that key low-carbon technology producing sectors are the electric cars and household appliances. Nevertheless, these findings are based on older datasets where industrial market shares and technology costs are very different from today. In this case study a new comprehensive assessment has been performed that delivers new insights that are discussed in detail in Part IX of this report.

Part IV The market of clean energy technologies today

Production and market share

The sectors producing clean energy technologies currently represent a relatively small global market size (0.1% of global GDP in 2005 and 0.2% in 2010). However, there is a large potential for expansion of clean energy production in the medium and long term depending on the reduction of their costs and adoption of ambitious energy and climate policies worldwide.

Photovoltaics

The regional production of photovoltaics has undergone a rapid transformation in recent years with a fast erosion of the Japanese dominance and the spectacular emergence of China as the dominant player in the global market, largely due to the massive Chinese exports to the EU-28 region (Table 3 is based on data collected from EPI, 2013a and Fraunhofer, 2016). As stated in JRC (2015), the share of EU production in global PV market has dropped from 26% in 2008 to a mere 5% in 2015 with Germany accounting for the bulk of EU production. The share of the Chinese production increased rapidly from 3% in 2004 to 55% in 2011 and thus China accounts for more than half of the global production of photovoltaic panels in the period after 2010. The regional production and global trade of the sector are determined by the evolution of the PV module cost and not by the overall capital cost[4] of the technology.

Table 3 Country shares in the global market for solar photovoltaics over 2003-2015

	China	**Taiwan**	**Germany**	**Japan**	**S. Korea**	**USA**	**Malaysia**	**Others**
2003	2%	2%	16%	49%	0%	14%	0%	17%
2004	3%	3%	16%	50%	0%	12%	0%	16%
2005	7%	5%	19%	47%	0%	9%	0%	13%
2006	14%	7%	19%	38%	1%	7%	0%	15%
2007	23%	10%	21%	25%	0%	7%	0%	14%
2008	28%	11%	21%	18%	1%	5%	2%	13%
2009	37%	12%	14%	13%	1%	5%	7%	10%
2010	45%	13%	9%	9%	3%	5%	6%	10%
2011	55%	12%	6%	7%	3%	3%	5%	9%
2012	56%	13%	4%	7%	3%	2%	5%	10%
2013	56%	13%	4%	8%	3%	3%	5%	8%
2014	56%	13%	5%	8%	3%	3%	6%	6%
2015	55%	12%	5%	7%	3%	3%	7%	8%

Source: E3-Modelling based on EPI, 2013a and Fraunhofer, 2015

Figure 6 Regional shares in the global market for photovoltaics (period 2008-2014)

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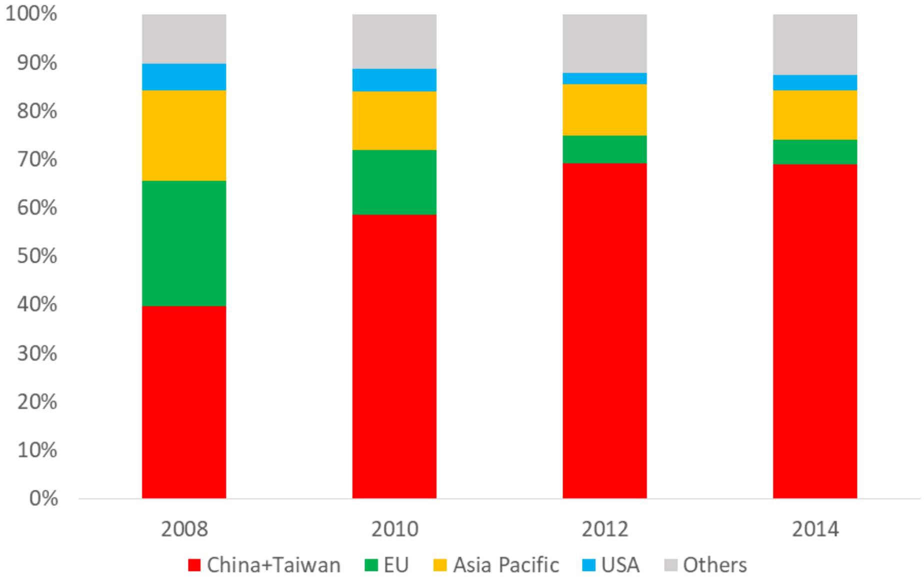
[4] In order to estimate data for the "Production of PV equipment" sector, the overall capital cost of photovoltaics (derived from the EU Reference scenario 2016) has to be decomposed into its structural parts by taking into account the cost structure of PV installations. The latter comprises of the PV module cost (solar cells, wafer, module assembly etc.) and the Balance of system (BOS) cost (inverters, wiring, electrical system costs, battery or other storage system). As indicated in Ernst & Young and Solar Power Europe (2015) Balance of System components are not traded on global markets, unlike PV modules. According to IRENA report, 2012 the BOS costs for utility-scale PV plants accounted for 20% of the overall PV capital costs for a simple grid-connected system in 2010. A more recent report (Ernst and Young and Solar Power Europe, 2015) identifies that the share of BOS components in gross value added of PV production in Europe is about 50%. Therefore, the GEM-E3-FIT sector "Production of PV equipment" is assumed to account for 80%of the overall PV production by region as derived from PV production data. Therefore, global trade of the sector is determined by the evolution of the PV module cost and not by the overall capital cost of the technology.



Source: E3-Modelling based on various data sources

Wind turbines

Historical data for global production of wind turbines (in MW of manufacturing) is obtained from data compiled by Earth Policy Institute (EPI, 2013b). Data for regional shares in the global wind power market are obtained from the Navigant Company, 2015 by major wind turbine producing company. Companies included in the analysis represented approximately 75%-80% of the world market for wind turbines in the period 2008-2012.

In contrast to the PV manufacturing industry that has been relocated outside the EU in recent years, the EU has managed to maintain a large share of global production of wind turbines mainly in Germany (Siemens, Enercon, Nordex and Senvion), in Denmark (Vestas) and in Spain (Gamesa).

Wind energy has more installed capacity than any other non-hydro renewable energy source amounting to about 487 GW globally in 2016. Wind turbines are sold into a global market, and each main manufacturer (GE, Siemens, Vestas, Gamesa) has its own supply chain. The manufacturing of wind turbines has become an established global industry with a (direct and indirect) value added of 32.5 billion USD in 2014 (CEMAC, 2016). The supply chain of the wind production industry includes:

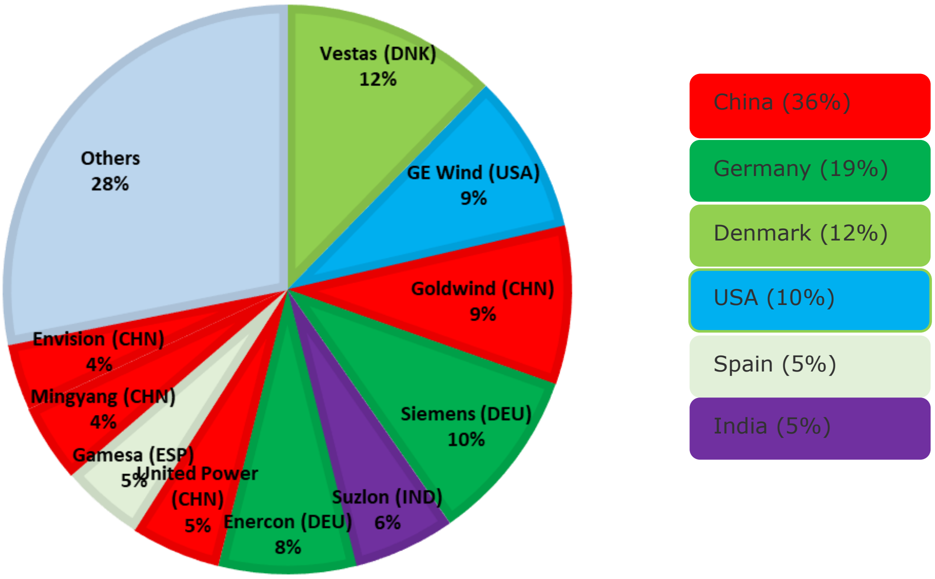
- Raw materials: Iron ore, silica, copper, aluminium;
- Processed materials: Steel, carbon fiber, fiberglass;
- Sub-components: Generator, steel components, magnets;
- End products: nacelle, blades, tower.

A specific feature of wind turbine manufacturing is that several parts of its supply chain connect well to established and mature manufacturing industries, such as steel production, industrial generator and gear production and carbon fibre manufacturing. Such complementarities create both opportunities and challenges for suppliers of wind turbine components. Europe has experienced robust wind power demand in the last decade and has established a sophisticated manufacturing sector.

Given the existing skill sets and infrastructure, EU manufacturers continue to supply the vast majority of domestic EU demand and export wind turbines to other economies that have not yet developed local competitive manufacturing capacity. On the other hand, high transportation costs can constrain the opportunities for further EU export potential to non-EU countries, while Chinese and U.S. manufacturers have increased their production capacity to cover anticipated growth of domestic demand. It is expected that high transportation costs and increasing size of projects (especially for offshore installations) will eventually lead to company mergers with many subsidiaries globally.

European companies (located in Germany, Denmark and Spain) hold major market shares in wind turbine production accounting for 44% of global turbine production in 2016 as a result of the EU's technology leadership (Navigant Research, 2016). EU companies represent 93% of global wind turbine exports in 2015 (Eurobserver, 2016). European companies despite numerous examples of protectionist policies outside the EU, have achieved a higher share in foreign markets than the share of non-EU manufacturers in the EU market. This is related to the EU's technology leadership (especially in Denmark and Germany) and its first mover advantage (Wind Europe (2016), Brandt and Svendsen (2004), Agora Energiewende (2015)). The large share of EU exports in global exports shows that transportation costs and external rivals are not yet a significant barrier to EU Wind manufacturers. In addition, European component suppliers (electronics, gearboxes, generators, blades, rotors), research institutes, consultancies and turbine developers are reaping significant benefits from the development of the global wind industry, particularly in China, India, USA and Latin America.

Figure 7 Company shares in the global market for wind turbines in 2014



Source: E3-Modelling based on Navigant Research, 2015

Overall, wind energy technology continues to evolve, driven by: mounting global competition; the need to improve the ease and cost of turbine manufacturing and transportation; the need to optimise power generation at lower wind speeds; and increasingly by demanding grid codes to deal with rising penetration of variable renewable sources. The wind industry has refined and improved materials, processes and design as well as installation and O&M regimes. Significant effort has been devoted to reduce logistical challenges and transportation costs. In parallel, the innovation process is very important to ensure cost-efficiency and improved performance of wind turbines, with recent innovations including two-part blades, nesting towers and portable concrete manufacturing facilities for tower construction.

As compared to other industries like the PV sector, the reasons why wind industry has succeeded in gaining and maintaining a high market share in global production can be summarised to the below listed factors that need to be considered in combination:

- **Early Action:** The Danish wind association was already established in 1981, despite the strong tradition of the Danish government not to support specific firms and industries (Denmark and the EU, Miles and Wivel 2014) and (Sidenius, 1984)

- **Transportation costs**: Transporting 30 meter blades atop a 60 meter tower requires sophisticated ships and cranes and in certain cases widening of roads new roads built. High transportation costs support the creation of regional markets of the wind turbines trade (mainly for off-shore wind).
- **Patenting and spillovers**: In order to build a Wind (or PV) tower requires cumulative knowledge expertise and semi-automated factories. In the case of PV, China succeeded to buy companies and attract skilled personnel and thus quickly covered the technology gap. In the wind industry, however, Chinese wind turbine manufacturers have secured only a few international patents and achieved moderate learning rates compared to the global industry's historical learning rate Tam et al (2017). High spillovers within the industry, although not always beneficial to the innovator (depending on the royalties policy), can always benefit the industry as a whole (as Wind power competes with other RES technologies).
- **Size and type of financial support**: Wind installations are sizable as opposed to solar PV (where also rooftop installations are possible). This feature creates a market where firms of a particular size can compete excluding the early entrance of small sized companies. Public support to rooftop solar panels benefited also many non – EU companies to penetrate the EU market.
- **Innovation**: Industry constantly invests in innovation[5] so as to improve its products along the whole value chain and to reduce costs faster than the market average, and thereby stay competitive (Vestas, 2016). Competition here is considered both among industries and among RES technologies.
- **Demand**: Up until today the growth in EU demand for wind turbine installations was a major factor considering that more than 60% of turbine manufacturing is installed domestically in EU countries.
- **Established Capacity**: The existing excellent know-how and innovation potential of EU wind manufacturers can be of great importance to enable the penetration in rapidly growing emerging economies. An example for this is EDF entering the Chinese market by acquiring UPC Asia Wind Management.

Electric cars

In recent years, plug-in hybrid and electric vehicles registrations follow an explosive path, as shown in the table below. In the year 2015 the global threshold of 1 million electric cars on the road exceeded, closing at 1.26 million. This achievement highlights significant efforts deployed jointly by governments and industry over the past ten years, as ambitious targets, policy support and increased R&D investment have lowered electric vehicle costs, extended vehicle range and reduced consumer barriers in a number of countries.

Electric vehicle sales are concentrated in three main markets, namely China, USA and EU-28, which jointly accounted for about 87% of global market in 2015 (IEA, 2016) and for 82% of the global stock of electric vehicles (cumulative registrations up to 2015). The early market developed in Japan has failed to develop at rapid rates and in 2015 China became the biggest world market exceeding sales in the USA for the first time. European sales have grown steadily from 2011 and Europe is now the second biggest market.

Table 4 Global and country sales of electric and plug-in hybrid vehicles over 2011-2015

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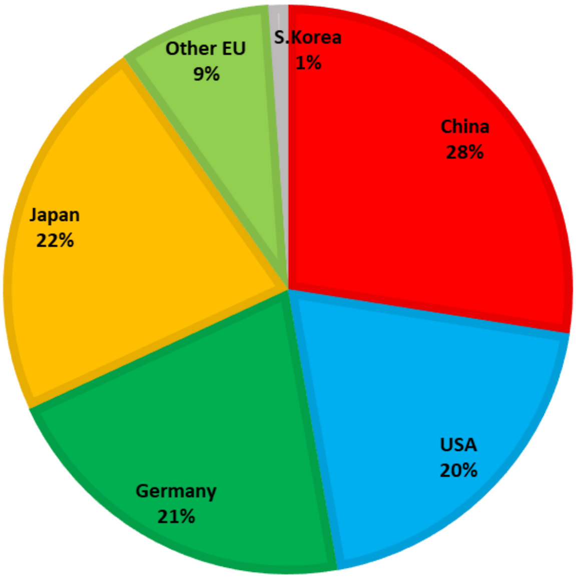
[5] The EU industries innovation focus on maximising turbine efficiency and reliability, improving towers and foundations as well as enhancing operation and maintenance.

1000s, vehicles	**2011**	**2012**	**2013**	**2014**	**2015**
World	48.2	118.6	203.9	323.7	550.1
China	5.1	9.9	15.3	73.2	207.4
EU-28	9.5	22.6	50.6	73.6	155.9
USA	17.7	53.2	96.7	118.8	113.9
Norway	2.0	4.4	8.2	19.8	35.6

Source: E3Modelling, Calculations based on IEA, 2016

The rapid growth in the Chinese electric car market is a result of the establishment of a range of incentives and other government interventions. This growth has been achieved largely through domestic vehicle manufacturers. The overall picture is that European manufacturers are competitive in supplying electric and plug-in hybrid vehicles and the EU has the potential to remain a particularly important player in the global market (both in production and in sales); The latter highly depends on continuation and even strengthening of ambitious CO2 reduction policies (especially CO2 standards in transport) and policies to support EU's technology leadership in a highly competitive global market. Given its ongoing investments in further production capacity for electric cars and their batteries and the rapidly expanding domestic demand, China is expected to remain one of the biggest global market players in electric car production (Transport and Environment, 2016).

Figure 8 Country shares in the global market for electric and plug-in hybrid vehicles in 2015



Source: E3Modelling calculations based on Electric Cars Report (2016)

The trade patterns indicate increased trade flows between regions (*Table 5*). A prominent feature of the Chinese electric vehicle market is that domestic manufacturers account for more than 90% of electric and plug-in hybrid sales. On the other hand, Chinese exports remain limited mainly as a result of high safety standards that are in place in all major developed economies.

Table 5 Trade flows of electric and plug-in hybrid vehicles in 2015 (Rows indicate producers)

Number of vehicles	**EU**	**China**	**Japan**	**Norway**	**S. Korea**	**USA**
Germany	64778	4200	1100	18059	443	7386
Japan	44293	4098	23160	8724	0	33743
USA	10298	12443	400	4077	0	68430
S. Korea	5537	0	0	2084	2367	0

China	1107	186642	0	0	0	0
France	19932	0	0	2666	0	0
Sweden	9966	0	0	0	0	0
Italy	0	0	0	0	0	4311
Total	**155910**	**207380**	**24660**	**35610**	**2810**	**113870**

Source: E3-Modelling calculations based on national sources

Batteries for electric cars

The battery is the key component that will determine the development and uptake of electric vehicles, as battery costs, availability and technical performance are key aspects for growth in e-mobility. Batteries used in electric cars are quite different from those used in consumer electronic devices such as laptops and cell phones, as they are required to handle high power and high energy capacity (tens of kWh) within a limited space and weight and at an affordable cost. Currently, there are two major battery technologies used in electric cars, namely nickel metal hydride (NiMH) and lithium ion (Li-ion). NiMH batteries are used in the vast majority of hybrid vehicles as they are a mature technology. Most Li-ion battery production knowledge was developed by consumer electronics firms, which have created integrated supply chains and accumulated significant production experience, much of which is transferrable to the production of Li-ion batteries for automotive markets (CEMAC, 2016). The adoption of Li-ion batteries is expected to grow fast in electric and plug-in hybrid cars, mainly due to the potential for obtaining higher energy density[6] and large cost reduction (Garcia-Valle, 2013). Vertical integration exists across Asian electrode materials and cell production, which may also contribute to lower input costs for certain manufacturers.

Since the 1980s battery production has been dominated by companies in South Korea and Japan, but in recent years the Chinese share has increased rapidly. Global battery production for EVs is currently dominated by Panasonic (Figure 9), which has a strategic partnership with Tesla to whom it sells most of its battery production (Cleantechnica 2016). Panasonic output is expected to increase drastically in the near future, due to the opening of Tesla and Panasonic's new joint venture "Gigafactory" in the Nevada Desert, with a planned output of 35GWh per year[7]. The Chinese BYD has invested billions into its own battery cell technology, is currently the second largest battery producer and is expected to rival Panasonic's battery production capacity by 2020. Overall, the global EV battery production is dominated by Asian manufacturers with Japan accounting for 56%, China 25% and Korea for 17% of the global manufacturing. Batteries currently represent[8] 35-50% of total costs of electric vehicles production. In addition, manufacturing of batteries as indicated by the production structure of IO tables are more labour intensive relative to vehicles manufacturing[9].

The continuing dependence on battery packs manufactured in the Far East is limiting the value added that Europe can get from deployment of electric cars, as batteries are to a large extent imported from Asia; thus a large part of the employment and value chain indirect impacts related to the production of electric cars is not created in Europe.

This concern however now appears to be receding with a number of announcements for new battery plants in Europe, e.g. Volkswagen as part of its new 2025 Strategy has outlined plans for a €10 billion battery factory in Salzgitter in Germany, Samsung and LG

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[6] It should be noted that there are several types of Li-ion batteries based on similar but certainly different battery chemistry.

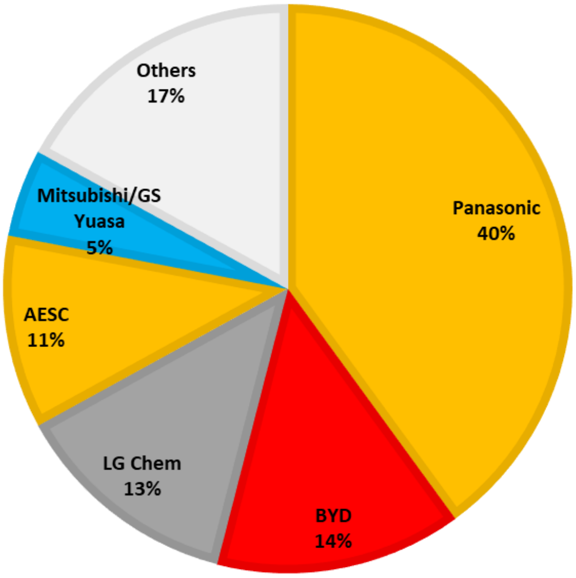
[7] This "Gigafactory" will increase current battery manufacturing capacity by about 70%.

[8] Fuchs et al (2014), An overview of costs for vehicle components, fuels and greenhouse gas emissions

[9] Using the SBS EUROSTAT statistics the employment required per 1. m€ sales of batteries is 3.1 persons and 1.8 for motor vehicles.

Chem plan to invest in EV battery factories in Hungary and Poland respectively to exploit the rapidly growing EU demand, while Ford, BMW and Tesla also consider building battery factories in Europe. Besides, the European Commission has now launched a European Alliance for Batteries in initiative, aiming at promoting the development of this sector in the EU.

Figure 9: Shares in global Battery production for automotive applications in 2015



Source: E3-Modelling calculations based on Cleantechnica 2016 and Transport and Environment, 2016

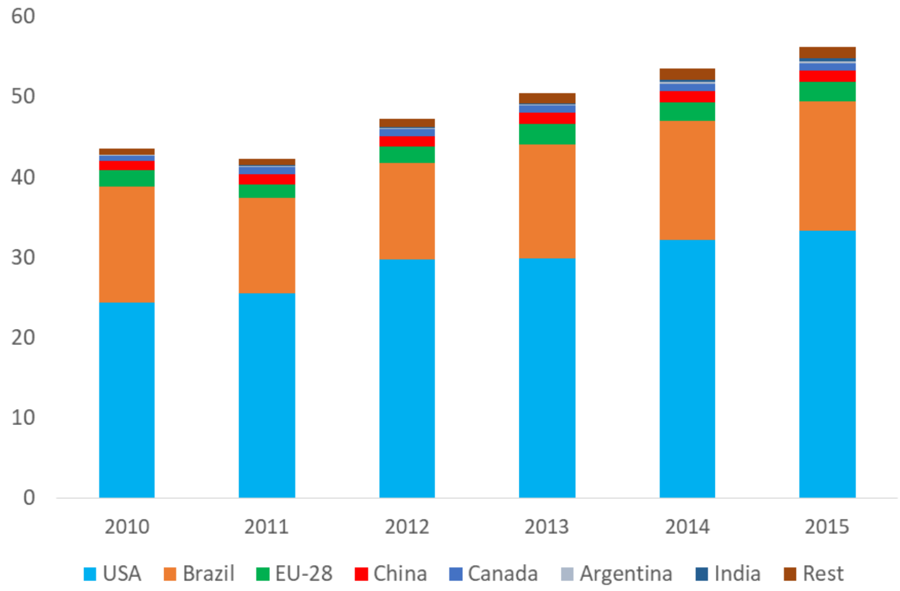
Biofuels

Biofuels constitute a major ingredient for energy and climate policies in the EU, as they substitute CO_2 emitting conventional liquid fuels in the transport sector, while also having the potential to improve energy security of the European economy. Biofuels are already widely used especially mixed with fossil fuels in several parts of the world notably in the EU, Brazil and North America largely motivated by high oil prices prevailing in world markets in recent years (especially in the period 2010-2014) and policy support.

In 2015 global ethanol production was higher than biodiesel and amounted to about 56 Mtoe (Figure 10). The production of ethanol has been known for several years and ethanol has played an important role as an additive in petroleum fuels for many years. Ethanol is produced using first-generation food crops, such as corn. The problem with ethanol is that, while it is a great fuel additive, it is a poor standalone fuel. Biodiesel, on the other hand, is a superior standalone fuel and can be used in conventional engines with little modification.

The USA leads the global bioethanol market with a production of 33.3 Mtoe in 2015; thus the US represent more than 59% of the global production in 2015 up from 43% in 2010. Brazil is also a major producer accounting for about 29% of the global bioethanol production in 2015, while the production in EU-28 and in China has not significantly increased from 2010 levels. Some countries use ethanol almost exclusively for fuel, while others use it only as an additive. The trade in ethanol is rather limited and accounted for about 3.5 Mtoe in 2015, as in most countries domestic production keeps up with domestic ethanol consumption. In terms of balance of trade, USA and Brazil are the major exporters accounting for more than 75% of global exports, while Canada and EU-28 are the main ethanol importers with Canada importing the bulk of ethanol from USA.

