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Horizon 2020 Societal challenge 5:
Climate action, environment, resource efficiency
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International Technology and Innovation Governance for Addressing Climate Change: Options for the EU

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1. Introduction

As estimates of average global temperature are projected to increase from 1.1 ºC to a high of 6.4 ºC by the end of this century (IPCC, 2007) potentially causing serious, widespread and irreversible damage to natural and human systems (IPCC, 2007; NRC, 2010), it is clear that low-carbon technologies will be an essential part of the toolkit to limit global warming to well below 2 °C'/1.5 °C (456 scenarios reviewed by the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2014) and various other reports underpin low-carbon and negative emission technologies to varying extents) (IPCC, 2017).

The proliferation of climate technologies globally in recent years has ensued at an unparalleled scale and speed – renewable energy for instance has become competitive to fossil fuel-based options and electric vehicles are operating albeit in relatively small numbers in all corners of the globe. However, more than 70% of the world's (rising) energy consumption still comes from fossil fuels (the rest comes from modern renewables like solar and wind, hydropower, nuclear and bioenergy together) the combustion of which is a leading cause of GHG emissions (Petrova, 2018). The transition to low/zero-carbon energy systems will primarily be based on low-carbon climate-friendly technologies and greater advancements in innovation which increase energy efficiency, replace high-carbon fossil fuels such as coal and oil with lower-carbon or zero-carbon alternatives, reduce energy (in particular fossil fuel) demand in various emission sectors, and capture and sequester CO2 already emitted, thereby facilitating the transition to a low-carbon economy.

While some key low-carbon technologies already are deployed (e.g. solar panels, wind energy and electric vehicles) on a large scale their deployment rate might not be sufficient to keep global average temperature increases under +1.5˚C or even +2˚C compared to pre-industrial levels. Furthermore, there is a broad group of climate-friendly (breakthrough) technologies and practices for each sector specifically which remain at various (sometimes even early) stages of development and have not yet reached broad deployment or diffusion (e.g. carbon capture and storage, smart-grids or CO2 free hydrogen production) (IEA, 2018a).

Further technological innovation (driven by R&D) will be critical in the transition to a low-carbon economy. One of the main hurdles here is to ensure that research and development of new low-carbon technologies survives the so-called innovation valley of death. This 'Valley of Death' is mostly a funding gap and exists between basic research and commercialization of a new product. Specifically, the Valley of Death occurs only in the presence of 'non-economic' investments (such as government expenditures on basic research) that are made in very early stage research without sufficient attention to the likely investment decisions at later stages of the innovation process (Beard et al., 2009).

But there also are non-technological barriers for the further diffusion of these technologies that are not directly related to the functioning of or innovation of the technologies themselves. For instance, supporting infrastructure might not be available (electricity and storage grids to absorb mass production of renewable energy), while promising low-carbon technologies will do little good if they're commercialised (at a global scale) too late or at a pace slower than the emission of GHG at current trends, or if the competitiveness of businesses is compromised while transitioning to low-carbon technologies and practices, and so on (OECD, 2011).

Not only is the vast majority of the development of low-carbon technologies taking place principally at the country or sector level but so is the choice of uptake or diffusion of these technologies. This choice will depend largely on the cost of these technologies, human capacity, the size and specifics of the emission sector in the country as well as the policy priorities set by the country (IPCC, 2018). Cost indeed remains one of the biggest barriers to the commercial diffusion of technologies. International cooperation can help the development and diffusion of technologies and innovations to the developing world through multilateral initiatives which seek to develop technologies cooperatively between countries or organizations or finance technology transfer and diffusion in developing countries (see Rayner et al., 2018, section 6) or bilaterally between countries through technology transfer and finance. A large number of low-carbon technologies have been developed in high income countries and their transfer to developing countries to implement their Nationally Determined Contributions (NDCs) effectively will be crucial. Such support would also elicit finance and capacity building. International cooperation can also help develop technical knowledge about low-carbon technologies and practices, but also build capacity for implementation.

Global cooperation on innovative technology deployment (including the financing thereof) is, given the need for rapid and deep decarbonisation, urgent. According to the IEA, holding temperature increase to well below 2°C will require OECD countries to transfer innovative technologies for industry to non-OECD countries where new capacity installations increase the potential to widely deploy innovative industrial process technologies. This has to happen very soon to avoid [further] carbon lock-in/stranded assets (IEA, 2017a).