Figure 10 Bioethanol production in major producers over 2010-2015 (in Mtoe)



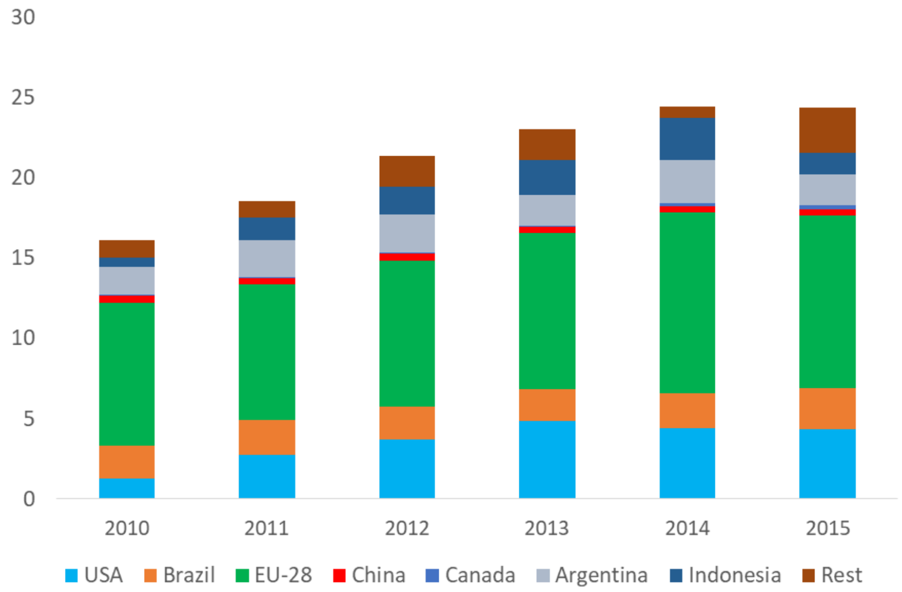
Source: E3-Modelling calculations based on Enerdata database (2017)

Main EU-28 ethanol consumers in 2015 were Germany, the United Kingdom and France, followed by Spain, Sweden, Poland and the Netherlands (European Commission, Renewable Energy progress report, 2017). In 2015, around 10% of bioethanol consumed in the EU was imported, most of which originating from USA (about 50%) as well as from countries participating in EU Special Incentive Arrangement for Sustainable Development and Good Governance ("GSP+"), i.e. Bolivia, Pakistan and Peru.

The EU is the world's largest biodiesel producer with production amounting to 10.8 Mtoe in 2015 (Figure 11); this represents about 45% of global production. EU biodiesel production is driven by domestic consumption and competition from imports. USA and Brazil are important biodiesel producers representing about 18% and 10% of the global production in 2015 respectively. Regulations on diesel emissions are an important factor explaining why biodiesel production lags in the U.S. relative to EU. Other major biodiesel producers include Argentina (1.9 Mtoe), Indonesia (1.4 Mtoe) and Malaysia (0.6 Mtoe). USA is the major importer of biodiesel with net imports amounting to 1.8 Mtoe in 2015 mainly from Argentina and Indonesia.

The largest EU biodiesel producers are Germany, Spain, France, Netherlands and Poland. EU biodiesel net imports have declined from 2.7 Mtoe in 2012 to only 0.5 Mtoe in 2015 (USDA, 2016) thus representing only 4% of domestic EU consumption. In an attempt to reduce biodiesel imports from Argentina and Indonesia, the EC enforced anti-dumping duties (AD) on biodiesel imports from 2013 leading to a considerable drop in EU imports from both countries in 2013 (imports from these countries stopped in 2014). The gap was filled with domestic EU production and higher imports from countries not covered by AD, like Malaysia, South Korea, and Brazil. EU exports to non-EU regions are negligible. On the other hand, there is significant intra-EU trade with Netherlands, Germany and Spain being the major exporters, while Italy, France, Sweden and UK are the major biodiesel importers.

Figure 11: Biodiesel production in major producers over 2010-2015 (in Mtoe)



Source: E3-Modelling calculations based on Enerdata database (2017)

CCS

Apart from small demonstration plants, Carbon Capture and Storage (CCS) technologies are virtually non-existent as no commercial CCS projects have been developed by the end of 2015.

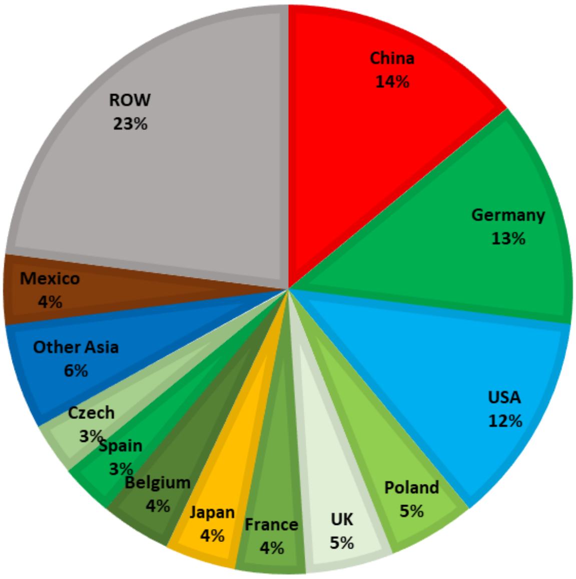
Insulation materials

Insulation materials are the building materials which form the thermal envelope of a building and/or reduce heat transfer. Insulation materials include bulky fiber materials, such as fiberglass, rock and slag wool, cellulose, natural fibers and rigid foam boards to sleek foils. Bulky materials resist conductive and (to a lesser degree) convective heat flow in a building, while rigid foam boards trap air or another gas to resist conductive heat flow. The classification of a specific good/ commodity as an "insulation material" is not straightforward, as it is the case for other clean energy technologies, such as solar panels and wind turbines.

As comprehensive data for the production of "insulation materials" by country are scarce, data from the United Nations Commodity Trade Statistics Database (UN Comtrade, 2017) are used to derive consistent estimates/proxies of regional production of insulation materials. In particular, exports of the commodities related to building insulation materials are derived from (UN Comtrade, 2017) and are used to calculate country production of insulation materials. The sector aggregates the following commodities of the COMTRADE data with classifications codes: 761010 "Aluminium Doors, windows, frames and thresholds", 390311 "Polystyrene, expansible in primary forms" , 6806 "Slag wool, rock wool, insulating minerals not asbestos", 7008 "Multiple-walled insulating units of glass" and 701990 "Glass fibres, glass wool and articles thereof".

The figure below presents the shares of major market players in global trade of insulation materials in 2015. Major exporters of insulation materials are China (14% of world trade), Germany (13%) and USA (12%). The share of EU in global trade amounts to about 44%.

Figure 12: Export Shares of key building insulation materials in 2015



Source: E3-Modelling calculations based on the UN COMTRADE database

Household Appliances

In recent years, the global market of energy efficient household appliances is growing rapidly, driven by increasing energy prices[10], global urbanisation trends, cost-efficiency relative to conventional appliances and establishment of ambitious regulations and standards in the EU and in other developed economies. Due to the lack of comprehensive dataset for country production of energy efficient household appliances, the UN COMTRADE data (UN Comtrade, 2017) has been used to derive proxies for the regional allocation of global production. In particular, the analysis aggregates the following commodities of the COMTRADE data with classifications codes: 841510 "Air conditioners window/wall types, self-contained", 8509 "Electro-mechanical domestic appliances, with self-contained electric motor", 841810 "Combined refrigerator-freezers, two door" and 842211 "Dish washing machines (domestic)".

Overall exports of household appliances are used as proxies to estimate production of energy efficient appliances by country. China is the major producer of domestic household appliances accounting for 43% of the global market. The EU is also a major producer with a 23% share in the global market for household appliances; its share in dish washers exceeds 65%. OECD economies with non-negligible shares in global market include Korea, Mexico, Germany and USA.

Figure 13: Production Shares of domestic appliances in 2015

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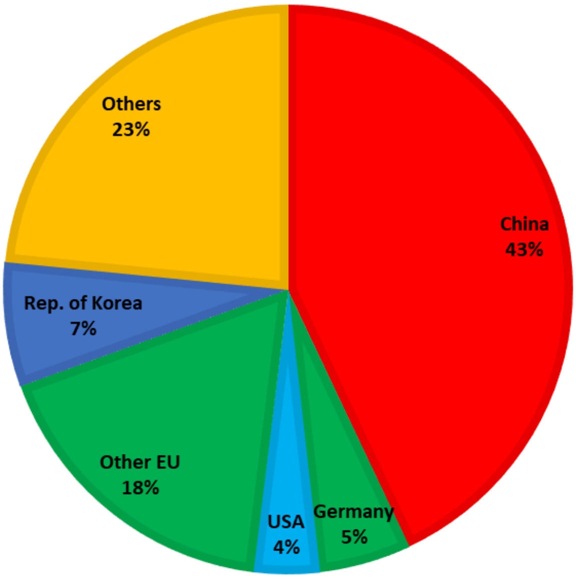
[10] At least until 2015



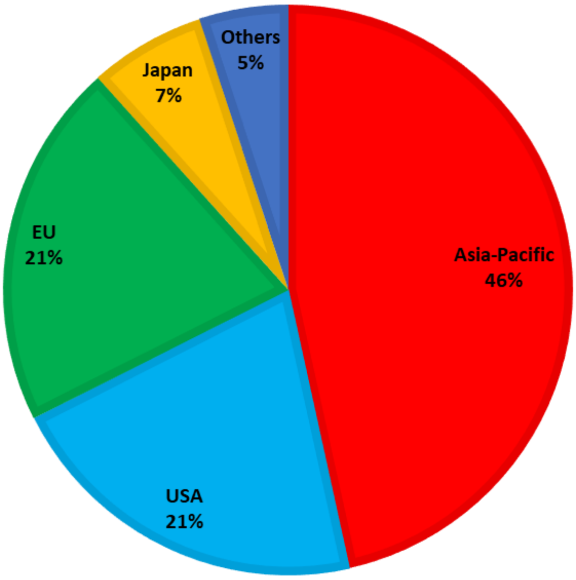
Source: E3-Modelling calculations based on the UN COMTRADE database

Batteries

The massive expansion of RES projected for the EU would imply requirements for electricity storage in order to smooth electricity load, to efficiently balance fluctuations in RES generation and meet the growing demand for electricity. Several options for storage exist, including pumped hydro storage, batteries, compressed air energy storage and power-to-X technologies that can act indirectly as storage systems by converting power to gas, synthetic liquid fuel or hydrogen. Contrary to EV applications, batteries for stationary storage do not suffer from mass or volume constraints. However, the cost per power or energy unit is crucial for their massive deployment. There are various types of batteries used today, including lead acid, lithium-ion (Li-ion), nickel cadmium (Ni-Cd), sodium sulphur (NaS) and vanadium redox (VRB). Their lower cost combined with positive technical characteristics make Li-ion batteries a competitive candidate in many industrial, grid storage and RES storage systems, where lead-acid systems are widely used today (Roland Berger, 2012). However due to the diverse set of requirements in grid uses, Li-ion batteries are not going to be the only feasible storage option (contrary to the EV market) and they would compete with lead acid, sodium sulphur and VRB batteries. The energy storage market ranges from photovoltaic installations for private users (energy management in buildings) to decentralised energy storage for grid management (e.g. for large-scale wind power generators). Requirements for the production of large-sized batteries constitutes a challenge for traditional battery manufacturers (Japan, Korea, China) and German suppliers can have a realistic opportunity of catching up the Asian lead (VDMA, 2014).

The market size of batteries used in energy storage applications is much smaller relative to the market for electric cars (Roland Berger, 2012). Combining data from UN Comtrade (commodity 8506), CEMAC (2016) and Future Market Insights (2015), an estimate of regional allocation of production of lead-acid batteries (which are currently the main option used in energy and power storage) is implemented. China and the USA are the major producers of lead acid batteries, while the dominance of USA manufacturers has gradually been eroded in recent years. The EU holds a significant share in global lead-acid battery production with a share of 21% in 2015.

Figure 14: Shares of major lead-acid battery producers in the global market in 2015



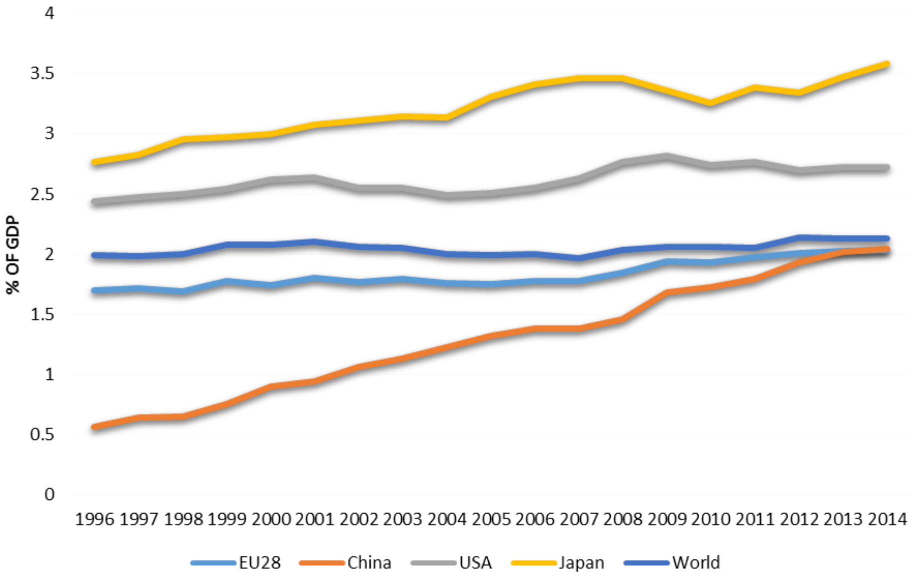
Source: E3-Modelling calculations based on the UN COMTRADE database and Future Market Insights (2015)

Part V R&D expenditure on clean energy technologies

The adoption of ambitious energy and climate policies from the EU can establish and orient the size of the clean energy technologies market, but cannot establish on their own right a first mover advantage for the EU. Both domestic and non-EU industries will compete for gaining a share in the EU market.

In parallel, R&D expenditure is a key determinant for building an increased potential on technological learning, innovation and knowledge absorption, thus plays a key role in developing a lead market. This is particularly the case for new technologies and for new markets that develop during a system transition, such as the low-carbon energy system transition. While at the global level total R&D expenditure is rather stable, as % of GDP, regional shares evolve in time (Figure 15).

Figure 15: R&D expenditure as % of GDP



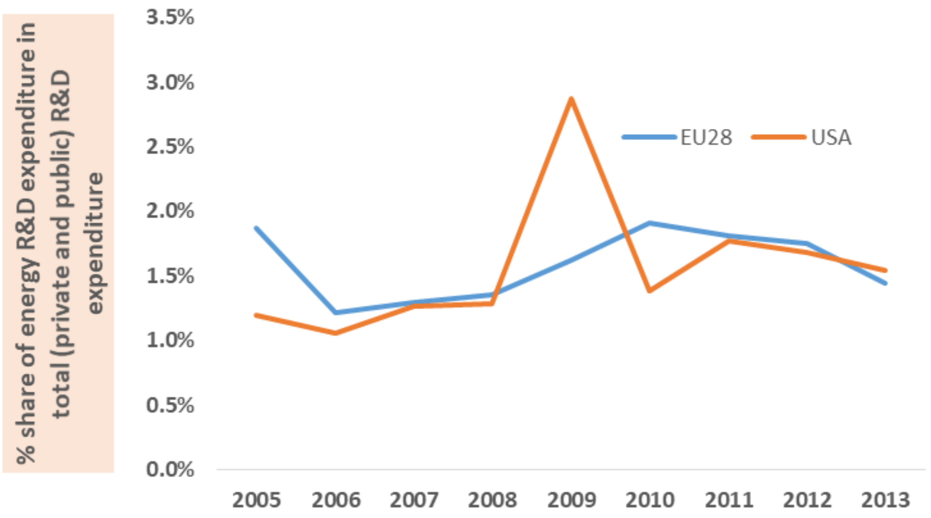
Source: Based on World-Bank data

R&D expenditure on clean energy technologies

R&D expenditure can increase knowledge stocks and thus is linked with the positive externalities of technological progress. With regards to energy technologies, Kouvaritakis et al (2000) introduced a two-factor learning curve that links the increase in knowledge stock to decreasing unit costs of production, while Klassen et al (2005) provide an empirical validation of the two-factor learning curve depending on cumulative capacity and R&D knowledge stock for the wind power sector. Similarly, Watanabe et al (2000 and 2003) reaffirm the link between knowledge and cost reduction of clean power technologies and in particular describe the "virtuous cycle" between R&D, market growth and price reductions by also providing the quantification of this cycle for PV development in Japan. Existing literature also links innovation (measured either through R&D expenditure or through the number of patents) to trade flows and shows a linkage with increasing exports (Buxton et al (1991), Zao and Li (1997), Aw et al (2009)), while more particularly Kim and Kim (2015) find significant interrelations between R&D and trade for different renewable technologies.

In 2013 total energy related R&D expenditure (including both public and private R&D) of the EU28 was 0.9% of total R&D expenditure. For USA in the period 2005-2013 this share was 1.3%, with the exception of 2009, when the US share reached 3.3% driven by increased R&D expenditures on fossil fuel based technologies (Figure 16).

Figure 16: Energy-related R&D expenditure in EU28 and USA (2005-2013)



Source: E3Modelling calculations based on IEA/OECD, Eurostat data

Figure 17 presents the evolution of R&D expenditures by energy technology in the OECD countries. Nuclear energy held the biggest share in total Energy R&D expenditure till the early 80s', while innovation in renewables and energy efficiency technologies is steadily gaining ground, enabling a more diverse and balanced energy R&D portfolio. R&D on fossil fuel extraction and combustion technologies is still high but with a decreasing gap from RES-related R&D expenditure.

In 2014, R&D on biofuels accounted for more than 50% of total R&D expenditure on clean energy technologies, followed by PV (around 24%) and wind (around 17%). The above-mentioned R&D structure across energy technologies is different when China is added to the analysis. Frankfurt School (2016) finds that in 2015 solar technologies constitute 50% of global R&D investment in RES technologies, followed by wind (20%) and biofuels (18%).

In 2015 "China's R&D spending on RES challenged Europe's for the first time" (Frankfurt School, 2016), with both economies being the global frontrunners and investing around 2.7bl €2015 or about 31% each of the global R&D in RES, followed by the USA (18%). China, in particular, is a rapidly growing investor in solar innovation technologies and is now even ahead of the US in certain key solar technologies (Ball et al 2017).

The EU28 has the largest share of R&D expenditure in wind technologies with 46% of wind R&D expenditure in the OECD in 2012, but with a decreasing trend as the respective share was 54% in 2000. Japan's main direction of R&D funds is nuclear power, while the EU28 maintains a stable share of around 30% in the OECD group. R&D in biofuel technologies has increased remarkably since 2000, but the respective EU share is steadily decreasing, leaving a gap that is being filled by the US. Biomass R&D expenditure is led almost entirely by the EU28 within the OECD, but its fraction in total energy related R&D is very low.

Figure 17: Historical R&D expenditures in energy technologies by OECD countries,

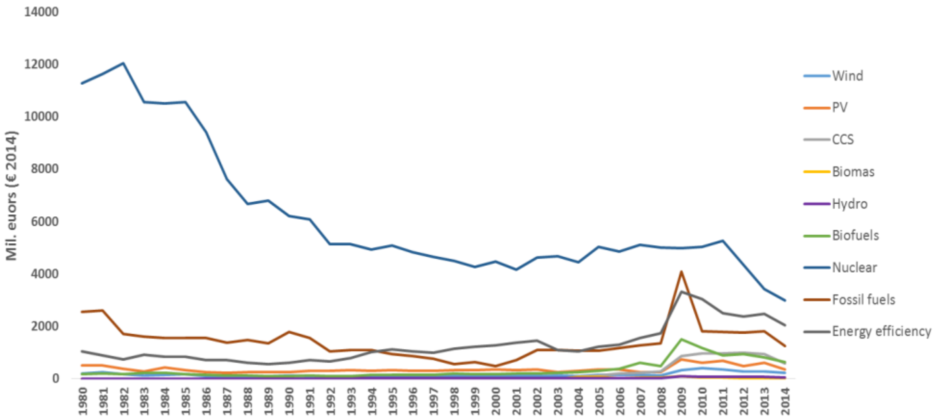
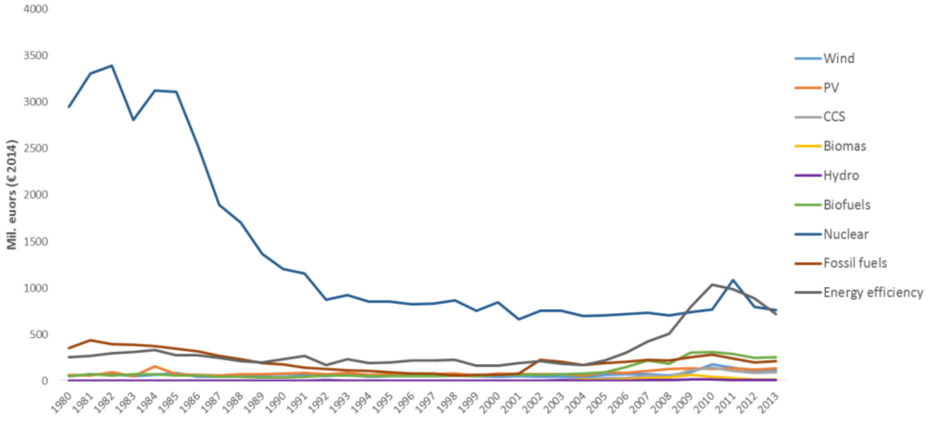


Figure 18: Evolution of R&D expenditures in energy technologies for EU28



Source: E3Modelling calculations based on IEA/OECD, Eurostat data

The number of patents regarding electricity innovations (Table 6) submitted to the European Patent Office (EPO) suggest that innovation on electricity is a priority for EU countries , as in 2013 17% of total European patents and 21% of total patents submitted to the European Patent Office were related to electricity.

Table 6: Electricity-related patent applications to European Patent Office (EPO), 2013, Eurostat data

	Total	Electricity	Electricity patents in total
European Union (28 countries)	**46,479**	**7,947**	**17%**
Turkey	335	30	9%
Russia	253	47	19%
South Africa	91	6	7%
Canada	1,827	491	27%
United States	29,497	5,511	19%
Mexico	65	9	14%
Brazil	160	15	9%
China (except Hong Kong)	4,808	2,361	49%
Hong Kong	63	17	26%
Japan	15,946	3,860	24%
South Korea	5,664	2,340	41%
Taiwan	1,092	412	38%
India	815	146	18%
Singapore	254	31	12%
Israel	997	158	16%
Australia	640	88	14%
New Zealand	132	7	5%
All countries of the world	**113,612**	**24,092**	**21%**

Source: EUROSTAT

Patents on clean energy technologies

Using patent data to trace innovation and other technology activities is a common practice in literature (e.g. OECD, 2011, Griliches 1990, Rogers 1998) as is thoroughly described in Albino et al (2014). Popp (2005) highlights the value of using both measures, namely R&D expenditure and patent data, in order to identify knowledge flows and stocks. Patent data, is available for a longer period compared to R&D expenditure data (Keller, 2004), and although it cannot be directly linked to a commercial value, patent data can provide information on knowledge spillover, inventor location and absorption time lags. Nevertheless, there are limitations to the use of patent data for tracing knowledge flows, posed by the different propensity to patent by technology and region (Jaffe and Trajtenberg, 2002), as not all inventions are patentable or actually patented. In addition, each patent has a different economic "value" that determines its corresponding contribution to the existing knowledge stock.

Patent data has been collected for the period 1995-2015 by using both the WIPO IPC Green Inventory classifications and a further refinement of search results through the use of Boolean operators for the inclusion or exclusion of certain key-words from the IPC categories. This process is demanding but necessary as IPC codes may include patents that are not directly related to our field of analysis. An even more disaggregate and complex search will be required for the purposes of a further update of patent data in order to include energy efficiency and other sustainable transport technologies (apart from electric cars) which are not currently covered in the literature or in the current analysis. Such an update is envisaged for future research and would benefit from the use of the CPC Y02 codes as those are allocated under each Energy Union R&I priority and SET Plan action in Fiorini et al. (2017).

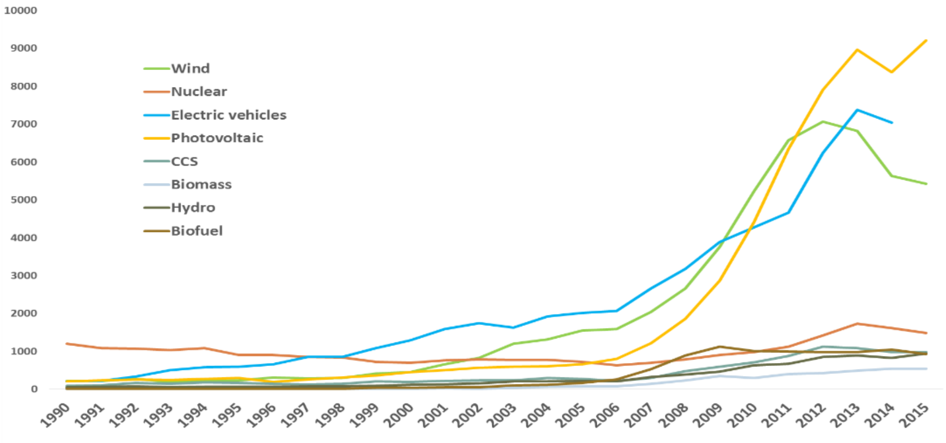
Figure 19 indicates a rapid increase in the number of patents in solar PV, wind and electric vehicles after 2005 while the rest of the technologies only increase moderately. The findings for the boom in PV and Wind patents can be associated with the rapid increase in the respective R&D expenditure. In order to investigate further the efficiency of R&D expenditure in terms of innovative products (i.e. patents), the number of patents per million US$ spent on R&D is estimated for each technology for those countries where both OECD R&D expenditure data and patent data are available. As shown in Figure 20, innovation in certain technologies (e.g. nuclear) is more capital intensive than in others (e.g. wind) and the marginal cost of innovation is decreasing in time, particularly so for new clean energy technologies.

To identify the front-runners in innovation for each technology for the period 1995-2015 the patent origin can be used via different proxies, such as the country codes[11] (prefixes) of the patent or the country of residence of the first named inventor. The different methodologies result in different findings, as inventors can choose to register their patent in a country other than their country of residence in order to obtain protection rights in the respective country, or due to a more facilitative legislation, due to the complexity of the product global value chain or other factors. Knowledge is generated in the location of the inventor while patent prefixes may not indicate a specific country of origin if the patent was filed or granted by the World Intellectual Property Organization (WIPO), the European Patent Office (EPO) or other such organizations.

Figure 43 to Figure 49 (in Appendix) present the origin of the patents for major clean energy technologies according to the location of the inventor. The dataset includes patents granted in the 1990-2015 period and calculations shown in respective figures are based on the total patent pool of the entire period.

The EU28 holds the largest share of wind patents (41%), in line with the findings on R&D expenditure, while for most other technologies the respective EU share is around 20%. Similarly, the US maintains the highest share in PV, CCS and biofuel patents (around 30%) while Japan is leading the innovation in nuclear power and electric vehicles. China is rapidly increasing its presence in global R&D and is becoming the largest global innovator in certain technologies, namely in solar PV and hydro.

Figure 19: Global number of patents by clean energy technology in the period 1990-2015



Source: E3Modelling calculations

Figure 20: R&D efficiency (number of patents per million euros spent on R&D for clean energy technologies in OECD countries)

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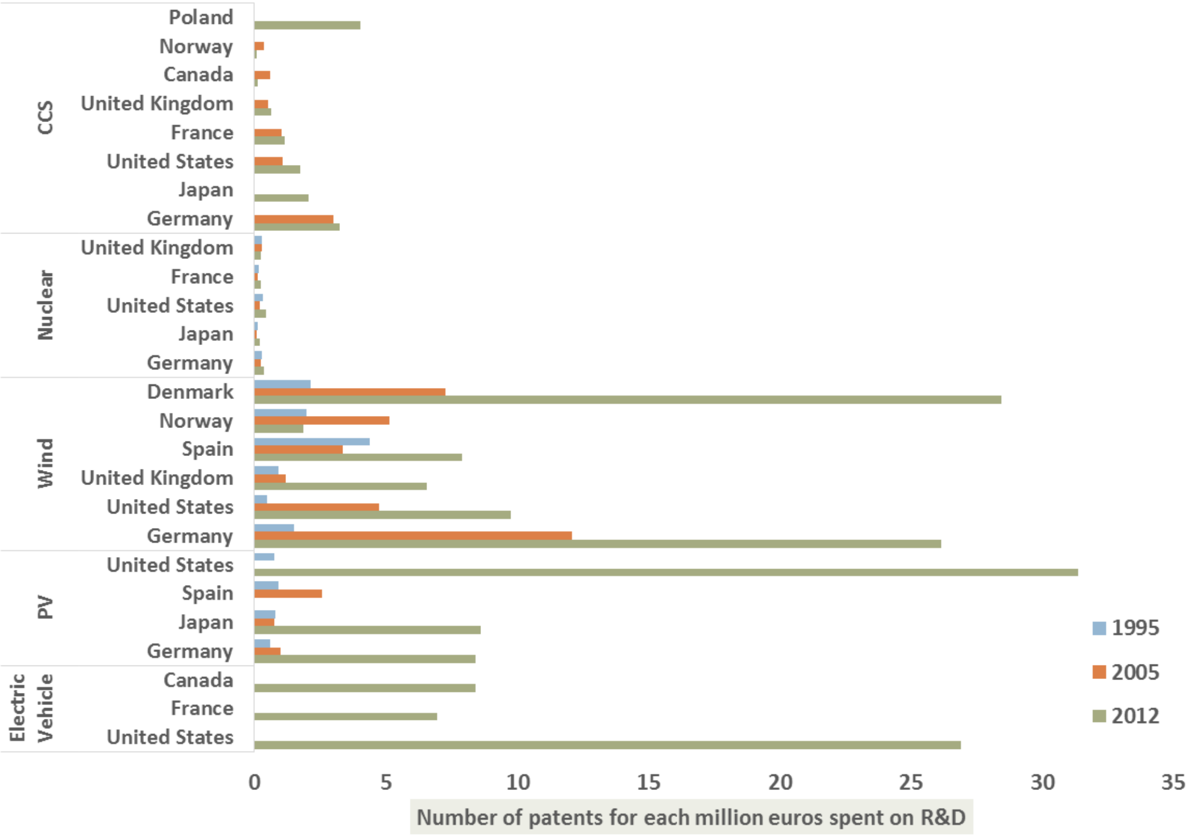
[11] https://rs.espacenet.com/help?locale=en_EP&method=handleHelpTopic&topic=countrycodes



Source: E3Modelling calculations based on OECD/IEA and patent data

The effect of technology innovation and spillovers on first mover advantages

Key drivers for growth are the ability to innovate so as to deliver commercialised products and the diffusion of knowledge that innovation produces. Most countries depend both on the innovation they are able to generate and on the knowledge they receive from innovation performed abroad. Growth in developed countries is mostly sourced from domestic innovation dynamics, whereas developing countries benefit mostly from technology diffusion.

Technological innovation is key in reaping first mover advantages as it has a strong, positive effect on three main factors that determine the potential of a country to become market leader. In particular, technological innovation can reduce costs and thus benefit the price competitiveness of the country. Similarly innovation can provide high quality and wider variety of products thus enhancing the quality competitiveness of a country. In addition, own innovation is a prerequisite for absorbing positive externalities from external innovation. On the other hand, the positive externalities received by a country in the form of knowledge spillover from other regions can actually form a disincentive for own R&D expenditure and hinder first mover advantages.

An industry innovates either to establish a technological leadership in a market segment or to sustain and expand its current market share. The key motivation of a first mover to undertake the risk to invest in a new market is derived from the monopoly rents she/he expects to enjoy. Once a first mover is successful, it is on her/his own interest to create barriers to entry to competitors and to make knowledge proprietary (Figure 21 shows the product life cycle in relation to the temporal profile of the first mover advantage).

Timely innovation that leads to a commercialised product is an essential element in creating a first mover advantage, whereas knowledge diffusion acts positively on the growth of competitors (technology diffusion is beneficial for aggregate growth but diminishes the first-mover advantages of the innovator). The first mover advantage can be mitigated by the cost reduction potential characteristics of the innovative product (i.e. a competitor can enter into the market by exploiting possible high potential for cost reductions through economies of scale – yet the competitor will need to pay the respective royalties in order to replicate the product).

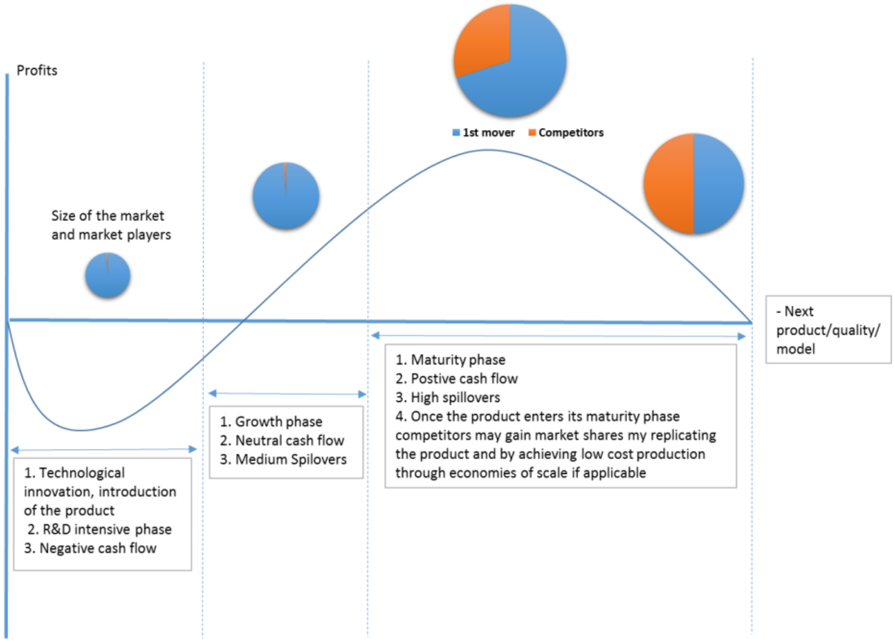
In case that the time period and the market where first mover retains its monopoly rents are not sufficiently large (so as to be compensated for its initial expenditures on R&D and physical capital), then his/her early action renders him/her disadvantaged and the profits are appropriated by the second or late movers. Below the key factors for creating a first mover advantage and their interactions are presented:

i) R&D and Technical progress: R&D expenditure is a necessary but not a sufficient condition to generate innovation and knowledge, as the outcome of R&D expenditure is inherently uncertain. At aggregate level (industry, national) the link between R&D and innovation is positive but different by country and/or industry. Innovation in one industry is positively related with innovation performed in other industries or the same industry in other countries.

ii) Technological spillovers: The time period when the first mover enjoys his/her rents depends on how fast others will be able to mimic/replicate his/ her product or introduce an even more innovative product. Patents purchased by competitors are both a source of income (in terms of royalties) and a loss of profits in terms of reduced market share.

iii) Human capital: The quality and quantity of human capital are essential drivers both for making innovation and for replicating it.

Figure 21: Product cycle and market size



Part VI Learning by doing and learning by research: Empirical Evidence

Learning by doing and learning by research

Learning by doing curves have been extensively used to understand historical cost trends and to forecast future cost reductions for a variety of energy technologies. Learning by doing curves (one factor learning curves) show by how much the unit capital cost of a technology is reduced when its installed capacity is doubled. The learning rate is given in [1] where b is the learning parameter.

$$LR = 1 - 2^{b} \ [1]$$

The unit cost of a technology, using the one factor learning curve is given by the power law, as in JRC (2012).

$$C_{t,y} = m \cdot Q_{t,y}^{-lr}$$

Where c= unit cost of production, Q = cumulative production, m = normalisation parameter, t = technology, y = period.

Learning by doing and learning by research are assumed to be interdependent. The two factor learning curve is given by:

$$C_{t,y} = m \cdot Q_{t,y}^{-lbd} \cdot KS_{t,y}^{-lbr}$$

Where c= unit cost of production, Q = cumulative production, KS = knowledge stock, m = normalisation parameter, t = technology, y = period. Empirical validation of technology progress dynamics is usually based on econometric estimation of learning by doing and learning by R&D rates of clean energy technologies, including wind, solar PV, electric vehicles, biofuels, batteries, CCS options and advanced energy efficient technologies and equipment.

Photovoltaics

Solar Photovoltaics have constituted over many years a classical case for studying technological learning dynamics and for estimating appropriate learning by doing rates (experience curves) due to their rapid technology progress and capacity growth.

Swanson (2006) reviewed the history of silicon technology development and estimated that the cost of photovoltaics has decreased by 19% for each doubling of installed capacity. Kobos et al (2006) used the two factor learning curve approach to estimate learning rates for photovoltaics using historical data and their econometric results for learning by doing and learning by searching rates are 18.4% and 14.3% respectively. Nemet and Husmann (2012) calculated a median learning rate for the PV experience curve equal to 0.21 over a sample of 253 time periods. The Fraunhofer institute (2012) estimated that in the period 2006-2012 the prices of Mono-Si and Multi-Si PV modules decreased by 29% and 30% respectively for each doubling of their cumulative production, while the learning rate for all PV technologies is estimated at 29.2%. The high learning rates calculated in the study are over a relatively short time period and thus the projection of continuation of so high learning rates to the future would be particularly risky. However, Fraunhofer (2012) estimated that the learning rate for photovoltaics over a longer historical period (1980-2012) is lower -19.6%- and close to the historical median of most studies of about 20%.

Recent analyses point towards the continuation of historical learning rates for photovoltaics. Fraunhofer (2016) estimated that in the last 35 years the PV module price decreased by 23% for each doubling of the cumulated module production. ITRPV and VDMA (2017) showed on their "International Technology Roadmap for Photovoltaic Results 2016" that the historical learning rate for photovoltaics (20%) continues with a very slight increase to 22.5%. Mauleón I. (2016) shows that learning rate for solar photovoltaics might reach values higher than those usually reported (18–20%). Criqui et al. (2000) estimated the solar PV learning by doing rate at 20% and the learning by research at 10%. Overall there is consensus in the literature that learning rates for photovoltaics in the long term have been around 0.20, with learning by research rates at lower levels of 0.1-0.14.

Table 7: PV learning rates

Study	Publication Year	Learning by doing	Learning by research
Criqui et al	2000	20%	10%
Swanson	2006	19%	
Kobos	2006	18.4%	14.3%
Nemet & Husmann	2012	21%	
Fraunhofer	2012	29% (short term) 19.6% (long term)	
Fraunhofer	2016	23%	
Mauleon	2016	20%	
ITRPV and VDMA	2017	22.5%	

Wind turbines

A major difficulty in the establishment of learning rate for wind turbines is related to the fact that most studies use old historical samples even in cases where they are relatively recent (Kobos et al, 2006). This constitutes a major handicap since older samples (when the wind technology was relatively immature) tend to produce learning rates that are generally higher compared to more recent experience. For example Wiser and Bolinger (2012) obtain a halving of the learning rate for wind turbines when they extend the sample from 2004 to 2012 (their data start in 1982). The fact is that the wind industry (mainly onshore)[12] appears to have matured in recent years with very modest improvements in the technology costs even though wind deployment continues to increase at a relatively fast pace both at the EU and global level.

Jungiger et al (2012) provide a detailed overview of experience curves (learning by doing) for wind technology published in the literature in the period 1998-2006 and find that global learning rates range between 0.15 and 0.19. Estimations of learning rates based on national data yield lower learning rates (0.06-0.09). G.F. Nemet (2009) calculated a median learning rate equal to 0.10 over a sample of 153 time series with the 5% upper percentile at 0.20 and the 5% lower percentile at 0.05. For time series ending in 2006 (a sample of 17 cases) he calculated a median learning rate of 0.08 (while the values for the upper and lower 5% percentiles are estimated to be 0.12 and 0.05 respectively). Qiu and Anadon (2012) found that China's learning rates from Learning by Doing and Learning by Research for wind power between 2003 and 2007 were around 4.1-4.3%. These values are in the low end of learning rates reported in the literature for Europe and the United States. This can be (at least partially) explained by the fact that the growth of the wind industry in China took place after the wind technology was already widely used in other global markets (in Europe and the United States) and thus the cost of wind power was already relatively low with limited potential for further cost reductions. Söderholm et al, 2007 and Klaasen et al, 2005 provide estimates for learning by doing and learning by research rates for wind turbines. Both studies find higher learning rates due to increased R&D expenditures compared to learning due to increased wind deployment.

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[12] In recent years there are limited cost reductions in wind onshore projects, which account for 91% of the EU wind installed capacity. Wind offshore has a high potential for further cost reductions, as highlighted by the recent UK auction, in which two offshore wind schemes won contracts at record-lows of £57.50 per MWh (https://www.carbonbrief.org/analysis-uk-auction-offshore-wind-cheaper-than-new-gas).

Table 8: Wind learning rates

Study	Publication Year	Learning by doing	Learning by research
Juninger	2012	15% - 20%	
Nemet	2009	10% - 20%	
Qiu and Anadon	2012	4.1%	4.3%
Söderholm et al	2007	3.8%	16.4%
Klaasen et al	2005	5.4%	12.6%

Electric vehicles

In examining the technology change dynamics of electric vehicles, it is important to separate ancillary costs that are common with ICE vehicles[13] from the specific costs of electrification, which include the costs of automotive battery, electric motor and auxiliary components. The success of electric vehicles in the car market highly depends on the reduction of battery costs, which constitute about 35-50% of the total cost of electric cars. The current battery technology used in electric vehicles is the "high energy and high power lithium-ion". Most studies in the literature assume learning rates for batteries without attempting to estimate them due to the lack of long time series of historical data. IEA estimates a learning rate for electric vehicles of 0.095 (IEA, 2013). Weiss et al (2012) using data for the period 1999-2010 estimate a median learning rate of 0.07 for the total costs of hybrid vehicles.

Nagelhout and Ros (2009) estimate a 0.17 learning by doing rate for lithium-ion batteries. An updated assessment of cost reductions for the dominate Li-on battery technology is presented by Nykvist and Nilsson (2015), confirming a (relatively lower) learning rate of 6-9%.Mayer et al (2012) estimate a two factor learning curve using patent data for a wide range of lithium-ion applications; they found a learning by doing rate of 0.08 (which is consistent with the assumptions made in recent studies), while learning by research rate is very high (0.27). The combination of learning by doing and learning by R&D rates would tend to produce a high overall learning for electric vehicles in line with recent studies.

Table 9: Electric Cars learning rates

Study	Publication Year	Learning by doing	Learning by research
IEA	2013	9.5% (based on assumption-expert judgement)	
Weiss et al	2012	7% (on total vehicle cost)	
Nagelhout and Ros	2009	17% for lithium-ion batteries	
Nykvist and Nilsson	2015	6-9% for li-on batteries	
Mayer et al	2012	8%	27%

Other energy technologies

The table below presents a literature review that has been performed by Rubin et al (2015) on the learning rates for a number of energy technologies. The table contains both learning by doing and learning by research estimates from the various studies. The main characteristic of these results is that learning by research rates appear to be higher than learning by doing ones.

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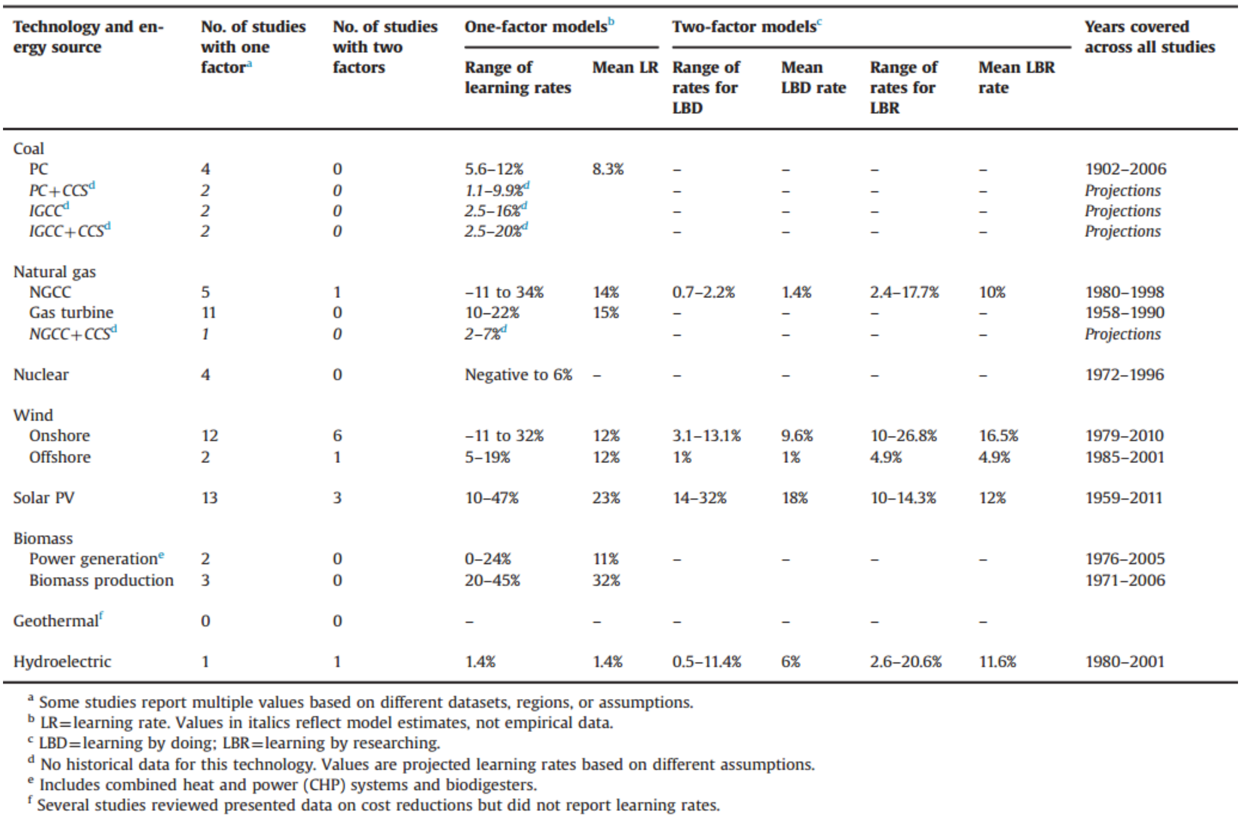
[13] Ancillary vehicle costs include the costs of the vehicle chassis, the suspension, the interior and the mark-up of retailers.

Table 10: Learning rates for energy technologies



Technology and energy source	No. of studies with one factor[a]	No. of studies with two factors	One-factor models[b]		Two-factor models[c]				Years covered across all studies
			Range of learning rates	Mean LR	Range of rates for LBD	Mean LBD rate	Range of rates for LBR	Mean LBR rate	
Coal									
PC	4	0	5.6–12%	8.3%	–	–	–	–	1902–2006
PC+CCS[d]	*2*	*0*	*1.1–9.9%*[d]		–	–	–	–	*Projections*
IGCC[d]	*2*	*0*	*2.5–16%*[d]		–	–	–	–	*Projections*
IGCC+CCS[d]	*2*	*0*	*2.5–20%*[d]		–	–	–	–	*Projections*
Natural gas									
NGCC	5	1	−11 to 34%	14%	0.7–2.2%	1.4%	2.4–17.7%	10%	1980–1998
Gas turbine	11	0	10–22%	15%	–	–	–	–	1958–1990
NGCC+CCS[d]	*1*	*0*	*2–7%*[d]		–	–	–	–	*Projections*
Nuclear	4	0	Negative to 6%	–	–	–	–	–	1972–1996
Wind									
Onshore	12	6	−11 to 32%	12%	3.1–13.1%	9.6%	10–26.8%	16.5%	1979–2010
Offshore	2	1	5–19%	12%	1%	1%	4.9%	4.9%	1985–2001
Solar PV	13	3	10–47%	23%	14–32%	18%	10–14.3%	12%	1959–2011
Biomass									
Power generation[e]	2	0	0–24%	11%	–	–	–	–	1976–2005
Biomass production	3	0	20–45%	32%					1971–2006
Geothermal[f]	0	0	–	–	–	–	–	–	
Hydroelectric	1	1	1.4%	1.4%	0.5–11.4%	6%	2.6–20.6%	11.6%	1980–2001

[a] Some studies report multiple values based on different datasets, regions, or assumptions.

[b] LR=learning rate. Values in italics reflect model estimates, not empirical data.

[c] LBD=learning by doing; LBR=learning by researching.

[d] No historical data for this technology. Values are projected learning rates based on different assumptions.

[e] Includes combined heat and power (CHP) systems and biodigesters.

[f] Several studies reviewed presented data on cost reductions but did not report learning rates.

Source: Rubin et al (2015)

Learning rates used in GEM-E3-FIT

Improvements in total factor productivity of clean energy production sectors are assumed to depend on changes in cumulative production (or capacity installations) and in the R&D "knowledge" stock Changes in total factor productivity imply changes in unit costs and/or higher performance. Learning curve elasticities are derived from econometric estimations and from a wide literature review (as presented in detail in previous sections of part VI of the report) and are summarised in the table below. Learning rates are defined as the rate of decrease of unit costs for every doubling of cumulative output (learning by doing) or for every doubling of R&D stock (learning by research rate).