The international legal regime is replete with generalized obligations for states to transfer green technology to other nations. The United Nations Framework Convention on Climate Change (Article 4.5) (UNFCCC, 1992) states that developed country Parties 'shall take all practicable steps to promote, facilitate, and finance, as appropriate, the transfer of, or access to, environmentally sound technologies and know-how to other Parties, particularly developing country Parties, to enable them to implement the provisions of the Convention', and to 'support the development and enhancement of endogenous capacities and technologies of developing country Parties'. The Convention also notes (in Article 4.7) that 'the extent to which developing country Parties will effectively implement their commitments under the Convention will depend on the effective implementation by devel-

oped country Parties of their commitments under the Convention related to financial resources and the transfer of technology' (UNFCCC, 2015).

New or (enhanced) existing processes and platforms enhancing bilateral and multilateral diffusion of technology and research cooperation are likely needed to foster such technology and innovation cooperation with the goal to help bring emission reductions in line with safeguarding a safe climate.

This report has the goal to explore the innovation status and challenges for (a selection) of sectors which represent a large share of global greenhouse gas emissions (i.e. the power sector and basic materials industries, including part of their value chains) and how international (bi-lateral or multi-lateral) cooperation on innovation can help accelerate the development and diffusion of clean-technologies in these sectors.

Chapter 2 seeks to identify the sectoral innovation challenges, with a focus on the energy and basic materials industries both from supply side (production) and demand side (consumption or storage) perspectives. First an innovation typology is developed which will be used later to assess and map the state and challenges of sectoral innovations. Next a brief introduction is given to the innovation process (from basic R&D to deployment) of clean technologies together with main drivers of innovation in this area. It further develops the state of technologies and innovation in the power sector and basic materials industry. The section concludes by discussing the overall challenges and mapping a selection of technologies onto the innovation typology. Finally, the three main sectoral innovation challenges are presented and discussed.

Chapter 3 explores the potential value added of international technology cooperation by looking at the types of international technology cooperation and the possible channels and stages of cooperation in this area. Next the chapter identifies and discusses barriers to international technology cooperation. The chapter concludes by discusses how international technology and innovation cooperation can help address the sectoral innovation challenges identified in chapter 2.

In order to inform recommendations for international governance/cooperation, Chapter 4 assesses the experience to date of national innovation and technology programmes and policies of the EU, the US and China in the area of climate-friendly technologies. It next briefly presents the bilateral technology and innovation policies between these three countries.

Chapter 5 builds upon the findings of chapters 2 and 3 and develops 17 case studies of international institutions that govern climate technology and/or innovation. They introduce the institution's main characteristics to make clear to what extent the institution addresses international cooperation barriers, creates value added, and/or addresses sectoral innovation challenges, or not.

Finally, chapter 6 looks specifically at the EU by arguing how the EU can improve its domestic climate innovation policies to encourage development and diffusion of climate friendly technologies, specifically addressing the challenges identified in chapter 2. The chapter end by presenting strategies and

instruments for the EU to engage in international cooperation aimed to advance clean technology and innovation both domestically and globally.

2. Innovation in climate-friendly technologies: mapping and understanding important sectoral challenges

This chapter seeks to identify the sectoral innovation challenges, with a focus on the energy and basic materials industries both from supply side (production) and demand side (consumption or storage) perspectives. First an innovation typology is developed which will be used later to assess and map the state and challenges of sectoral innovations. Next a brief introduction is given to the innovation process (from basic R&D to deployment) of clean technologies together with main drivers of innovation in this area. Section 2.3. further explores the state of technologies and innovation in the power sector and basic materials industry. The section concludes by discussing the overall challenges and mapping a selection of technologies onto the innovation typology. Finally, the three main sectoral innovation challenges are presented and discussed.

2.1. Defining an innovation typology

Innovation is defined by Everett Rogers as “an idea, practise or object that is perceived as new by an individual or other unit of adoption” (Rogers 1983). Merritt and Merritt (1985 p.11) define an innovation as “the introduction of a new idea, method or device” into a social unit wherein the introduced change need only be new for the adopting unit, even though it may already have been in use elsewhere. For Rogers, the perceived newness of an idea constitutes an innovation, regardless of the time lapse since the its first use or discovery (Rogers 1983). Technologies are not things, but complex socio-technical systems.

Technological innovations are often divided into two types. One type are the evolutionary, continuous, incremental or ‘nuts and bolts’ technologies or innovations that seek to improve an existing product, process or business model. The other type are the more revolutionary, discontinuous, ‘breakthrough’, radical, emergent or step function technologies (Florida and Kenney 1990; Morone 1993; Utterback 1994).

Recently, Christensen has added the concept of disruptive innovation. Broadly speaking disruptive innovation is an innovation that creates a new market and eventually disrupts an existing market by displacing established market-leading firms and products (Christensen & Euchner, 2011).

Henderson and Clark introduced the term architectural innovations, which are innovations that change the way in which the components of a product are linked together, while leaving the core design concepts (and thus the basic knowledge underlying the components) untouched (Henderson and Clark, 1990).

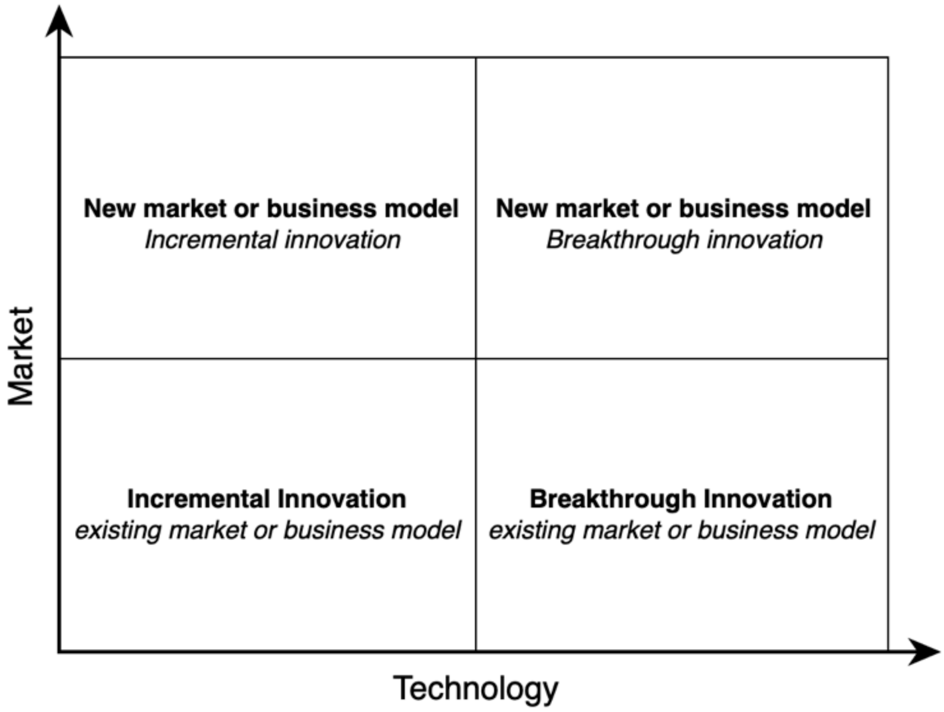
In general, these types of innovations can happen to production processes, products and business models, sometimes affecting more than one of the aforementioned (e.g. in the case of disruptive innovations).

For the purpose of assessing the climate friendly technologies and innovation challenges a new typology is proposed, which builds upon a combination of the aforementioned innovation types. The types of technological innovation distinguished are incremental or breakthrough innovations. These are linked innovations happening in an existing market or maintaining existing business models or innovations that create new products and/or generate new business models. This brings about four innovation types:

- *Incremental innovation in an existing market (or existing business model):* Incremental Innovation is the most common form of innovation. It uses existing technology and increases value or performance to the customer within the existing/incumbent market. Examples are more efficient internal combustion engines or silicon PV systems with higher efficiencies.
- *Breakthrough innovation in an existing market (or existing business model*): These are innovations that radically change the production process but still focus on bringing the same or similar product into an existing market. Examples could be battery electric vehicles or industrial processes using carbon capture and storage. The breakthrough technology will often (but not always) be inferior or more costly in the beginning to existing market technology. Only after iterations of incremental improvement can the newer technology become superior to the incumbent one.
- An innovation that establishes a new market (or new business model) but with incremental (or existing) technology or technologies: This type of innovation creates a new market or business model but does this by using (or combining) existing or incremental technology. Examples are services such as Amazon or Uber which use existing technology to establish new markets and business models. In some cases different pieces of technologies can be combined to create or access a new market, for instance the system level combination of renewable energy and energy storage, which can give access to a new 'prosumer' market, where actors both consume and produce e.g. electricity. In this sense, this type of innovation resembles the architectural innovations as mentioned before. Architectural innovation is simply taking the lessons, skills and overall technology and applying them within a different market. This innovation can lead to increasing new customers as long as the new market is receptive.