Table 11: Learning rates used in GEM-E3-FIT

Clean energy producing sectors	Learning by Doing rate	Learning by Research rate
Equipment for Wind power	0.07	0.105
Equipment for Photovoltaic	0.17	0.12
Equipment for CCS technologies	0.07	0.07
Equipment for electric vehicles	0.08	0.15

Part VII Technology progress and knowledge spillovers

An important element of technological progress that actually serves as the "engine of endogenous economic growth" (Grossman and Helpman, 1995) is the spillover of knowledge, i.e. the positive externalities accruing from the use of generated knowledge by actors other than the innovator. This positive effect of knowledge is directly linked to its characteristics of non-excludability and non-rivalry. At the same time, knowledge spillover represent the manifestation of the public good characteristics of knowledge and thus provide an incentive to free ride as latecomers may benefit from their delay to innovate in case that they feature an adequate absorptive capacity (i.e. skilled human capital and own R&D stock (Keller, 2004 and 1996)). Thus knowledge spillovers may lead to underinvestment in the development of new innovations, and as highlighted in Gerarden et al (2015) in the case of energy-efficient innovations such underinvestment can increase the energy-efficiency gap with negative impacts for the overall economy. It is thus important to examine the issue of knowledge spillovers of clean energy industries and their relations to economic and competitiveness impacts of climate policies.

The key factors affecting spillovers are the geographical proximity, trade relations, distance to the technological frontier, human capital, FDI, R&D expenditures and property rights policy. Although competition and proprietary rights may limit a firm's own patenting efforts if a rival firm wins the patent race, once innovation is actually generated it is bound to diffuse following channels that depend on the absorptive capacity of the recipient firms and the relevant legal and policy framework. The latter two factors determine both the time lag between the actual innovation and its diffusion and the level of such a diffusion. Empirical findings show that at a micro level, "one firm's own R&D investment is small relative to the potential spillover pool" and thus the innovation performance of a firm can be greatly affected by other R&D spending (Branstetter, 2001). Given the above, it is essential that models represent explicitly the sectors performing R&D and host or produce spillovers in order to capture the potential growth impacts of policies.

Knowledge spillovers differ from the simple pecuniary benefits gained by the use of more advanced products as intermediate goods that provide static productive gains. As noted in Keller (2004), "international technology diffusion is important because it determines the pace at which the world's technology frontier may expand in the future". Nevertheless, Keller (2004) highlights also the importance of domestic R&D that can enable the diffusion of knowledge built in other regions. Similarly, with regards to intra and inter-sectoral knowledge diffusion, Cohen and Levinthal (1989) identify the enhancement of a firm's absorptive capacity through R&D of other firms, thereby noting that own R&D is a prerequisite for receiving the benefits of knowledge diffusion. Especially with regard to impact assessments of policies for clean energy technologies, incorporating knowledge spillovers is important as the intensity of such spillovers for clean technologies is above the overall average patented technology (Dechezleprêtre, 2016).

Technological spillovers can be classified in three types:

1. Own sector: The knowledge created in one industry increases the knowledge in the same industry and can be replicated/mimicked by competing firms of the same industry
2. Cross Sectoral – direct: The knowledge created in one industry can be used to increase knowledge in other industries
3. Cross Sectoral – indirect: The knowledge created in one industry facilitates the processes in other industries

Current modelling approaches of spillovers do not include: i) the impacts of patents with extreme value that can change radically production and consumption patterns (e.g. nuclear fusion) ii) the spillovers that are not covered by patents and typical R&D methods, e.g. knowledge spillover from biofuels to other crops (Arndt C. et al. (2010)) iii) a quality assessment of patents (e.g. citation-weighted patent data analysis as in Jaffe and Trajtenberg, 2002).

Technical Progress

Exogenous representation of technological progress has been the default option in most applied large-scale energy-economy models. Recently macro-economic models have started using alternative methodologies to incorporate endogenous representation of technical change, which include experience-induced and R&D-induced technological changes, the so-called learning by doing and learning by research paradigms respectively (Weyant et al, 1999).

R&D-induced technological change treats innovation as the result of investment in R&D, while learning depends on the accumulated stock of knowledge and a flow of R&D investment into that stock of knowledge. In recent studies, this approach has been reinforced by direct application of microeconomic empirical evidence.

Knowledge generates spillovers to other firms, which according to Jaffe et al., 2005 are the primary driver of economic growth. The neoclassical growth framework is extensively used in energy-economy-climate models, which (following the endogenous growth theory) include the knowledge stock directly in the economy-wide production function.

Another strand of literature focuses on learning by doing effects that are defined as the reduction of technology costs as a function of cumulative output, as first proposed by Arrow, 1962. Learning by doing is often measured in the form of learning curves that quantify the reduction in costs of technologies as a function of their cumulative installed capacity. Learning curves have been observed in several industries and are a well-established empirical concept. Endogenous technological change mechanisms are also included in multi-sector CGE models. Goulder and Schneider, 1999 model induced technological change through the inclusion of knowledge capital in the production function. CGE models differ from other modelling approaches as the economy is disaggregated into several production sectors, and thus, economic activity is modelled within and between sectors. CGE models (like GEM-E3-FIT) can provide quantitative assessments on the interaction between sectors, including possible spillovers or crowding out effects. However, they tend to be data intensive and computationally demanding, as stated by Gillingham et al., 2007. Thus, the literature review provides limited examples of CGE models with endogenous technology dynamics and in particular simulating R&D and/or learning by doing technology progress.

Representation of technology and spillovers in E3ME

The representation of technology in E3ME is described in the model manual (Cambridge Econometrics, 2014) and the report for work package 2 of the project. In summary, technology is represented in three different ways in E3ME, which are described below.

Firstly, there is explicit representation of technologies in the power, heat and passenger vehicle sectors through the bottom-up FTT energy sub-models (Mercure, 2012; Lam and Mercure, 2015). In each case a set of specific technologies is defined (e.g. nuclear, coal, gas, renewables in the power sector) and detailed characteristics on costs, efficiencies and lifetimes are included in the model. The model determines the rates of take up of each technology based on the relative costs and following a pattern of technology diffusion that incorporates learning effects.

While FTT provides a highly detailed representation of technologies in key energy sectors, it is not possible to define every technology across a modern economy in this way. The second representation is therefore more implicit in nature and is defined at sectoral level (and by country). In each sector a set of indices are used, derived from an approach outlined in Lee et al (1990). The equation defines technological progress using cumulative gross investment, enhanced by R&D expenditure, to form a quality adjusted measure of investment.

The third option for representation of technology in E3ME is through a scenario-based approach that focuses on a particular technology or set of technologies. Key model data and inputs (for example input-output coefficients or rates of fuel consumption) can be modified to represent specific paths of technological change. This approach allows for a very specialised analysis that goes into even more detail than the FTT models can. A recent example is the Fuelling Europe’s Future series of studies that assess paths to electrification in light-duty vehicles (European Climate Foundation, 2015).

The FTT submodel includes technology spillovers through the application of its learning curves. The costs of new equipment are determined by cumulative installation at the global level and the changes in costs are reflected in all countries. There is thus a full spillover between geographical regions in the power sector. There is also some spillover between energy technologies as well, following a similar approach. For example, if CCS technology is developed more rapidly in a scenario then it could be used in connection with coal or gas-fired plants. Similarly, developments in onshore wind technology could be expected to spill over to offshore wind.

Outside of the sectors that have an FTT treatment, the current specification of E3ME includes only limited direct technology spillover effects. One route by which technology spillovers could have an impact in E3ME is via the technology terms that appear as a determinant in a number of equations (e.g. trade, prices, employment). At the moment, however, the technology terms are formed by accumulating investment and R&D carried out only in the sector/region concerned, so no spillover effects are allowed for in most sectors. An exception is made for the machinery and transport equipment sectors because of the importance of multinational firms in these sectors. In these cases, global R&D in the mechanical engineering (machinery) and motor vehicles sectors is summed and the terms are added to the econometric estimation for energy demand.

The current treatment of spillover effects in E3ME is in the process of being revised. As part of an early draft of the report for WP1 of the project, Cambridge Econometrics estimated a set of energy equations that included more detailed spillover terms derived from R&D expenditure so that improved energy efficiency could be explained by best available technology made available by R&D spending anywhere in the world. Several different specifications were tested, including simple global aggregates, trade-weighted aggregates and input-output based sectoral aggregates. The results were often insignificant but there were some cases that suggested that geographical spillovers beyond those in the current equations could be important.

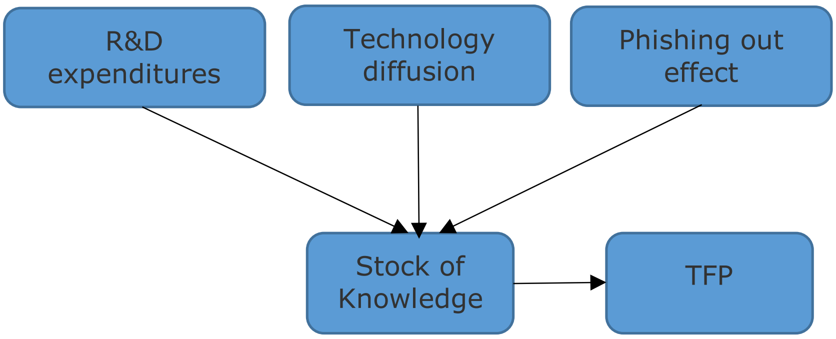
More generally, the treatment of technology spillovers in E3ME (in both the economic and energy equation sets) will be revised in the H2020 Monroe project, which focuses on the treatment of innovation in macroeconomic models (and also includes GEM-E3). Further econometric estimation, based on both sectoral and geographical linkages will be tested. The challenge is to determine empirical relationships based on the available data.

Representation of technology and spillovers in GEM-E3-FIT

The GEM-E3-FIT model has a detailed representation of the R&D sector and the creation of the knowledge stock. This section provides an outline of the key elements regarding the representation of technical progress and spillovers in GEM-E3. In the model, knowledge is created through R&D expenditures and spillovers. The mechanism of knowledge spillovers is based on the patent-citations approach as presented in Johnstone and Haščič (2010) and Schoenmakers and Duysters (2010) where it is assumed that knowledge generated in one sector as a result of R&D is diffused to other sectors and countries according to the destination of citations that a patent made in this sector received. In this study the patents citations matrix of GEM-E3-FIT has been updated to the most recent statistics (see Part VI and next section of this report).

A detailed representation of R&D and spillovers is available at Karkatsoulis (2014). Figure 22 presents schematically the factors that affect the building up of the stock of knowledge.

Figure 22: Factors affecting stock of knowledge in GEM-E3-FIT



R&D is modelled as separate sector in GEM-E3-FIT. Each other sector of the economy decides on its optimal spending on R&D according to its expected payoffs. R&D expenditure leads to innovation and to the generation of knowledge that eventually leads to higher productivity (labour, energy or total factor productivity) through the accumulation of the stock of knowledge. The latter depends on R&D expenditure of the same sector, spillovers from other sectors and/or countries (and the capacity to absorb spillovers), knowledge depreciation, technology diffusion and phishing-out effects (that indicates decreasing return to scale).

The decision of R&D expenditure of each firm can be exogenous or endogenously made by solving an intertemporal profit maximisation problem where the R&D payoffs are known.. Knowledge is assumed to lead to innovation and technical change. Innovation depends on the accumulated stock of knowledge and on a phishing out effect indicating that improving a given invention is subject to decreasing returns to scale (the next improvement comes at a higher marginal cost). Innovation also depends on the spillover (within and cross sector and country).
The type of spillovers that are taken into account into the GEM-E3-FIT model are the following:

- Spillovers through trade: Once a firm improves its product as a result of R&D expenditures this increases productivity in other firms to the extent that this is used as an intermediate product
- Spillovers through knowledge diffusion: The knowledge generated in one firm as a result of R&D diffuses in other industries and countries according to a patent-citation matrix.

Empirical justification of spillovers in GEM-E3-FIT

Incorporating up-to-date data with regards to R&D intensity, knowledge spillovers and productivity is of great importance in enabling an accurate assessment of policies and first mover advantage potentials, as knowledge-induced productivity determines the competitiveness of a country and knowledge spillovers determine the intensity and duration of such advantages. The matrix of technology transfers (spillovers) of GEM-E3-FIT model, which is based on the patent-citations approach, has been updated to the most recent statistics available (2015). Key in the incorporation of the technology transfer matrix in a modelling framework is the sectoral disaggregation of the model. GEM-E3-FIT model is being updated constantly towards that aim, by further disaggregating the supply sectors of the model so as to be able to capture the inter-technology flows.

The patent pool used for the calibration of the GEM-E3-FIT model consists of 220359 patents and forward citations are provided by the Patent inspiration services for the respective patent codes. All citations have been grouped by IPC family codes for the purposes of sectoral spillovers and by geographic indicator for the purposes of regional spillovers. As patents filled more recently have generally less forward citations than previous ones (Albino et al 2014), several researchers have used a truncation of forward citations after 10 years (Nemet, 2012); however for this analysis no truncation has been imposed as the focus is not the assessment of the value of each patent but the identification of knowledge flows which should still consider older patents. Furthermore, the analysis follows the common approach of many such assessments of excluding self-citations but does not exclude intra-family citations as in Noailly and Shestalova 2017, as those are essential in identifying the intra-technological knowledge flows.

A demanding process for the preparation of spillover matrices to be used by GEM-E3-FIT model has been the matching of patent classifications to technological domains and the respective correspondence to the GEM-E3-FIT economic sectors. The analysis includes more than 1000 different IPC codes (4th level of classification, e.g. B32B3/00) and expert judgement was essential in order to derive to the suitable mapping. IPC v8 to NACE Rev.2 (Eurostat 2015) concordance tables have been used but since those only include 4-digit IPC codes (3rd level) further assumptions were necessary. In order to harmonize to the GEM-E3-FIT sector specification, further correspondence tables have been used, namely UNSTATS correspondence tables from NACE Rev.2 to ISIC Rev.4 and GTAP correspondence tables from ISIC to GSC (GTAP) sectors.

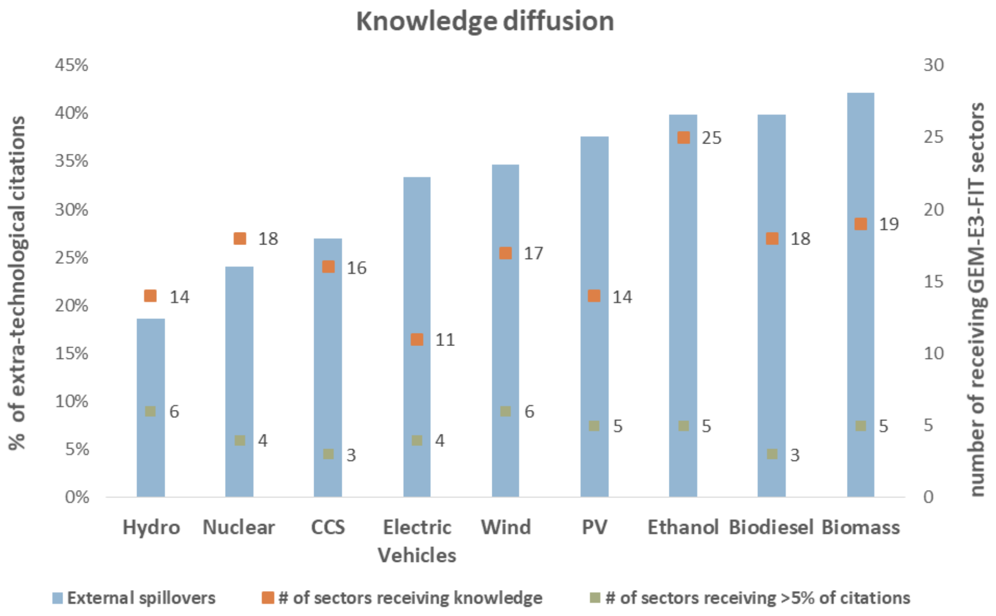
Including the intra-technology forward citations enables an analysis of technology-specific knowledge diffusion as presented in Figure 23. Technology-specific knowledge diffusion is an important indirect positive externality that can first be absorbed by the inventor (i.e. the pioneering country) due to proximity and linguistic reasons. Technologies with lower rates of extra-technological citations present a high level of technological centrality and are thus less likely to produce intensive positive externalities through knowledge diffusion to other sectors. Figure 23 further depicts the range of diversification of the sectors that receive knowledge. Although many of GEM-E3-FIT sectors receive knowledge (e.g. 20 sectors out of 37 for biomass feedstock technologies), the number of sectors that receive more than 5% of external citations is significantly smaller but almost equal across clean energy technologies. It is worth noting that external spillovers in this analysis are considered as upper potentials since IPC codes not directly related to the technologies under analysis may still include some patents of the clean energy technology due to multiple allocation of IPC codes to each patent. Results indicate that innovation primarily in bioenergy and subsequently in PV and Wind technologies, spills knowledge to external sectors, while hydro power innovation is less likely to do so. While Noailly and Shestalova 2017 have similar findings with regards to bioenergy, they find that hydro energy innovation spills to external sectors more than any other technology and that wind innovations are only relevant to own sector innovations. The different findings could be explained by the different data pools, as Noailly and Shestalova 2017 patent dataset ends in 2006 (when diffusion and R&D in RES was relatively limited) while our data expands to 2015. In addition our data covers all patent offices (including China), while Noailly and Shestalova 2017 only account for European, US and Japanese patent offices.

Table 12presents the aggregate sectoral technology transfer matrices, namely the sectors that receive knowledge spillovers from innovation in clean technologies. The shares shown in the table illustrate the external forward citations of the technology patent pool, excluding intra-technology spillovers. Patents on biomass and biofuel technologies relate closely to the chemical industry and provide a large number of such spillovers (e.g. cosmetic products, silicate absorbents, sugar refining methods) and thus present a high share of extra-technological citations, in contrast to hydro and nuclear power technologies that have limited linkages with other sectors. Solar PV technologies are also linked to a number of other sectors especially electronic and equipment goods (e.g. electrode devices, phase current detectors, integrated circuits), while wind technologies spill knowledge towards transport and other equipment goods (e.g. airplane wing, yaw control design). Examples of external knowledge spillover flows can be found in Table 13. Overall, the manufacturing sectors enjoy the most benefits of knowledge spillover from clean energy technologies and in particular the Electronic and equipment goods and the Chemical sectors. These findings are in line with the ones presented in Noailly and Shestalova 2017 (and in particular in their Table 4).

Cross-country spillover linkages are identified and are incorporated in GEM-E3-FIT model. These are important for the evaluation of first mover advantages since knowledge spillovers to competitors (in this case regional competitors) can diminish the advantages of pioneers. The construction of updated regional spillover matrices is conducted by registering the inventor location of the original patent and the location for the forward citation as described previously. High intra-regional spillover shares imply that new knowledge is more likely to create positive externalities in the inventor region. This may be due to patent protection legislation, language or other cultural barriers, market characteristics and other factors. The level of openness is also related to the market share of the region for the specific sector. As shown in Figure 24, Japan holds a high intra-regional share in the sectors where its market share is also high (e.g. nuclear, electric cars), while its respective share is low in technologies like PV and wind. EU28 also presents a high intra-regional share in technologies for which the stock of knowledge is already more competitive relative to other regions (e.g. wind). Interestingly, China shows the highest intra-regional share for most technologies thus reconfirming the notion of the linguistic and geographical barriers to knowledge diffusion. On the contrary, China has registered a very high absorptive capacity over the last decade (Lili et al, 2017 and Yang and Lin 2012), namely it has proved a high capacity in absorbing technology transfer through FDI and utilizing this knowledge for own innovations. Table 14describes the main knowledge flows across regions as those are introduced in the updated spillover matrices of the GEM-E3-FIT model (selected regions are presented based on their R&D performance).

Knowledge spillover is introduced in GEM-E3-FIT for both intra/inter-regional and intra/inter-sectoral flows. In line with the literature, time lags are imposed on both the development of useful knowledge from R&D expenditures to innovation (see for example a review in Klassen et al, 2005) and on the diffusion of this knowledge to other sectors or regions. Contrary to past empirical findings that defend an almost immediate “leak out” of innovation (described in Branstetter, 2001), the GEM-E3-FIT approach follows the findings of Battke et al (2016) and Noailly and Shestalova (2017).

Figure 23 Knowledge diffusion and technological centrality of clean energy technologies



Source: E3Modelling

Table 12: Aggregate sectoral spillover matrix for clean energy technologies

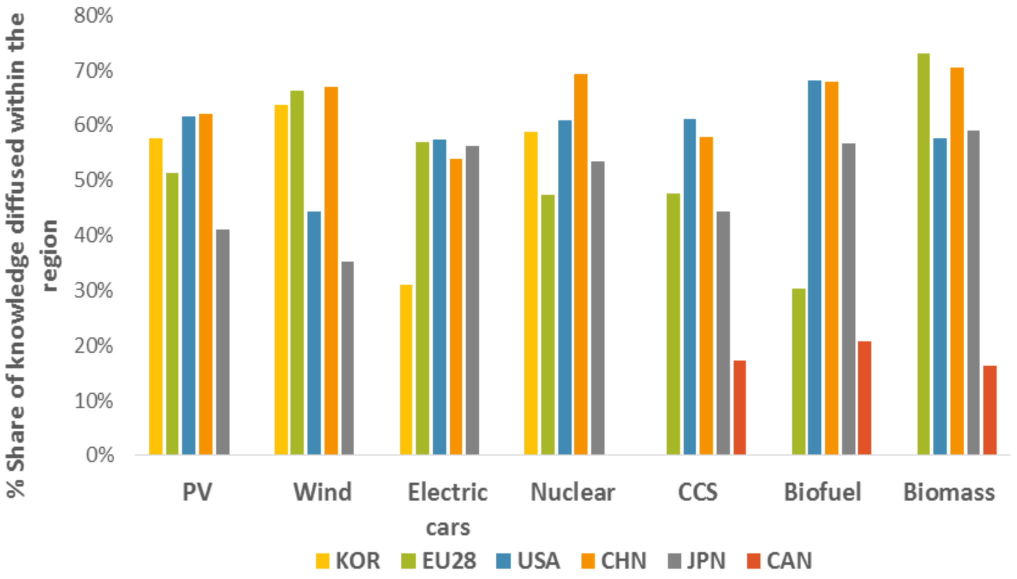
	Wind	PV	Hydro	CCS	Nuclear	Biomass Feedstock	Biodiesel	Ethanol	Electric Vehicles
Agriculture	0%	0%	1%	1%	0%	2%	5%	9%	0%
Fossil fuels & Utilities	0%	0%	0%	6%	0%	25%	11%	8%	0%
Metals and minerals	6%	8%	1%	5%	18%	2%	0%	2%	11%
Chemical and paper products	2%	6%	1%	36%	10%	45%	57%	40%	1%
Electronic and equipment goods	66%	75%	50%	47%	67%	17%	15%	24%	84%
Consumer goods	0%	1%	1%	2%	0%	1%	2%	4%	0%
Transport	0%	0%	0%	0%	0%	0%	0%	0%	0%
Contruction	7%	8%	6%	0%	1%	0%	0%	0%	0%
Services	0%	0%	7%	4%	2%	7%	4%	4%	0%
Biomass Feedstock	0%	0%	0%	0%	0%	0%	0%	4%	0%
Ethanol	0%	0%	0%	0%	0%	1%	3%	0%	0%
Bio-diesel	0%	0%	0%	0%	0%	0%	0%	2%	0%
Equipment for wind power technology	0%	0%	32%	0%	0%	0%	0%	0%	3%
Equipment for PV panels	1%	0%	0%	0%	0%	0%	0%	0%	0%
Equipment for CCS power technology	0%	0%	0%	0%	1%	1%	1%	2%	0%
Electric Vehicles	2%	1%	0%	0%	0%	0%	0%	0%	0%
Hydro equipment	15%	0%	0%	0%	1%	0%	0%	0%	1%
Nuclear equipment	0%	0%	0%	0%	0%	0%	0%	0%	0%

Source: E3Modelling

Table 13: Examples of knowledge spillovers flows to external sectors

	Examples of external knowledge spillover flows
Wind	Airplane wing
	Aircraft with yaw control by differential drag
	Hydro-electric farm
Hydro	Wind Driven Venturi Turbine
PV	Biologically integrated electrode devices
	Power conditioning unit with voltage converters
	Alternative Switch Power Circuitry Systems
CCS	Process for purifying a gas stream of its N2O impurities
Biodiesel	Lubricants and wellbore fluids
	A method of processing lipid materials
	Closed system bioreactor apparatus
Bioethanol	Method for refining sugar by rapidly degrading reed fibers
	Low aromatics composition
	Method for recycling paper products glued and/or coated with biodegradable polymers
Nuclear	Systems and methods for remotely controlling a machine
	Process data development and analysis system and method
	Methods for producing silicon carbide fibers
	Recombination device and method for catalytically recombining hydrogen
Electric Vehicles	Radial counterflow muffler for NO reduction and pollutant collection
	Cash back during dispenser transaction
	Heat pump with integral solar collector
	Vehicle air conditioner

Figure 24 Intra-regional knowledge spillover expressed as the share of forward citations that are located in the same region as that of the original patent



Source: E3Modelling, 2017

Table 14: Aggregate regional spillover matrix for clean energy technologies

Origin	*Citation*	**PV**	**Wind**	**Electric cars**	**Nuclear**
USA	USA	61%	44%	57%	61%
USA	EU28	14%	34%	18%	17%
USA	China	5%	3%	3%	2%
USA	Japan	6%	5%	13%	8%
USA	S.Korea	4%	2%	2%	5%
EU28	USA	25%	14%	19%	30%
EU28	EU28	51%	66%	57%	47%
EU28	China	4%	3%	1%	3%
EU28	Japan	5%	5%	15%	8%
EU28	S.Korea	3%	1%	1%	4%
China	USA	19%	7%	22%	21%
China	EU28	7%	10%	8%	2%
China	China	62%	67%	54%	69%
China	Japan	1%	2%	6%	1%
China	S.Korea	0%	1%	2%	1%
Japan	USA	33%	11%	20%	22%
Japan	EU28	11%	24%	14%	12%
Japan	China	3%	5%	2%	3%
Japan	Japan	41%	35%	56%	53%
Japan	S.Korea	5%	9%	4%	7%
S.Korea	USA	16%	11%	25%	16%
S.Korea	EU28	7%	11%	14%	13%
S.Korea	China	7%	5%	5%	6%
S.Korea	Japan	4%	1%	17%	3%
S.Korea	S.Korea	58%	64%	31%	59%

Origin	*Citation*	**CCS**	**Biofuel**	**Biomass**
USA	USA	61%	68%	58%
USA	EU28	20%	13%	24%
USA	China	3%	4%	2%
USA	Japan	4%	3%	2%
USA	Canada	4%	4%	6%
EU28	USA	30%	34%	2%
EU28	EU28	47%	35%	1%
EU28	China	3%	2%	2%
EU28	Japan	6%	6%	30%
EU28	Canada	1%	1%	47%
China	USA	23%	20%	19%
China	EU28	7%	3%	5%
China	China	58%	68%	71%
China	Japan	3%	1%	0%
China	Canada	2%	1%	1%
Japan	USA	25%	18%	10%
Japan	EU28	15%	12%	9%
Japan	China	3%	3%	8%
Japan	Japan	44%	57%	59%
Japan	Canada	3%	1%	2%
Canada	USA	46%	52%	51%
Canada	EU28	19%	13%	21%
Canada	China	3%	3%	2%
Canada	Japan	6%	2%	1%
Canada	Canada	17%	21%	16%

Source: E3Modelling, 2017

Part VIII Model-Based Scenarios

The E3ME and GEM-E3-FIT models have been used to analyse the economic, sectoral production and competitiveness impacts of the EU's first mover energy and climate action. Towards this end two sets of scenarios have been quantified by the models:

a) The first set of scenarios aims to examine the conditions under which the EU may enjoy first-mover advantages in the context of asymmetric global energy and climate change mitigation policies. All emissions reduction options are available and optimally used.
b) The second set of scenarios assesses the impacts of different assumptions with regard to technical progress and spillover effects so as to examine the sensitivity of model results to specific input assumptions.

In these simulations, the updated dataset on clean energy manufacturers[14] and the updated spillover matrices[15] have been used.

This chapter is split in two parts: The first part presents the model results of E3ME and GEM-E3-FIT for a series of climate policy and first mover scenarios and illustrates differences between the modelling approaches in their treatment of R&D and spillovers. The second part presents the results of a series of sensitivities around key parameters of the GEM-E3-FIT model.

Climate policy and First Mover scenarios

Three alternative GHG mitigation scenarios are examined with differentiated emissions reduction targets and climate policies by region. All three scenarios are compared to a baseline scenario, which is largely based on a series of socio-demographic, macro-economic, technology and policy assumptions as analysed in detail in the EU Reference scenario 2016, European Commission (2016). The **Baseline scenario** for the EU largely follows the EU Reference scenario 2016 where it is assumed that by 2020 EU28 pursues its 20 – 20 -20 climate targets and thereafter a gradually tighteningcap is imposed on the ETS sectors. Energy efficiency, RES expansion and other bottom-up energy and climate policies are simulated to ensure that climate targets for 2020 are met; the intensity of these measures is assumed to decline in the period after 2020. For the non-EU countries moderate energy and climate policies apply in line with Copenhagen-Cancun pledges (there is no implementation of INDCs assumed in the baseline).

The **EU Alone decarbonisation** scenario explores the challenges and benefits for the EU-28 of adopting the 2030 Energy and Climate Policy Framework and the EU INDC (at least 40% GHG emission reduction relative to 1990) and the long-term decarbonisation objectives (80% reduction of GHG emissions in 2050 relative to 1990 levels) while the climate and energy policies in non-EU regions remain the same as those in the Baseline scenario by 2050.

The **Delayed Global Mitigation scenario** (**450delay**) assumes stabilisation of atmospheric concentrations of GHGs to the level of 450 ppm of CO_2 equivalent by 2100 while cumulative global CO2 emissions do not exceed 1000 GtCO2-eq in the period 2010-2050 (Kriegler et al, 2014). The scenario assumes delayed climate change mitigation action in all regions of the world and thus in the period 2010-2030 the Baseline scenario policies apply. The model is constrained to satisfy the cumulative carbon budget of 1000 GtCO2 in the period 2010-2050 and therefore the global emission constraint is imposed in the period after 2030 implying a global uniform carbon price for all sectors, regions and countries. The EU is assumed to adopt the Low Carbon Roadmap objectives only after 2030 and thus the stringency of emissions reduction post-2030 is

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[14] As these are presented in Part VI of this report

[15] As presented in Part VII of this report

greater relative to the EU Alone scenario. The sum of EU and non-EU CO_2 emissions are compatible with the carbon budget constraint of 1000 GtCO2 in the period 2010–2050.

The **EU first-mover scenario** (**EU-FMA**) where the EU is assumed to adopt stringent climate policies after 2017 with the objective to implement its INDC for 2030 and the EU Low Carbon Roadmap targets for 2050 (same as in the EU Alone decarbonisation scenario). Other world regions are assumed to follow Baseline climate policies until 2030 and join the ambitious early EU climate actions only after 2030 by increasing their efforts to mitigate CO_2 emissions so as not to exceed the specified global carbon budget of 1000 Gtn of CO_2 equivalent by 2050 (same as in the 450 delay case). A globally harmonised carbon price is calculated endogenously in the model in order to ensure that the global carbon budget (cumulative carbon emissions in 2010-2050) of 1000 $GtCO_2$ is met.

Table 15: Scenario definition

			Climate policy up to 2030		**Climate policy 2030 - 2050**	
Scenario name	**Global target**	**EU target**	**EU28**	**Non-EU**	**EU28**	**Non-EU**
Baseline	None	Reference 2016	Reference 2016	Reference	Reference 2016	Reference
EU Alone	None	80% reduction in 2050/consistent with Roadmap budget	EUCO27 450ppmv	Reference	EUCO27 450ppmv	Reference
Delayed Action	450 ppm	80% reduction in 2050/consistent with Roadmap budget	Reference 2016	Reference	EUCO27 450ppmv	450 ppmv
EU First Mover	450 ppm	80% reduction in 2050/consistent with Roadmap budget	EUCO27 450ppmv	Reference	EUCO27 450ppmv	450 ppmv

E3ME model results

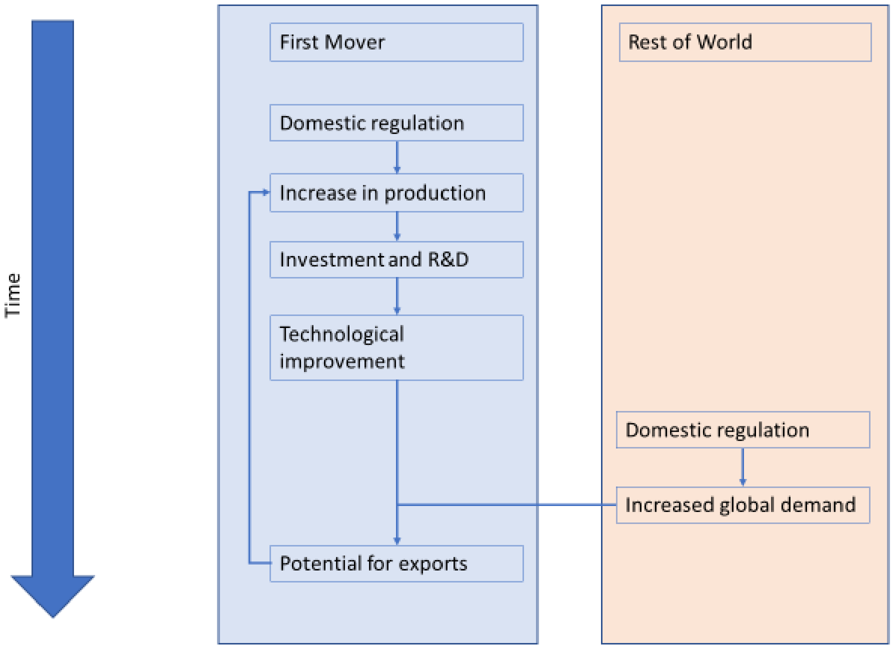
E3ME has previously been used to assess FMA in an assessment for DG CLIMA, which was published in Pollitt et al (2015). The scenarios in that study made clear assumptions about the share of the market that was captured by EU production, based on assumptions about development times and the protection of intellectual property. The results from E3ME showed that, while the EU could benefit during the period of (assumed) increase in market share (which could offset some of the costs of decarbonisation), there were no sustained benefits – i.e. the results were driven by assumptions rather than endogenous model-based relationships.

In the present exercise, we do not make prescriptive assumptions about the market shares that are captured by EU production but instead rely on the model's endogenous relationships.

Figure 25 shows how a first mover advantage could be established and sustained in the E3ME framework, starting from the exogenous policy inputs. The process relies on a combination of accounting relationships and behavioural relationships that are estimated through the model's econometric parameters. It should be noted that if any one step in the process fails, then FMA cannot be maintained. Most likely, this would be:

- If an increase in production does not lead to additional investment and/or R&D, for example if firms increase production of existing goods without making further improvements.
- If the technological advances are not sufficient to capture market share in global markets – that is, if the technology parameter in the bilateral trade equations has a small or non-significant value.

Figure 25: How first-mover advantage could be sustained in the E3ME model



Technology in E3ME is measured as a stock of accumulated knowledge in each sector, developed from original work in Kaldor (1957) and formulated in Lee et al (1990). Dixon and Thirlwall (1975) discuss the approach in the context of trade and competitiveness.

Although there is some depreciation to this knowledge over time, it requires quite a large change in investment to see substantial increases in a sector's *stock* of knowledge. At the level of aggregation in E3ME (NACE 2-digit), the impact on sectoral production required to move the technology indices substantially is very large. It does not, however, need to be sustained, as the method of accumulation means that shocks to the technological stock can be long-lived.

Although the impacts of technological progress on trade in E3ME can be substantial (Barker and de Ramon, 2006), previous model results from E3ME have not tended to show substantial FMA. This is in part because of issues related to aggregation (so that trade in detailed, specific technologies is not distinguished from the broader sector of which the technology is part), but also the relatively low values for the trade elasticities in E3ME (Chewpreecha et al, 2015). In short, E3ME tends to find that production locates to where the demand is rather than seeing major disruptions to trading patterns.

It seems likely, therefore, that the E3ME results miss potential benefits for senior managers and shareholders in the firms that are able to exploit FMA through royalty payments or cross-border ownership of production – and that, if this extra wealth is spent rather than saved[16], there could be some wider economic benefits. However, the primary finding that most of the jobs are created outside the country that established FMA remains valid unless profit margins become large enough to exceed labour costs, which seems unlikely in reality.

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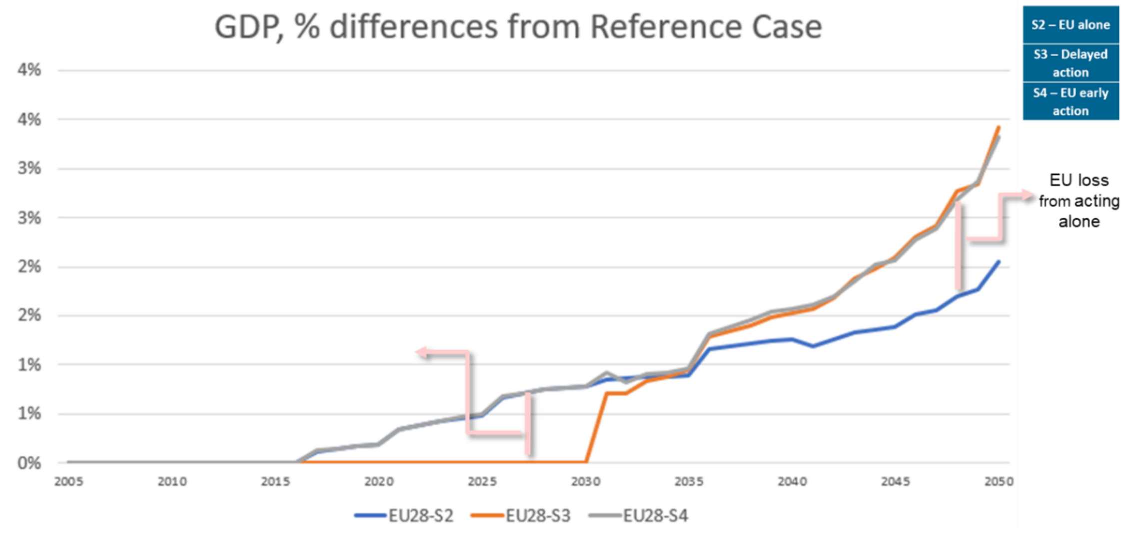
[16] This would be a major assumption, as studies that estimate the marginal propensity to spend additional non-housing financial wealth typically find low values, usually less than 0.1 and possibly even less than 0.05 (see e.g. Iacoviello, 2011).

Macroeconomic Impacts

Figure 26 shows the macro-economic results from the E3ME modelling. Overall, the GDP effects are positive in all scenarios examined, because there is revenue recycling and a double dividend effect on the EU economy (with higher GDP mainly led by reduced fossil fuel imports) and the model results show that the benefits for the EU would be higher if other countries also took measures to reduce emissions (limiting negative competitiveness effects).

With regards to FMA, the key distinction is between the orange and grey lines on the chart. The grey line shows the case where the EU takes early action and has the potential to establish FMA ahead of the rest of the world tackling emissions from 2030 onwards. Under the scenario represented by the orange line, all countries take action together so there would be no FMA. The model results from E3ME show that there is the potential for a small FMA in the period immediately after 2030 (around 0.1% of GDP) but that this effect dissipates quickly and there are no lasting impacts.

Figure 26 EU28 GDP temporal adjustment in all scenarios examined



Source: E3ME

Table 16: Macroeconomic effects of the EU Alone, FMA and Delay scenarios

cumulative change 2020 - 2050 from reference scenario, in %		**GDP**	**Investment**	**Private consumption**	**Net exports (trillion € 05) Clean Energy Technologies**	**Employment in Clean Energy Technologies**
Full Spillovers	**EU - Alone**	*1.0*	*2.1*	*0.8*	*0.17*	*0.2*
	Delay	*1.2*	*2.0*	*1.0*	*0.21*	*0.3*
	EU - FMA	*1.4*	*2.3*	*1.1*	*0.22*	*0.4*

Source: E3ME

Sectoral Impacts

Going to sectoral level (see Table 17), there are also no noticeable impacts of FMA (obtained by comparing the results for S4 with S3); the small impacts that we do see at sectoral level reflect lagged effects from earlier time periods, rather than developments that could be attributed to FMA.

Table 17: Impact on selected E3ME sectors

E3ME Sector	Impact of FMA on output, %, 2031-2050
Metal products	0.12
Electronics	-0.03
Electrical equipment	0.08
Other machinery and equipment	0.00
Motor vehicles	-0.01
Other transport equipment	0.02

The results from these scenarios are consistent with the previous analysis that was carried out for DG CLIMA, given the different modelling assumptions, i.e. without specific assumptions about the markets that are captured, little impact is shown. If the EU is to establish FMA in key environmental technologies, it must be through the specific development of new products that are both substantially different to those that exist at present and would be different for companies in other countries to imitate. A stricter enforcement of intellectual property rules could facilitate the establishment of FMA, although this could be perceived as against the spirit of the Paris agreement, which foresees a role for technology transfer.

GEM-E3-FIT model results

In the GEM-E3-Fit model, the policies for the decarbonisation of the energy system drive R&D expenditures on clean energy technologies. R&D expenditures result in the creation of knowledge and knowledge accumulation results in innovation and increased productivity. The productivity established through R&D is derived from the deterministic learning by research curves[17] introduced into the model. This productivity is then diffused into other industries and countries according to the spillover matrices that have been presented in Part VII of this report. The speed at which this diffusion takes place is determined exogenously and in the standard runs it is set to one model period (i.e. five years). Variants with cross sectoral and cross country spillovers are examined and are reported in the section Sensitivity Runs.

Macroeconomic Impacts

Profits from the EU's early action regarding the development of clean energy technologies depend on the size of the market and the potential for market penetration that can be achieved. The time window for EU early action is set to 5 years (in 2030 all countries adopt ambitious energy and climate policies). In the EU alone scenario, the cumulative (2020-2050) EU28 GDP falls by 0.1% as compared to the baseline scenario. The expansion of clean energy technologies in the EU reduces their production cost but the demand from non-EU countries is relatively small as there are no comparable energy and climate policies. The cost reductions are not sufficient for the clean energy technologies to break-even with the respective conventional fossil fuel technologies hence the GEM-E3-FIT model does not project a significant increase in EU exports. The EU-FMA scenario presents higher GDP relative to the EU-Alone scenario by 0.06% (cumulative 2020-2050). This is mainly driven by higher investments and exports of clean energy technologies.

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[17] The exact values of the learning by research curve are presented in the Section VI of this report.

Table 18: Macroeconomic effects of the EU Alone, FMA and Delay scenarios

cumulative change 2020 - 2050 from reference scenario, in %		**GDP**	**Investment**	**Private consumption**	**Net exports (trillion € 05) Clean Energy Technologies**	**Employment Clean Energy Technologies**
Full Spillovers	**EU - Alone**	-0.10	0.75	-1.53	0.10	8.29
	Delay	*-0.62*	*0.12*	*-2.29*	0.70	9.14
	EU - FMA	*-0.04*	*0.90*	*-1.54*	0.81	11.06

Source: GEM-E3-FIT

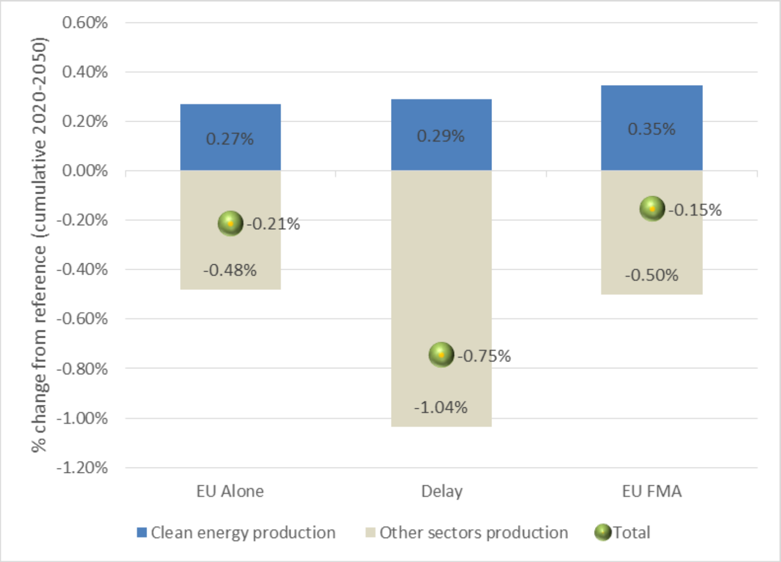
In the Delay Scenario, the cumulative (2020-2050) EU GDP is reduced by 0.62% as compared to the baseline scenario. The economy and energy restructuring required in such a short term globally is achieved at a high cost as technology maturity of RES and electric vehicles fails to achieve full potential and capital requirements are much greater relative to the other scenarios, where investment plans and R&D expenditures span over a longer time period.

EU28 performs better in the EU-alone scenario than in the delay scenario. The EU bears the consequences of competitiveness losses in the EU Alone scenario, whereas the EU bears mainly the consequences of global GDP reduction in the delay mitigation scenario. The EU GDP losses are at a small extent offset in the EU-FMA scenario by the competitive advantage achieved in the EU thanks to its early ambitious climate action.

Sectoral Results

In all the alternative scenarios, clean energy production sectors benefit from the decarbonisation efforts and their sectoral production increases cumulatively to 2050 (Figure 27). The production of fossil fuel supply and energy intensive industries is reduced from the baseline scenario in all cases examined, as these sectors are directly impacted by ambitious climate policies and high carbon prices. In the Delay scenario the production of non-clean energy sectors in the EU is reduced from baseline levels mainly due to the stronger decarbonisation effort post 2030 and the depressive effect of worldwide mitigation action on global GDP which exerts a downwards pressure on demand for EU exports.

Figure 27: EU28 production adjustment in all scenarios examined



Source: GEM-E3-FIT

Table 19 and Table 20 present the results from GEM-E3-FIT regarding the size of the global clean energy market in the Baseline and EU-FMA scenarios and how this is shared among the different clean energy technologies. The size of the market of clean energy technologies is driven both by the number of units sold and the unit costs. Unit costs are reduced as a result of R&D and learning by doing hence despite the rapid increase of production of clean energy products in the EU-FMA scenario, the size of the respective market does not increase proportionally. For example, in 2050 global PV installations (measured in GW) are projected to increase by 35% in the EU-FMA scenario relative to the Baseline, while the economic value (sales) of global PV production increases by only 18% from Baseline levels, as the unit cost of PV has been reduced by 13%.

Table 19: Global Market size of clean energy technologies in the Baseline scenario

bn. €	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**	**Cumulative 2015-2050**
Solar	55	52	55	48	88	101	125	140	2880
Wind	96	107	124	251	261	310	365	477	8710
Electric Cars	21	8	28	95	121	232	276	419	5101
Bioethanol	65	86	144	191	229	258	291	322	7099
Biodiesel	24	32	54	72	86	97	110	121	2671
Total	**261**	**286**	**405**	**658**	**785**	**999**	**1167**	**1479**	**26462**

Source: GEM-E3-FIT

Table 20: Global Market size of clean energy technologies in the EU - FMA scenario

bn. €	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**	**Cumulative 2015-2050**
Solar	55	52	55	48	142	172	168	165	3733
Wind	96	110	124	251	503	478	433	587	11323
Electric Cars	21	8	28	95	436	520	1871	2045	20972
Bioethanol	65	86	146	192	232	256	288	330	7123
Biodiesel	24	32	55	72	87	96	109	124	2680
Total	**261**	**288**	**408**	**658**	**1401**	**1523**	**2862**	**3240**	**45831**

Source: GEM-E3-FIT

The technology cost reductions are presented in Table 21. The large penetration of solar PV and Wind technologies in the energy system achieved already in the Baseline scenario would drive their unit costs down close to their technical potential ("floor costs"); hence the additional deployment of clean energy technologies in the EU-FMA scenario implies a relatively limited cost reduction by about 12% and 5% respectively from the baseline scenario in 2050. Electric vehicles is a technology that will not reach maturity (in terms of cost reductions) in the baseline scenario; thus they present the highest potential for price/cost improvements in case of ambitious energy policies adopted (26% from Baseline in 2050).

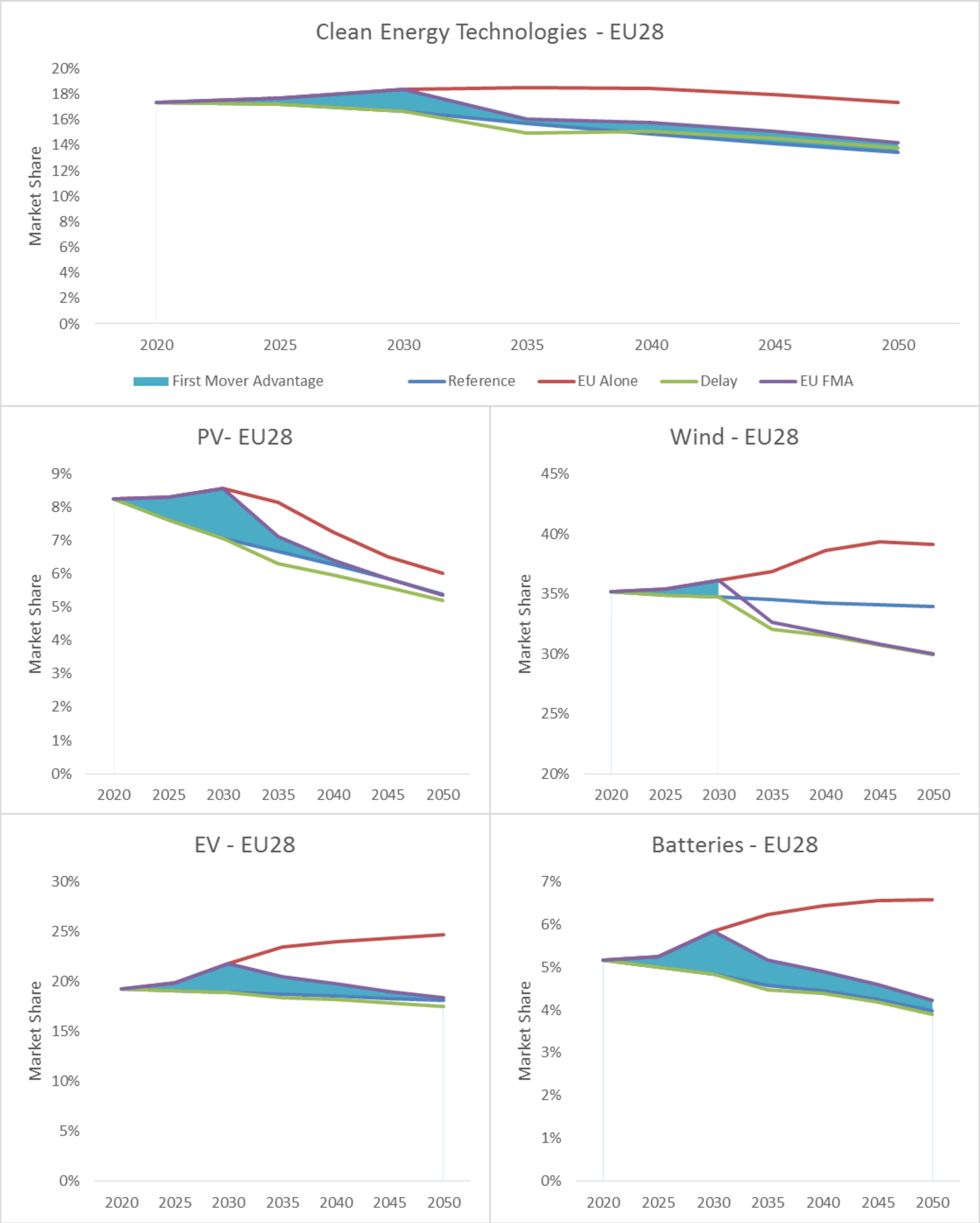
Table 21: Evolution of Technology unit costs in Baseline and EU-FMA scenarios

Technologies	Unit Cost					
	2015	2030 (Baseline)	2030 (EU - FMA)	2050 (Baseline)	2050 (EU - FMA)	
Solar	1409	976	933	651	568	€/KW
Wind	1568	1253	1245	1073	1015	€/KW
Electric Vehicles	42871	27501	27117	20019	14732	€/vehicle
Bioethanol	1183	951	951	856	852	€/toe
Biodiesel	1102	886	886	798	794	€/toe

Source: GEM-E3-FIT

In the case where EU acts alone the additional demand for solar PV equipment and batteries (which is EU based) is met mainly via imports. In the FMA scenario, this changes since the EU has already established a comparative advantage and can gain increased shares in the global market in all clean energy technologies. The highest increase of market share is projected for the electric vehicles market which is also the largest market amongst the clean energy technologies examined. As presented in (Table 19, Table 20) the size of the market increases in all scenarios examined. The advantage for the EU as indicated by a higher market share is presented in Figure 28.

Figure 28: EU28 world market shares in key clean energy technologies



Source: GEM-E3-FIT

As compared to the previous modelling exercise performed by E3M in 2015 (with the GEM-E3 model), the updated modelling results showed that the time window that the EU has in order to perform early climate action is getting shorter as other countries (mainly China) have already started increasing their share in clean energy technologies market. As the time for early action is getting shorter (assuming that non-EU countries will embark in producing and using clean energy technologies from 2030) the potential for innovation and cost reduction through economies of scale is reduced. The model results indicate that electric vehicles seem to have the highest potential for first mover advantage, a result which is in concordance with previous findings.

Sensitivity runs

The key modelling features used to identify technology competitive advantages and the associated uncertainties are the following:

a) **Innovation**: The link between R&D spending, knowledge, innovation and productivity improvement is quite uncertain. There are few empirical estimates on the leverage of R&D and the disruptive character of an innovative technology is rarely captured by applied large-scale models.

b) **Technology diffusion mechanism**: Transfer of knowledge between industries and countries. The uncertainty in this mechanism is on the ability of agents to absorb[18] knowledge and the direction of the diffusion.

c) **Patenting**: Speed at which the replication of clean energy patents takes place. Replication can take place either through purchase of a patent, purchase of the rival firm or reverse engineering.

d) **Geographical fragmentation of production:** Although the sectoral detail of the GEM-E3-FIT model has been increased so as to identify separately the manufacturing of clean energy technologies, it cannot capture the manufacturing of different components of a product. For example it is assumed that the sector producing the electric vehicles includes the production of electric batteries.

e) **Royalties:** Currently in the modelling the replication of a patent is costless in terms of purchasing a patent. The lack of royalties has a two a sided effect: i) it reduces the revenues of the innovator and ii) benefits the replicator as he/she is not subject to any costs that otherwise should have been recovered either by higher selling prices or by lower profits. GEM-E3-FIT does not include a database on intellectual property royalty rates.

In order to address the uncertainty that arises from the above mentioned characteristics of the modelled mechanisms the following actions have been taken:

i) **Innovation**: We have constructed a distribution of R&D expenditure and payoffs and we run the model 100 times extracting a random pair (R&D expenditure – payoff) each time.

ii) **Technology diffusion mechanism and patenting**: Absorption capacity has been reduced in half for all regions. To reflect different speeds at which the replication takes place, the lag in adoption has been set to five or ten years respectively

iii) **Royalties:** Income stream to the innovator. This is an illustrative application as no real data have been used on royalties and purchased patents. In this variant it is assumed that 50% of the earnings (of the purchaser of the patent) are paid back to the innovator perpetually as a royalty.

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[18] This is proxied by the stock of human capital and the cumulative R&D expenditures of an industry.

Regarding the Geographical fragmentation of production this requires the extension of the IO tables to account separately for the production of key components of the value chain of electric vehicles such as electric batteries. This in turn requires extensive data work (regional production shares, bilateral trade, production costs, data reconciliation from different data sources, balancing of the IO tables) which could not be undertaken in the scope of this study.

Innovation

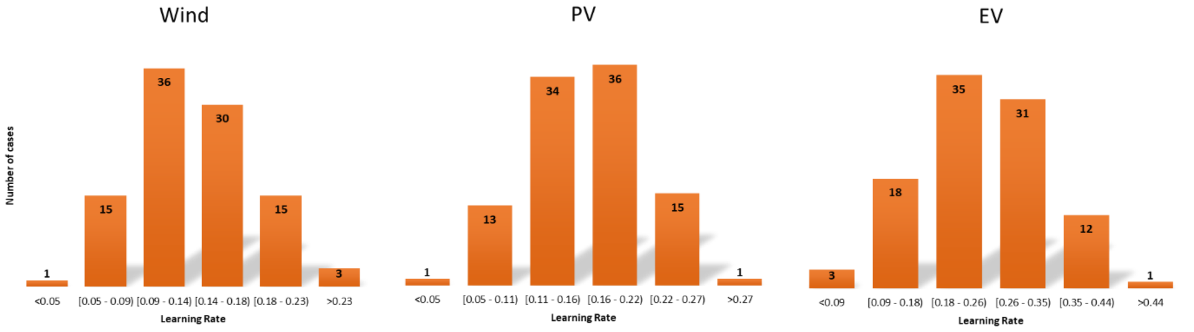
In order to examine the robustness of GEM-E3-FIT model results with respect to the assumed learning by R&D rates for clean energy technologies, the EU-Alone and FMA scenarios were simulated with the GEM-E3-FIT 100 times for random pairs of R&D spending and productivity gains. To perform the sensitivity runs the learning rates available from the literature have been used as mean values (as presented in detail in part VI of the report). It has been assumed that the learning by research rates of clean energy technologies follow a normal distribution (with mean the values available in the literature and standard deviation the 1/3 value of the mean). Technologies that are considered to be mature like solar PV and Wind have low learning rates and standard deviations (Table 22).

Table 22: Mean values and standard deviations used to derive the normal distribution

Technology	Mean value of Learning Rate	Standard Deviation
Electric Vehicles	0.25	0.083
Wind	0.14	0.047
PV	0.16	0.053

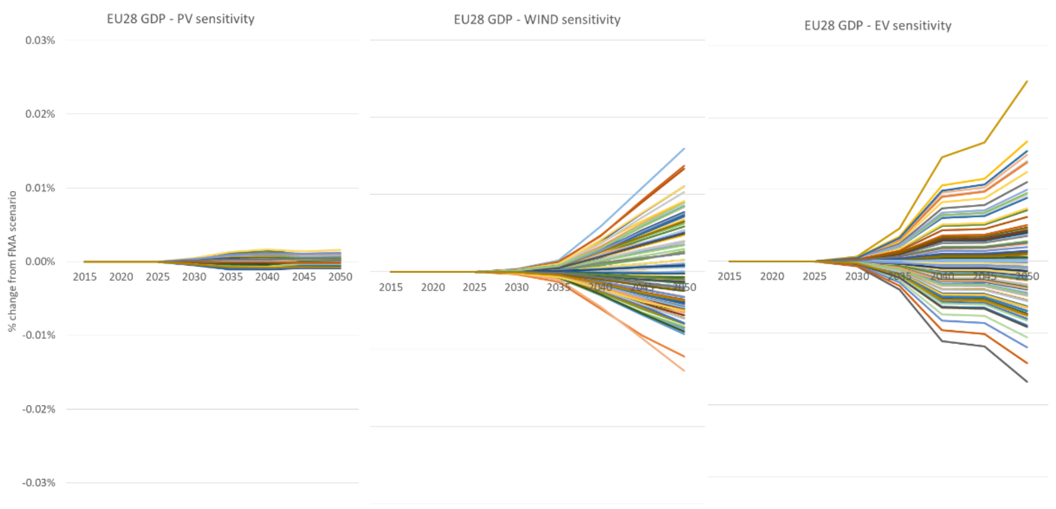
The empirical distribution of the learning rates used in the model for each technology (Electric Vehicles, Wind and PV) is presented in Figure 29.

Figure 29: Empirical distributions of Learning Rates on clean energy technologies



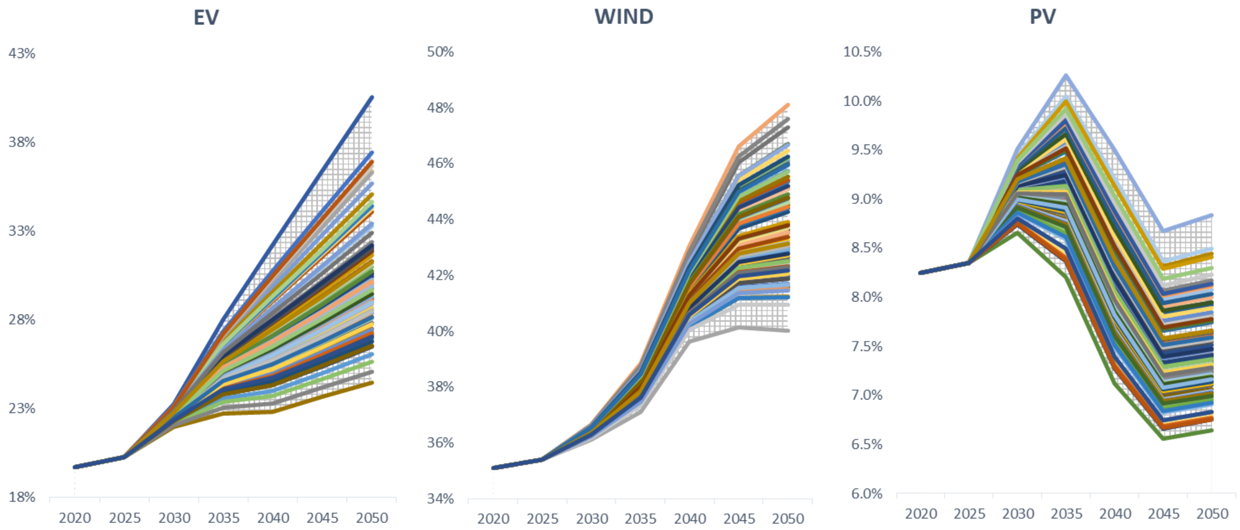
The different learning rates were applied in the EU alone and in the FMA scenario. The sensitivity analysis showed that the macro results on average are not particularly sensitive on the assumption regarding R&D expenditure and its impact on total factor productivity. In particular the changes in EU GDP range from -0.01% up to 0.02% in the period 2020 to 2050. The uncertainty regarding the link between R&D expenditures and innovation is more relevant to new and currently immature technologies like electric vehicles and less on relative mature technologies like wind and solar PV (Figure 30).

Figure 30: GDP impacts of 100 alternative pairs of R&D and productivity in key clean energy options



The market shares of the different technologies in world production are presented in Figure 31 supporting the finding on the variations on GDP.

Figure 31: Clean energy technology market shares for 100 GEM-E3-FIT runs



Source: based on GEM-E3-FIT

Technology diffusion

In order to test for the importance of licensing and spillovers, two alternative cases to the base case has been considered:

i) Case a: The capacity of competitors to absorb knowledge generated elsewhere is reduced to 50%

ii) Case b: The proprietary period after which competitors can replicate patents increases to 10 years,

Reduction in spillovers acts to the benefit of the EU clean energy manufacturers as they achieve increasing market share throughout the simulation period. Spillovers act in reducing the cost of the low-carbon transition at the global level, but at the country level diminish technology cost advantage of the early mover.

The lag effect (delaying the replication of the patent) intensifies the FMA advantage in the short term, but in 2050 delivers lower sales for the EU clean energy manufacturers relative to the case where spillovers are limited. In the case where the patent replication pace slows down, non-EU countries may reduce the adoption rate of clean energy technologies as they are more costly; thus global demand for EU clean energy exports is reduced (Table 23).

Table 23: Impact on GDP for alternative assumptions about knowledge spillovers

cumulative change 2020 - 2050 from reference scenario, in %		***GDP***	***Investment***	***Private consumption***	***Net exports (trillion € 05) Clean Energy Technologies***	***Employment in Clean Energy Technologies***
Full Spillovers	***EU - Alone***	*-0.10*	*0.75*	*-1.53*	*0.10*	*8.29*
	Delay	*-0.62*	*0.12*	*-2.29*	*0.70*	*9.14*
	EU - FMA	*-0.04*	*0.90*	*-1.54*	*0.81*	*11.06*
Case a: Reduction of absorption capacity	***EU - Alone***	*-0.08*	*0.74*	*-1.55*	*0.11*	*8.32*
	Delay	*-0.62*	*0.10*	*-2.31*	*0.71*	*9.14*
	EU - FMA	*-0.03*	*0.87*	*-1.57*	*0.84*	*11.10*
Case b: 10-year lag in patent replication	***EU - Alone***	*-0.08*	*0.74*	*-1.54*	*0.11*	*8.31*
	Delay	*-0.62*	*0.10*	*-2.31*	*0.71*	*9.15*
	EU - FMA	*-0.04*	*0.87*	*-1.56*	*0.84*	*11.10*

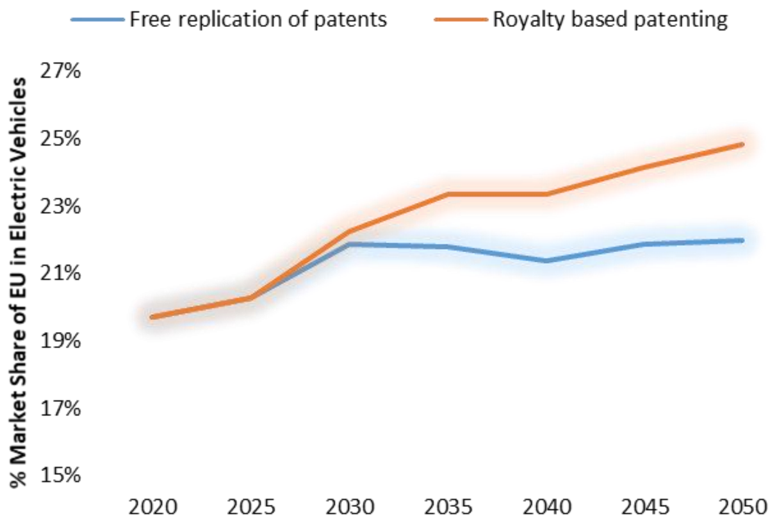
The technology spillovers impact the EU economy through two main channels: i) Negative impact through the reduction of first mover advantage in clean energy industries and ii) Positive impact through stimulating world demand for EU products (the cost free adoption of EU patents enables non-EU manufacturers to produce carbon free technologies at reduced cost and hence adjust better to a low carbon energy system). The case where EU competitors have limited absorptive capacity (either through well protected patents or scarcity of skilled labour in non–EU countries) is the most favourable case for the EU of all scenarios examined. It should be noted however that the differences are quite small between the scenarios

Royalties

Decentralised production makes production efficient and competitive as it involves the creation of the patents in places endowed with high skilled labour and the mass scale production in places with low wages and production costs. Such production structures that involve geographical segmentation entail an increase in income (in the form of profits for the shareholders of the firm) for the country that produces innovation and an increase in income (in the form of higher employment) in the country that performs the physical production. Innovation can also generate income to the innovator in a secondary form through selling patents licensing (royalties). Purchased patents or cited patents reflect the knowledge spillovers that occur with a time lag once the initial innovation is licensed.

An illustrative simulation was designed where in the EU alone scenario and FMA scenarios EU electric cars manufacturers receive royalties for each patent that is used by non-EU established industries. It is assumed that the royalty rate is set to 50% of the earnings of the competitor that accrue due to the use of the patent. No knowledge spillovers are assumed. The inclusion of royalties impact the modelling results through two channels: It increases the revenues of the inventor and increases the cost of the purchaser hence further increasing the benefits to the innovator. Licensing helps to retain the first mover advantage for a longer period but makes the adjustment of non-EU countries more costly hence the world demand for EU non-clean energy products is lowered. The patent licensing reduces the non-EU production of electric vehicles and increases the income for EU firms and subsequently EU households (i.e. in the form of dividends). Hence the market share of the EU in global production of electric vehicles increases by 3 p.p. by 2050. This has a marginal positive impact on EU cumulative GDP in the FMA and EU alone scenarios.

Figure 32: Market share of EU in global production of electric vehicles in alternative scenarios



Source: GEM-E3-FIT

E3ME

The E3ME model has performed different sensitivities regarding the importance of geographical segmentation of production and potential for the EU to acquire a different market share as a result of different degrees of patented innovation that can be protected through international Intellectual Property rights. The sensitivities examined are:

- The EU establishes a 5% global market share in low-carbon technologies that is additional to the baseline[19]. European firms produce the goods in the EU and exports them around the world.
- The EU establishes a 5% global market share in low-carbon technologies that is additional to the baseline. European firms produce the goods close to market and repatriate profits back to Europe.
- The EU establishes a 2.5% global market share in low-carbon technologies that is additional to the baseline. European firms produce the goods in the EU and exports them around the world.
- The EU establishes a 2.5% global market share in low-carbon technologies that is additional to the baseline. European firms produce the goods close to market and repatriate profits back to Europe.

The total size of the market is estimated as the additional investment that is made by non-EU countries over the period 2030-50 in the sectors (i.e. the difference in investment between EU Alone and EU First Mover Action in these sectors). Profits are estimated as 10% of the investment, with half of profits being distributed as dividends to households' current incomes, rather than retained or distributed to pension and other financial funds.

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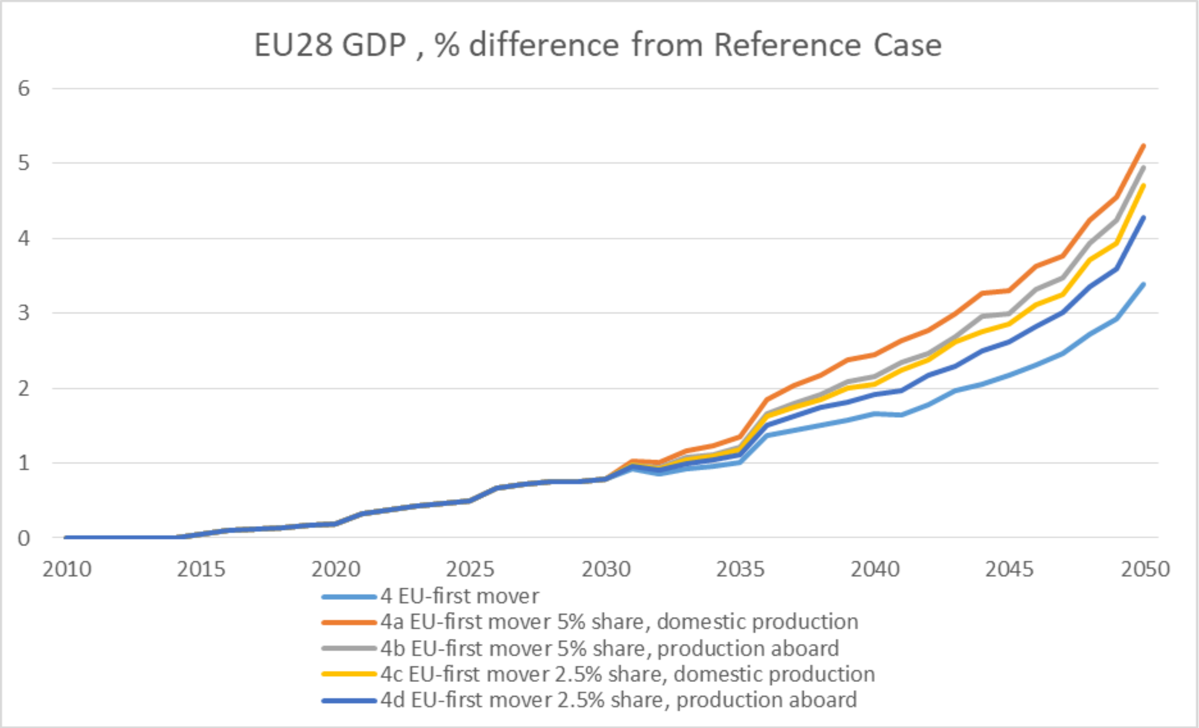
[19] In the baseline, the EU global market share is around 18% in 2050.

The 5% and 2.5% shares of this market, while arbitrary, represent different degrees of patented innovation that can be protected through international Intellectual Property rights. Although small, once we account that around half the investment concerns installation, these cases do represent a reasonable share of market value captured.

The other difference between the sensitivities reflects how the location of production might develop in the future. Two approaches are tested; the first is where EU firms manufacture the equipment domestically and export it to where the demand is, and the second where the production takes place outside the EU but still contributes to European firms' profits. While both cases lead to financial benefits for the EU, the case where production takes place in Europe is likely to lead to better employment effects.

Figure 33 EU28 GDP in S4 and its variants



Source: E3ME

Figure 33 shows the impacts on GDP in scenario S4 and its variants. The increase in EU GDP could be enhanced by up to 5.2% relative to the Baseline if FMA is considered and European firms produce the additional goods domestically. Even if production does not take place in Europe, there is still a potential benefit to EU GDP of 5% by 2050. Although these results clearly reflect the arbitrary assumptions made, they give a good indication of the potential size of FMA to the EU, if European companies were able to capture an additional share of the global market for low-carbon equipment. A range of 0-6% of GDP seems plausible in this context, which would be roughly comparable to the impact of the decarbonisation measures described previously in this section.

The variant assuming a 5% increase in EU market share leads to a 0.9% increase in GDP compared to the main FMA scenario (

Table 24). In E3ME simulations, it is assumed that the EU produces the clean energy technologies at a break-even cost with its competitors.

Table 24 EU28 Macro Summary, average impacts between 2031-2050 as % difference from the EU FMA scenario

	4a EU-first mover 5% share, domestic production	4b EU-first mover 5% share, production aboard	4c EU-first mover 2.5% share, domestic production	4d EU-first mover 2.5% share, production aboard
GDP	0.9	0.66	0.54	0.34
Investment	0.71	0.52	0.43	0.26
Consumer spending	1.09	1	0.58	0.51
Imports (extra-EU)	0.98	0.42	0.81	0.23
Exports (extra-EU)	1.25	0.15	1.08	0.11
Employment	0.25	0.17	0.16	0.09

Source: E3ME

Table 24 shows the results for the main macroeconomic indicators. In this table the impacts are compared to S4, i.e. they isolate the potential effects of FMA. The table shows the different mechanisms behind the results. In the cases where production takes place outside the EU, the direct stimulus is through household incomes and consumption. Consumption also increases when production takes place domestically, but here there is also a boost to exports, meaning that GDP increases by more. The other key indicators (employment, investment, imports) all follow patterns of the total changes in GDP.

Table 25 Impact on selected sectors, average impacts between 2031-2050 as % difference from S4

	4a EU-first mover 5% share, domestic production	4b EU-first mover 5% share, production aboard	4c EU-first mover 2.5% share, domestic production	4d EU-first mover 2.5% share, production aboard
18 Metal products	1.82	0.55	1.23	0.3
19 Electronics	2.27	1.09	1.48	0.55
20 Electrical equipment	3.89	0.65	3.02	0.3
21 Other machinery and equipment	3.62	0.47	3.02	0.46
22 Motor vehicles	1.23	0.32	0.84	0.17
23 Other transport equipment	2.09	0.53	1.44	0.27

Source: E3ME

Table 25 shows results for the main sectors that could benefit directly from FMA. Some of the increases in production are quite large, for example Electrical equipment could increase output by 3.9% on average between 2031 and 2050 compared to S4; the relative size of the increase depends principally on the ratios between existing production and the size of the potential export market. Other factors that determine the possible increase in output include import shares in supply chains, i.e. how many of the components would need to be imported to make the final products for export.

If a multinational company opens a factory abroad, the activities of that factory accrue to the country in which it is based, not the country in which the firm is headquartered. In terms of jobs this is of course the correct treatment, but E3ME does not automatically include an income effect from the potential repatriation of profits from international production.

Part IX Modelling Caveats and suggestions for model developments

There are certain elements in the modelling that can be improved in order to better represent the mechanisms that are key in establishing comparative advantages. Below we list the elements considered most relevant:

1. Models that are used to assess industry comparative advantages need necessarily to have the required sectoral resolution. It is important that the production structure, employment requirements, market share and bilateral trade transactions reflect the most recent statistics. Results from models with sectoral aggregation will be misleading.
2. Knowledge and technology diffusion representations require improvement. In the cases where patents-citations are used as a proxy of the technology transfer matrix, it is required to include only the patents that have a market value. Data on purchased patents and their associated citations should be used. Patents - citations matrices should be quality adjusted according to the criteria of the patent office they have been submitted. Patents submitted in EPO have lower chances to be accepted from those submitted in certain national patent offices.
3. The link between R&D expenditure – innovation – productivity is based on learning by research rates which are deterministic and relevant for short term projections. The link between pubic R&D and private R&D and the channels for economic leverage is a critical aspect that is not well covered in current modelling tools.
4. The importance of royalties of patents as an income stream to the innovator and a cost to the purchaser needs to be addressed by using detailed data on intellectual property royalty rates.
5. Project risks and associated financing require better empirical justification or sensitivity analysis.
6. As transportation costs are important for the market penetration of certain RES technologies (especially for wind turbines), these need to be estimated to the latest available statistics.
7. Cross sectoral indirect spillovers are not captured by the modelling (e.g. conventional farming is benefited by the advanced farming techniques used for bioethanol feedstock production). These spillovers although important are not captured by knowledge transfer matrices based on patent – citation approach.
8. Due to low trade elasticities, models tend to find that production locates to where the demand is rather than seeing major disruptions to trading patterns. Empirical estimation of trade elasticities for key sectors is required.
9. Knowledge spillovers created through R&D in non-clean energy sectors are not taken into account. Knowledge created through innovation in fossil fuel related technologies and the associated spillovers are not included in the analysis.
10. The current study focuses on technology innovation and not systemic innovations (i.e. innovations for business models, financing schemes, configurations of the power system etc.) that might be important in the development and establishment of some clean energy technologies (e.g. combinations of decentralised PV with small-scale batteries).
11. Quality and safety concerns that impact the sales of each clean energy technology are not being addressed in the current study.
12. In the cases where learning is a function of global capacity and cost reductions are simultaneously achieved in all countries (like in the case of the E3ME model),

it is not possible to capture potential first mover advantages through economies of scale and learning-by-doing.

13. Corporate strategic decisions regarding the geographical dispersion of production chains are not well captured as much more detailed datasets are required that represent in a high resolution the geographical production of high value components and the chain of international firms ownership and income flows.

Part X Conclusions and key findings

The picture on the current production and market shares of clean energy technologies is mixed. Concerning PV module production, China holds the lead with a 55% share in global production, while other emerging Asian economies account for more than 20% and the share of EU has declined to 5% of the global market. In contrast to PV manufacturing industry that has been relocated outside the EU, the EU has managed to maintain a large share in the production of wind turbines (40% in 2015) with Chinese production accounting for 35%. Production of electric vehicles follows an explosive path with EU playing an important role accounting for 25% of the global market, while it also exports to other OECD markets (USA and Japan). On the other hand, Chinese exports to EU remain limited due to EU high safety standards imposed. EU is the leading market in the production of biodiesel representing about 50% of global production in 2015, while ethanol is mainly produced in USA and Brazil (88% of the global market), with EU representing a mere 4%.Based on the patents-citations analysis the technology of biofuels has the highest spillovers both cross sectoral and within the industry. The origin source of citations indicate that the innovation generated within EU is diffused at a faster and larger scale than other countries. On the opposite side, innovation produced in China is not diffused as in EU, USA, Japan probably due to limitations imposed by language.

Data on current R&D expenditure, patents registration and market share in clean energy manufacturing indicate that the time-lag window that EU could use in order to perform early action is reduced and the potential to reap gains from first mover advantage through price competitiveness is limited. In particular EU competitors in clean energy technologies are already directing a significant share of their R&D to these technologies and produce a significant number of patents.

An even more disaggregated and complex search will be required for the purposes of a further update of patent data in order to include energy efficiency and other sustainable transport technologies (apart from electric cars) which are not currently covered in the literature nor in the current analysis.

The model based results show that under specific conditions a first mover advantage for the EU exists but it diminishes over time. The FMA advantage ranges from 0.1% of EU GDP to 0.05% depending on the assumptions of spillovers and learning through research. A key sector regarding EU first mover advantage concerns the manufacturing of electric vehicles. The analysis of industrial and first mover advantages should take into account apart from the potential cost reductions that can be achieved through R&D and massive production, the role of high quality and safety standards in extending market shares (where EU is in a leading position and can thus enhance its comparative advantage).

These conditions are:

- Clean energy technologies have a potential of cost reduction if developed at a large scale, as a result of R&D and economies of scale in mass production
- The European internal market is sufficiently large and unified to allow for achieving a large part of the learning potential for clean energy technologies
- The Rest of world needs to follow ambitious energy and climate action with a sufficiently large time lag (at least 10 years). Clean energy technologies are massively deployed in non-EU regions allowing the EU to reap export benefits from its leading action
- Establishment of integrated vertical supply chains for the manufacturing clean energy technologies in order to exploit in full the potential for economic growth and net job creation (e.g. wind turbine manufacturers in EU)
- The speed and magnitude of technology, innovation and knowledge diffusion to non-EU regions and to other sectors (cross-sectoral spillovers) needs to be balanced. A slow technology diffusion will extend the lifetime of the EU first

mover advantage but will impact negatively overall global economic growth as technology progress is not shared.

The realisation of first mover advantage needs to be both demand and supply driven. The EU energy and climate policies define the size of the EU market for clean energy technologies. In this market both EU and non EU industries compete to gain a market share since free trade is established. Current modelling approaches can capture the implications that early action delivers in terms of production costs and competitiveness. Models can also identify and quantify the role of non-market barriers (i.e. high transportation costs) and the importance of technology diffusion and spillovers. However given the uncertainty on the technology diffusion process and diffusion channels, extensive sensitivity analysis is required around key variables such as the spillovers rate and R&D induced productivity rates.

In the current study it has been found that the role of R&D, spillovers and the speed of technology diffusion are important for the establishment of a first mover advantage. Spillovers impact EU economy through the following channels: i) when technology diffusion is fast it reduces the first mover advantage as competitors can replicate the front runner technology and acquire market share, ii) increase of revenues from royalties (selling of patents to competitors outside the EU), iii) sustain global growth through shared use of advanced technology. The link between R&D expenditure, productivity improvement and GDP gains is important mainly for new technologies that are far from their learning potential. The endogenous representation of R&D, technical progress and technology spillovers are critical model mechanisms in capturing the economic impacts of clean energy technology dynamics. In the absence of these mechanisms, it is impossible for a model to identify potential first mover advantages that are driven through competitiveness improvements.

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Part XII Appendices

Production of clean energy technologies

Photovoltaics

China accounts for more than half of the global production of photovoltaic panels in the period after 2010. However, after 2011 the Chinese position in global market is showing signs of saturation with its share in global PV production stabilising at the level of 55%, a situation can be partly attributed to the establishment of antidumping and anti-subsidy duties on Chinese solar products by the EU and the quota agreement between the EU and Chinese manufacturers. This situation is likely to consolidate in the future as EU duties on Chinese photovoltaics are extended recently (in March 2017), similarly to the ongoing US countervailing duty tariffs and the emergence of new players (like Malaysia and Taiwan). To some extent the increase in Malaysia and Taiwan was due to a change in the Chinese value chain of PVs as a response to the EU and US trade measures, Ball et al (2017). In 2015, other important players in global solar photovoltaic market are Taiwan (12%), Japan (7%) and Malaysia (7%). Amongst the 20 biggest cell/thin film PV manufacturers in 2013 as recorded in JRC, 2016, only Hanwha Q CELLS (South Korea, Germany, Malaysia and China) still has production facilities in Europe (however it has subsequently announced that it is pulling out of Germany and shifting production to Malaysia and Korea). The largest module producing companies are located in Asia with the exception of First Solar (USA). The absence of European companies reflects the severe decline which has occurred over the last years with many companies squeezed out of the market by the intense competition from low-cost modules produced in China and other Asian counties. Other EU companies lacked financial resources (JRC, 2015) to compete in the face of intense price competition, small profit margins and a contracting domestic market. As a result, many have gone out of business or been sold to international investors. The main difference of the PV production market compared to other high-tech products (like cell phones, computers and telecommunications) is related to the fact that major companies are Chinese and do not relocate large parts of their production to other countries in contrast e.g. to communication companies located in OECD economies, whose industrial activities are moved to low-cost developing countries (mainly in Asia).

Electric cars

In 2015, the market share of electric cars reached 23% in Norway, which has more electric cars than any EU country reflecting strong fiscal incentives, coordinated campaigns to develop a national recharging infrastructure and strongly supportive local measures in urban areas. The importance of the Chinese market is demonstrated by the BYD automobile manufacturer topping the ranking of global sales of plug-in hybrid and battery electric vehicles with Tesla and Nissan competing strongly for the second place and BMW, Volkswagen and Renault completing the top 6 global manufacturers. According to the Electric Cars report (2016), in 2015 China accounted for 28% of the global production of electric and plug-in hybrid vehicles, with the EU leading the market with a share of 29.6%. German car manufacturers accounted for 21% of global sales of electric cars (mainly with VW and BMW), while electric cars were also produced in France (share of 6%), Sweden (1.2%) and Italy (1.6%). Other important producers include Japan covering 21% of the world market (Nissan and Mitsubishi) and USA with a 20% share (with the rapid expansion of Tesla and traditional car manufacturers like GM and Ford). Data for 2016 from Electric Car Report (2016) indicate that all Chinese car manufacturers gained market shares in the first half of 2016 and therefore China’s share in the global market of electric vehicles reached about 39%. On the other hand, most car manufacturers outside China lost shares, with the notable exception of Volvo that increased its share from 1.2% to 2.7% of global production.

BYD is the best-known electric car manufacturer outside China with sales in several EU countries. However, it is likely that a number of Chinese brand names will become increasingly familiar in Europe's EV markets over the next few years based on their low-costs and quality improvements (Transport & Environment, 2016). Japanese companies account for the bulk of the Japanese market, while they also maintain significant export shares in other OECD economies, especially in USA, EU and Norway. USA domestic production of EVs represent about 60% of the USA sales; at the same time USA brands (mainly Tesla) have already penetrated in the EU, Norway and Chinese markets. EU manufacturers of electric vehicles account for about 60% of the domestic EU market (EU-28 countries and Norway). At the same time, EU electric vehicles penetrate also in other markets, especially in USA and in South Korea. Largest EU manufacturers include VW, BMW, Renault and Volvo.

Wind Turbines

Table 26: Top 10 wind turbine manufacturers

No	Company	Location Country of Headquarters	Global Market Share
1	Vestas	Denmark	13.2
2	Goldwind	China	10.3
3	Enercon	Germany	10.1
4	Siemens	Germany/Denmark	8
5	Senvion	Germany	6.3
6	GE	US	4.9
7	Gamesa	Spain	4.6
8	United Power	China	3.9
9	Ming Yang	China	3.7
10	Nordex	Germany	3.4

Source: Smead, K (2014) "Top 10 Wind Turbine Suppliers" Energy Digital, November 2014, pp 41-47.

Table 27: Country Share in global exports of Wind turbines

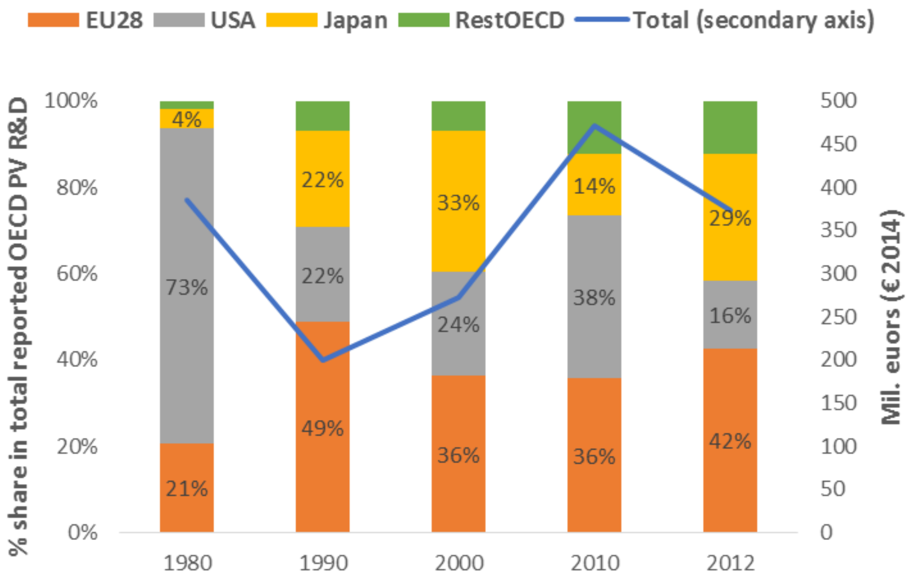
Country	**Share of global exports**		**Net exports [in € Mio]**	
	2014	2015	2014	2015
Denmark	42.54%	41.73%	2821	2978
Germany	25.08%	30.24%	1251	1755
Spain	17.74%	18.55%	1168	1305
Netherlands	0.52%	0.92%	-18	-4
Portugal	0.48%	0.36%	31	21
Estonia	0.32%	0.44%	21	30
Greece	0.25%	0.16%	-34	-123
Ireland	0.20%	0.12%	13	9
Finland	0.12%	0.00%	-76	-92
Belgium	0.07%	0.01%	-202	1
Poland	0.06%	0.08%	-105	-214
France	0.05%	0.04%	-110	-66
United Kingdom	0.05%	0.12%	-444	-299

Lithuania	0.03%	0.06%	1	3
Italy	0.03%	0.06%	-27	-44
Czech Republic	0.02%	0.01%	-2	1
Romania	0.02%	0.00%	-86	-9
Austria	0.01%	0.00%	-19	-51
Bulgaria	0.01%	0.11%	-4	6
Slovakia	0.00%	0.00%	0,1	0
Sweden	0.00%	0.02%	-108	-139
Latvia	0.00%	0.00%	0	0
Croatia	0.00%	0.00%	-9	-28
Slovenia	0.00%	0.00%	0	0,0
Luxemburg	0.00%	0.00%	0	0
Hungary	0.00%	0.00%	-0,4	0
Malta	0.00%	0.00%	0	0,0
Total EU	87.59%	93.02%	4060	5040
USA	6.18%	1.88%	268	-77
China	3.44%	3.68%	221	262
India	0.94%	0.06%	62	2
Canada	0.15%	0.10%	-444	-381
Japan	0.02%	0.03%	-63	-77
Norway	0.00%	0.00%	-35	-9
Turkey	0.00%	0.00%	-263	-376
Switzerland	0.00%	0.00%	0	-1
Russia	0.00%	0.00%	-404	-78
Rest of World	1.67%	1.23%	-1575	-1776

Source: EurObserv’ER 2016, https://www.eurobserv-er.org/pdf/annual-overview-2016-en/

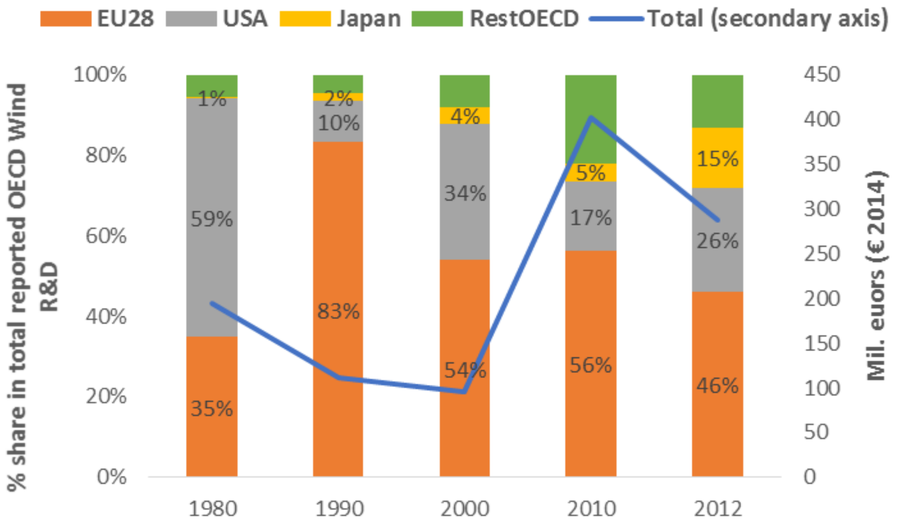
R&D Expenditures

Figure 34: Evolution of PV R&D expenditure for OECD and EU28, USA, Japan share in total OECD expenditure



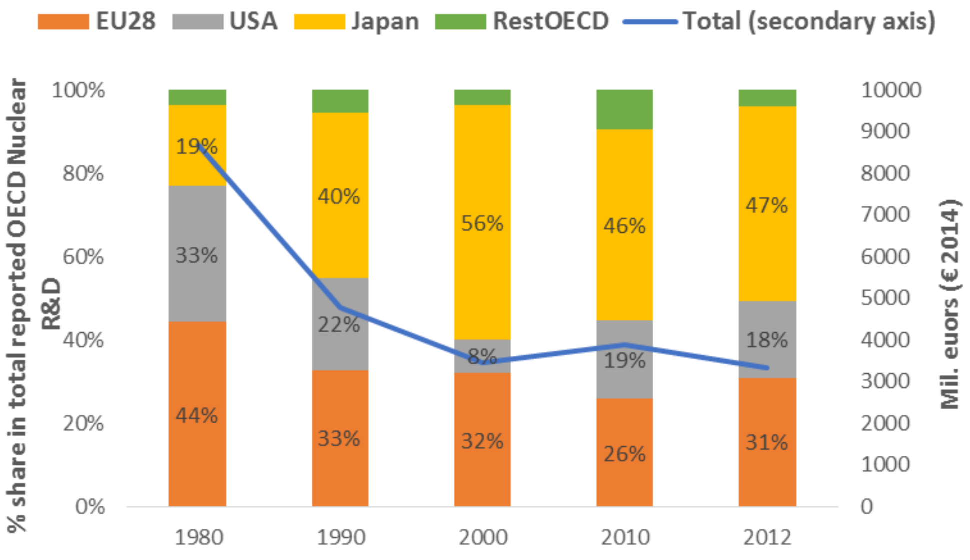
Source: E3Modelling calculations based on based on IEA/OECD; adjusted to data availability

Figure 35: Evolution of Wind R&D expenditure for OECD and EU28, USA, Japan share in total OECD expenditure



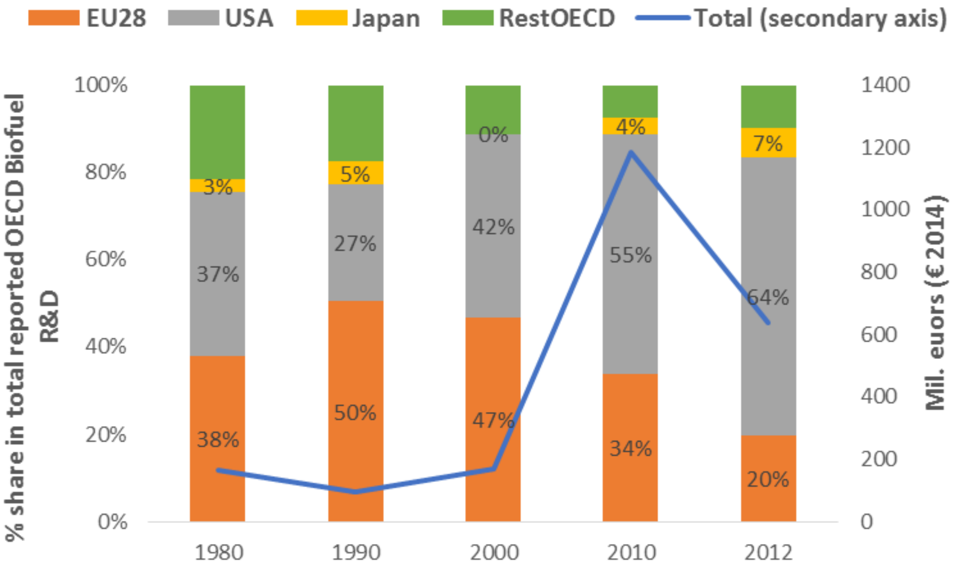
Source: E3Modelling calculations based on based on IEA/OECD; adjusted to data availability

Figure 36: Evolution of Nuclear R&D expenditure for OECD and EU28, USA, Japan share in total OECD expenditure



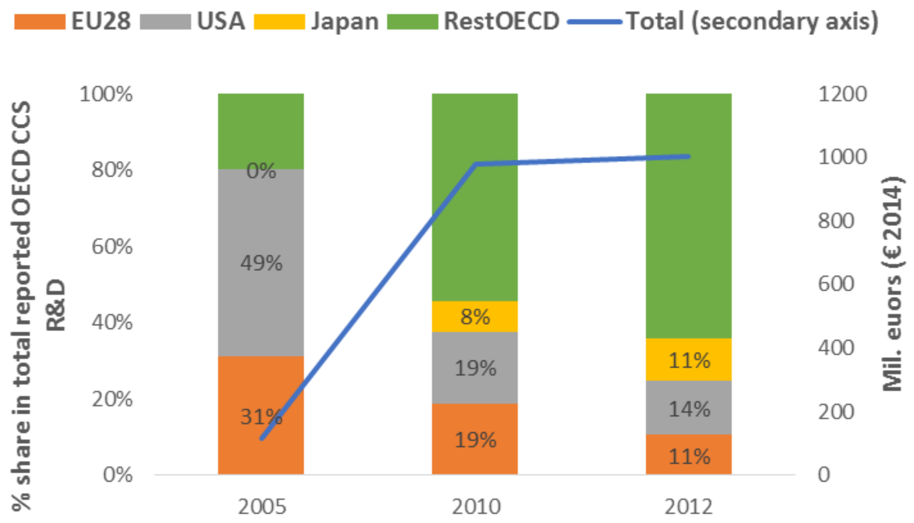
Source: E3Modelling calculations based on based on IEA/OECD; adjusted to data availability

Figure 37: Evolution of Biofuel R&D expenditure for OECD and EU28, USA, Japan share in total OECD expenditure



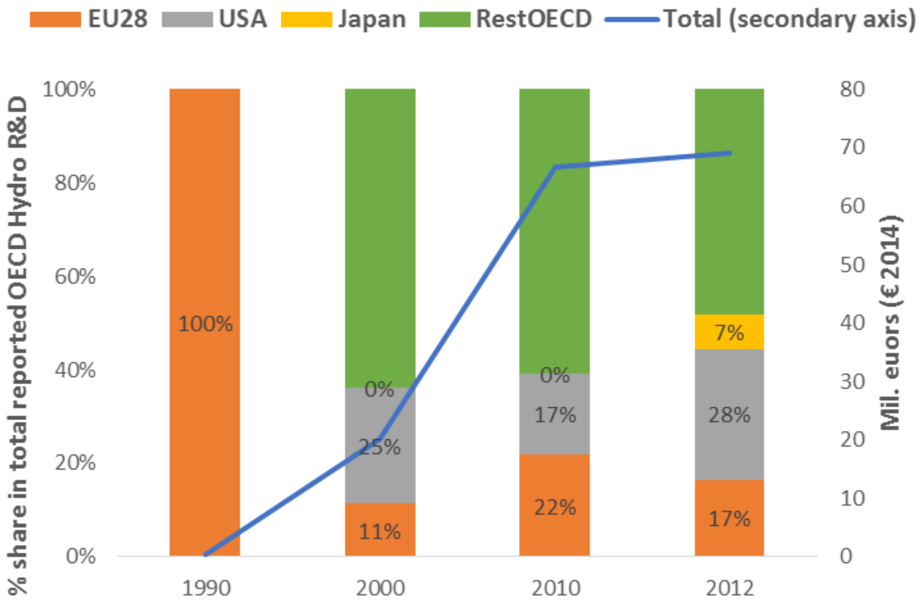
Source: E3Modelling calculations based on based on IEA/OECD; adjusted to data availability

Figure 38: Evolution of CCS R&D expenditure for OECD and EU28, USA, Japan share in total OECD expenditure



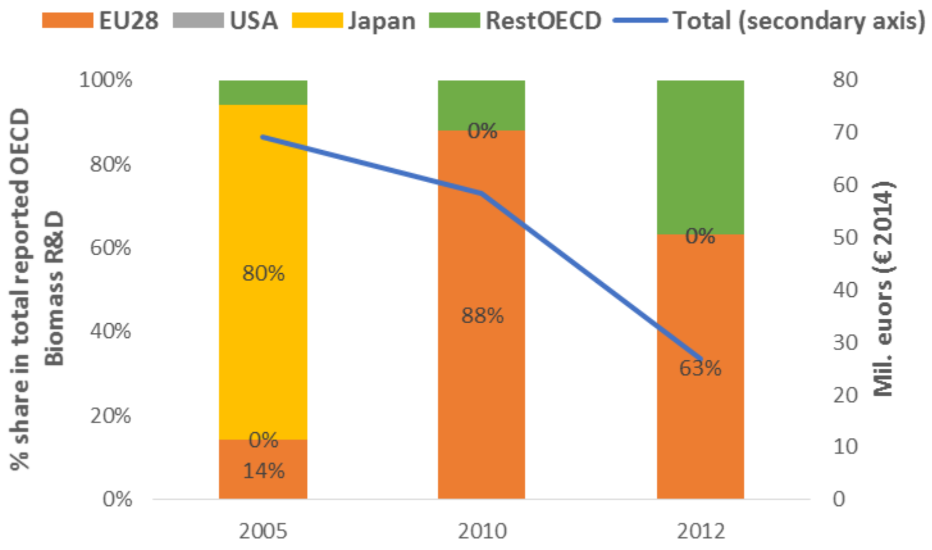
Source: E3Modelling calculations based on based on IEA/OECD; adjusted to data availability

Figure 39: Evolution of Hydro R&D expenditure for OECD and EU28, USA, Japan share in total OECD expenditure



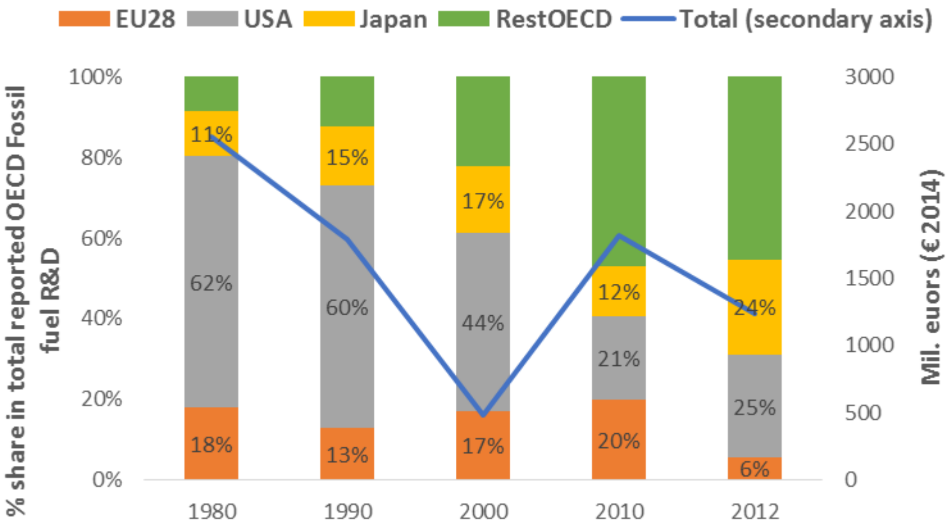
Source: E3Modelling calculations based on based on IEA/OECD; adjusted to data availability

Figure 40: Evolution of Biomass R&D expenditure for OECD and EU28, USA, Japan share in total OECD expenditure



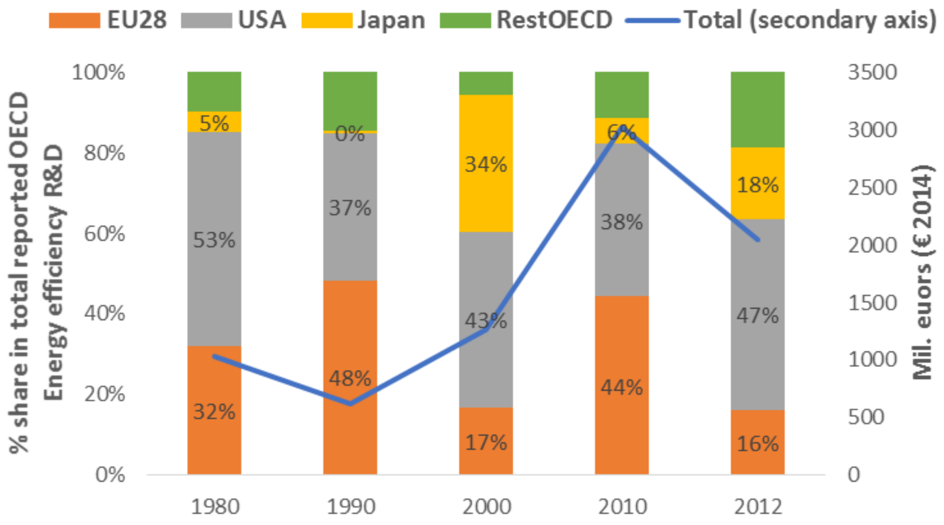
Source: E3Modelling calculations based on based on IEA/OECD; adjusted to data availability

Figure 41: Evolution of Fossil fuel R&D expenditure for OECD and EU28, USA, Japan share in total OECD expenditure



Source: E3Modelling calculations based on based on IEA/OECD; adjusted to data availability

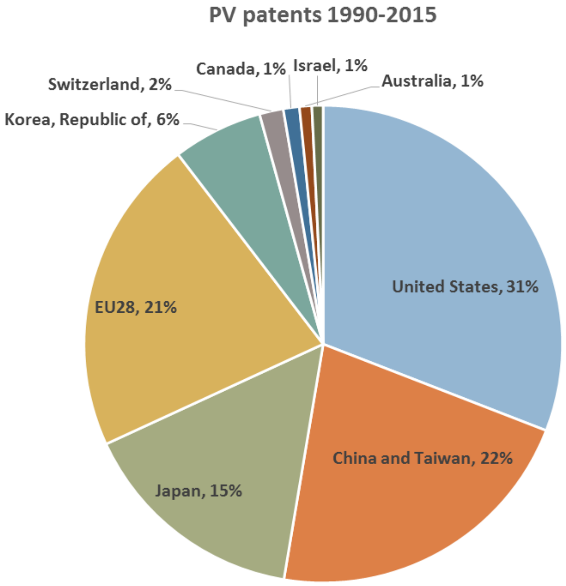
Figure 42: Evolution of Energy Efficiency R&D expenditure for OECD and EU28, USA, Japan share in total OECD expenditure



Source: E3Modelling calculations based on based on IEA/OECD; adjusted to data availability

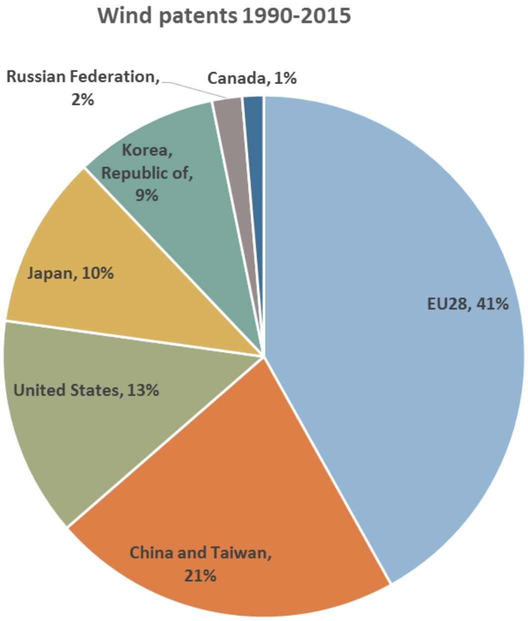
Patents

Figure 43: Regional share of PV patents for the period 1990-2015



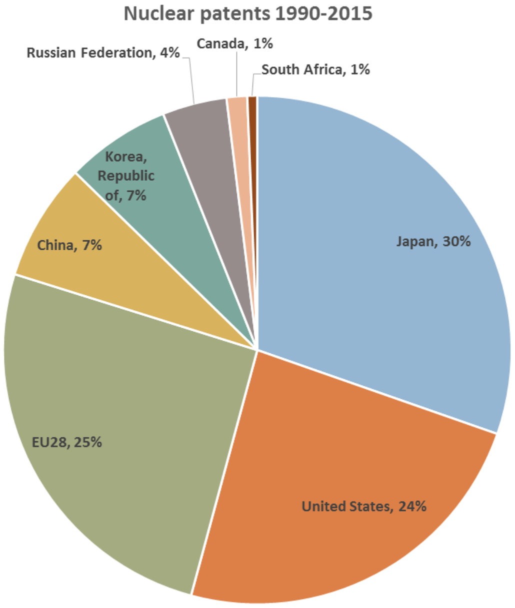
Source: E3Modelling

Figure 44: Regional share of wind patents for the period 1990-2015



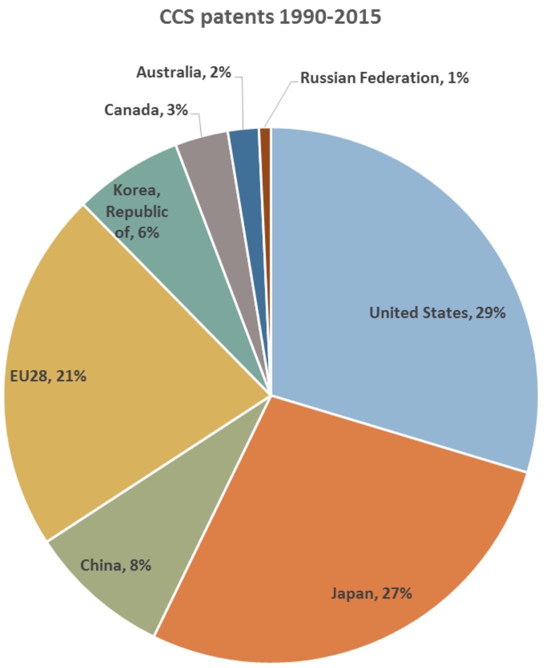
Source: E3Modelling

Figure 45: Regional share of nuclear patents for the period 1990-2015



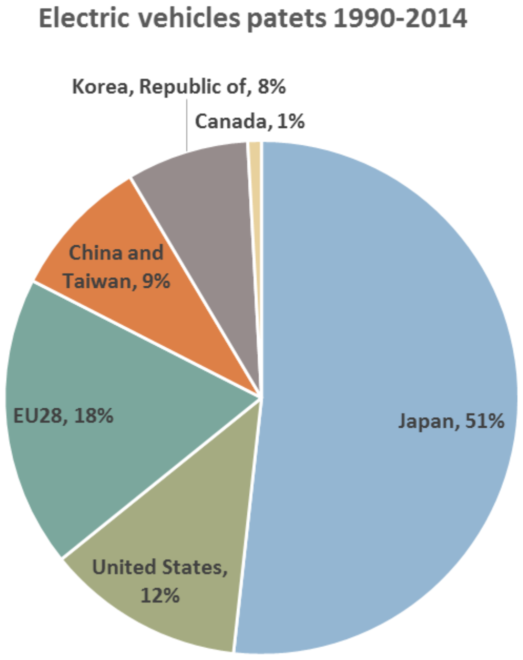
Source: E3Modelling

Figure 46: Regional share of CCS patents for the period 1990-2015



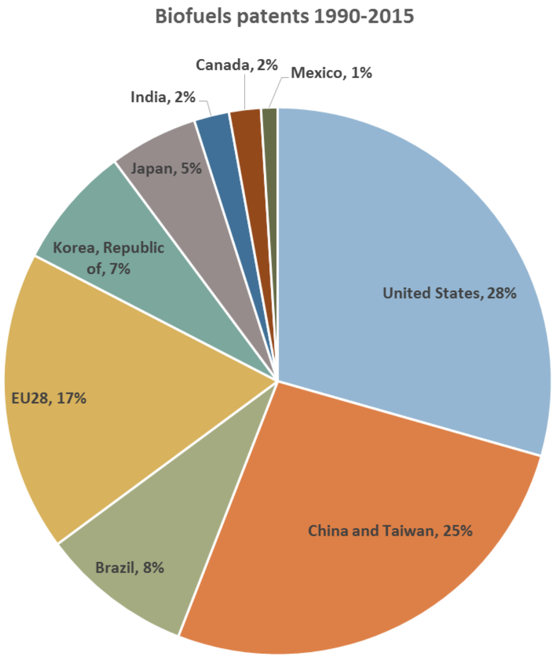
Source: E3Modelling

Figure 47: Regional share of electric vehicles patents for the period 1990-2015



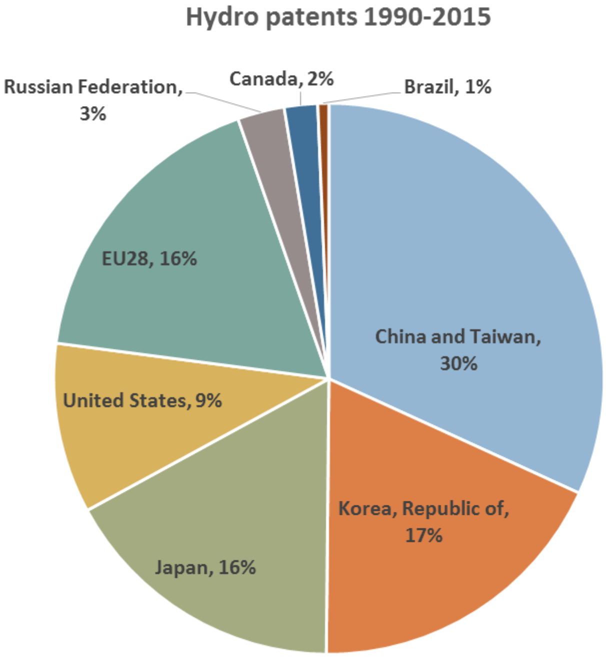
Source: E3Modelling

Figure 48: Regional share of biofuel patents for the period 1990-2015



Source: E3Modelling

Figure 49: Regional share of hydro-power patents for the period 1990-2015



Source: E3Modelling

Representation of first mover advantage in GEM-E3-FIT

The GEM-E3-FIT model is used to evaluate in quantitative terms the potential first-mover advantages that the EU economy can get from pursuing unilateral and ambitious climate policies and the role of spillover effects in assessing the economic and competitiveness impacts of climate and energy policies of the EU region. The GEM-E3-FIT model is equipped to perform this type of analysis as it comprehensively represents the sectoral structure of the economy and accounts for the complex interactions between the energy system and the overall economy. The most important characteristics of the GEM-E3-FIT model that are important for the current analysis are:

1. Explicit representation of clean energy producing sectors. The GEM-E3-FIT model explicitly represents the manufacturers of clean energy technologies as industrial sectors (solar PV, wind turbines, biodiesel, ethanol, electric cars, CCS technologies, advanced energy appliances in households, and buildings' retrofitting). The conditions favouring industries producing the high-technology components of the RES and energy efficiency equipment are rarely analysed in EU studies. Thus, special effort is dedicated for the collection and reconciliation of data for the employment and value added in the entire chain of clean energy producing industrial sectors.
2. Bottom-up representation of the energy, power generation and transport sectors, that enables endogenous model decisions or detailed calibration of GEM-E3 to reproduce with high accuracy the projections from specialized and technology-rich energy system models, like PRIMES, POLES and PRIMES-TREMOVE
3. Fully-fledged representation of the financial sector that is particularly important for the macro-economic assessment of energy and climate policies. The model assumes that households and firms can borrow from capital markets without facing increasing unit capital costs. The model assumes that agents annually pay back interests and principal of the loans; interest rates are determined by the evolution of the debt to income ratio (representing a financial stability rule). The inclusion of the financial sector improves the policy realism of model simulations as debt accumulation directly impacts investment decisions while interest rates are computed endogenously also depending on financial stability of each agent and country.
4. Endogenous learning mechanisms for clean energy technologies
5. Incorporation of spillover effects from innovation in low and zero carbon technologies. Updated data for R&D expenditures and spillover flows within and across industrial sectors as well as within and across regions have been collected and utilised to derive spillover matrices that are incorporated in GEM-E3-FIT model in order to catch the positive externalities of knowledge.
6. Technological change is semi-endogenously modelled in the GEM-E3-FIT model.

Modelling of the technological change in the GEM-E3-FIT model draws on endogenous growth theory developed by Acemoglu, 1998. Technological change in the model is expressed as productivity improvement by production factor (capital, labour, energy, materials) and/or total factor productivity. Technological progress in GEM-E3-FIT depends on R&D expenditures (public and private) and on accumulated stock of knowledge. The potential of productivity improvement is based on the so-called learning curves. The R&D supply sector in the model is represented as an individual activity (R&D services), while R&D expenditures are split into public R&D (undertaken by public institutions, governments, etc.) and corporate R&D (originating from the private sector). Investments in R&D result in cost reduction in clean energy technologies, driven by total factor productivity gains by sector, especially for those at early stages of development and commercial uptake, such as electric vehicles, renewables, CCS and novel efficient appliances.

The modelling assumes that increased energy costs drives increases in R&D spending, which in turn enables productivity gains in the production of clean technologies and alternative low-carbon fuels. At the same time, high fossil fuel prices lead to substitutions towards clean energy forms and technologies but also higher spending in R&D to mitigate costs. Higher R&D spending enables productivity gains along the learning potential curves, which exhibit diminishing returns to scale. Gains take place primarily in the region or the country pursuing ambitious climate policies. A secondary effect simulated in GEM-E-FIT3 is that productivity gains are also spilled to a certain degree over other regions, as a result of technology diffusion, assumed to take place in addition to equipment trading.

The GEM-E3-FIT model derives the mix of production factors (capital, labour, materials and energy) in production, and the mix of goods/services in consumption as a result of substitutions driven by relative prices. Substitution possibilities in production sectors are simulated with constant elasticity of substitution functions that follow a nested scheme, involving the various production factors. The producer is assumed to optimise the allocation of resources to R&D simultaneously with decisions about acquiring capital, labour, energy and material. The demand for R&D services is addressed to the R&D supply sector, which uses a production function with diminishing scale returns to determine unit costs of R&D as a nonlinear function of demand for R&D. The use of R&D services increases productivity for specific production inputs or for products depending on the orientation of R&D. Improved productivities lead to lower factor prices and lower prices of products. Therefore, R&D expenditures induce lower prices and higher demand of the targeted products; this is the so-called learning-by-doing process, which in the model is calibrated to follow learning-by-doing potential curves with learning rates for each type of clean energy technology derived from extensive literature review.

R&D expenditures improve quality of products and reduce unit costs. Depending on the inclusion of the financial sector and as financial resources are assumed to be limited in the general equilibrium framework, R&D expenditures can exert a crowding out effect on investment in other sectors, but only temporarily because productivity gains induced by R&D enlarge the market prospects and can induce higher investment in the long term. Thus, R&D expenditures may induce positive economic growth.

The basic equation linking technological change to R&D is given in the following equation that applies on each sector and country (sector and country indices are omitted for simplicity):

$$QF\dot{I}_{f,t} = a_f \cdot \frac{\left(\frac{K_{f,t}}{K_{f,t-1}}\right)^{\varphi}}{\left(QFI_{f,t-1}\right)^{\beta}} \cdot \frac{RD_{f,t}}{FD_{f,t} \cdot (1+EG_{t+1})}$$

$QF\dot{I}_{f,t}$: Factor productivity change over time

a_f: scale parameter

$\left(\frac{K_{f,t}}{K_{f,t-1}}\right)^{\varphi}$: Spillover effect

$K_{f,t}$: The total knowledge stock (across all sectors, national and international, public and private, inter-sectoral and intra-sectoral)

$\left(QFI_{f,t-1}\right)^{\beta}$ represents the fishing out effect that accounts of the negative effect of past innovations that increase the difficulty for present innovations

$RD_{f,t}$: R&D expenditure, which is endogenous for firms and is derived from firms' production functions. R&D expenditure of the government is set exogenously.

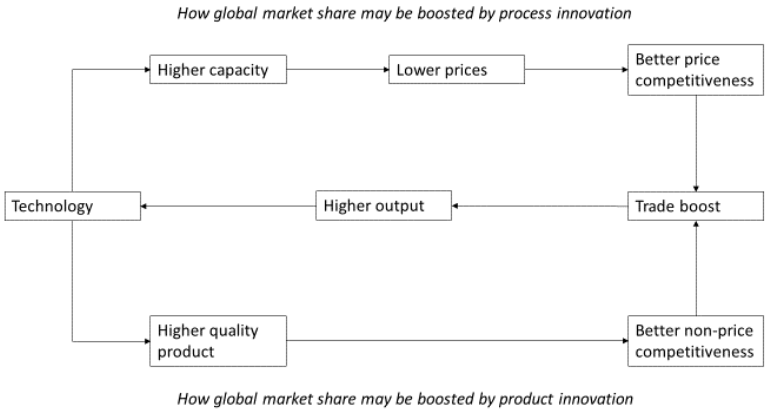
EG_{t+1}: expected growth of sector

$Factor_{f,t}$: Factor demand derived endogenously in the model from production functions

Representation of first mover advantage in E3ME

There is no explicit representation of first-mover advantage in E3ME. However, FMA is a potential emergent result from the model's economic equations. The starting premise is that a higher level of domestic demand leads to the development of new technology in key sectors. Through paths of both product and process innovation, this could lead to higher levels of output in the future (see Figure 50).

Figure 50 Schematic representation of first mover advantage in E3ME



The figure shows how a boost to technology could be self-perpetuating, i.e. when there are economic benefits through trade patterns, the boosts to output could lead to further technology development that enhances the sector's global position.

FMA represents a specific positive example of the relationships above. When FMA occurs, not only does the sector in question benefit from a boost to its global market share of production, but the size of the global market also increases. There is thus the potential for two positive effects on the sector in question, which is why FMA receives attention from policy makers.

It is important to note that there are also several reasons why FMA might not occur in E3ME. Most obviously, if the link from output to technology is broken (i.e. firms do not use higher profits to invest in technology) then the feedback loop is incomplete. Perhaps more importantly, if other countries are able to boost their technology levels through either spillover effects or weak protection of intellectual property, then the boosts from trade may not be realised.

In an era where a large share of innovation (especially in energy) is carried out by international firms, there is also an issue about splitting real and financial effects. The current version of E3ME focuses on the real effects only, meaning that trade in goods and services are accounted for but international financial flows are not. So if a global company develops a technology in one country but then manufactures its products in factories in other countries, there is little benefit to the first country.