- *A breakthrough innovation that also innovates into a new market (or business model):* Finally, a radical technological breakthrough can go together with the establishment of new markets and business models. Examples are the internet (in the broad sense) giving rise to a new a diverse market ecosystem and the ipod/iphone which linked the computer market into the music business. This type of innovation comes close to what earlier was defined as disruptive innovation.

Figure 1 Typology to assess climate friendly technologies and innovation challenges.



2.2. The Innovation process in the context of climate-friendly technologies

Technological progress and innovation will play a key role in achieving low-carbon transition in the energy and industrial sectors. Therefore, it will be necessary to further develop, demonstrate and diffuse climate-friendly solutions in these industries. There are numerous paradigms used to separate the process of technological change into distinct phases. The IPCC (2007) considers technological change as roughly a two-part process, which includes:

(1) The process of conceiving, creating, and developing new technologies or enhancing existing technologies – the process of advancing the 'technological frontier'.

(2) The process of diffusing or deploying these technologies, including issues related to public acceptance.

The technological innovation process starts with ideas and inventions covered by basic research. An experimental or theoretical proof of concept is established next followed by laboratory scale production or demonstration. The next phases focus on the development of a (small scale) functional

prototype. The next phases move on to larger scales of piloting and demonstration of the new technology, including in a production environment. When demonstration of the new technology at scale and in a production environment has been successful, the development of a 'first of a kind' (FOAK) commercial installation can be considered. A more schematic way to describe the evolution of technologies are the technology readiness levels (TRLs) which were introduced by NASA but are now widely used including in the EU's Horizon 2020 programme (European Commissions, 2014):

TRL 1 – basic principles observed

TRL 2 – technology concept formulated

TRL 3 – experimental proof of concept

TRL 4 – technology validated in lab

TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)

TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)

TRL 7 – system prototype demonstration in operational environment

TRL 8 – system complete and qualified

TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

There exists a dynamic relationship between the private and the public sector during the innovation process. The first phase, basic research is often publicly funded, mostly via research institutions. Later in the process when the innovation is tested at scale the private sector takes a more important role. However, the road between a discovery generated from basic research to a commercial product or process is long and rife with significant roadblocks. Innovators and investors alike routinely claim that a 'funding gap' or 'Valley of Death' exists between basic research and commercialization of a new product. Specifically, the Valley of Death occurs only in the presence of 'non-economic' investments (such as government expenditures on basic research) that are made in very early stage research without sufficient attention to the likely investment decisions at later stages of the innovation process (Beard et al., 2009).

In the next stage of innovation, new products and processes (or products produced through new processes) will seek deployment in the market followed by diffusion. There can exist several hurdles for new products or processes to access the market. First of all, there might not exist a market for these new products e.g. because of their novelty. Secondly, existing standards and regulation might prevent access to the market, for instance because they are set for a market of incumbent technolo-

gies. It is often the case that new processes and products are more expensive compared to incumbent technologies or processes given that the former ones have not yet benefited from technology learning curves and economies of scale.

There are also risks related to the supply and value chain that prevent innovation reaching the market. For instance, new processes or products might require different inputs for which a supply chain has not been established or is not running efficiently. At the other end of the value chain it is possible that customers are not familiar with, ready to use or even object to the new products. Finally, new infrastructure might be required for innovative processes (e.g. hydrogen, electricity, CO2, waste streams, …) and hence lack of infrastructure can prevent the scaling up of innovative processes and products. (Wyns et al., 2018)

It is even possible to have a systemic 'lock-in' in incumbent processes and products due to some of the above-mentioned factors negatively reinforcing themselves. For instance, due to conservative standards the end users may not be familiar with alternative processes or products and are hence reluctant to use these (Wesseling and Van Der Vooren, 2017).

In general, all these barriers might also induce a so-called 'first mover disadvantage' where the first innovator fails to gain market access but might lower the threshold for the ones to follow and hence benefit from the failed innovation. This can deter innovation or innovators from proceeding in the first place.

Once a new product or process enters the market it will require further diffusion. In particular for climate friendly technologies wide-scale diffusion is important to assist economies in achieving e.g. net-zero emissions by mid-century. Large-scale diffusion can be difficult or slower than expected. First of all, costs of new technologies or products might not come down fast enough to compete with incumbent technologies. This can be because the value or supply chains have not yet been fully optimized or that R&D in incremental innovations is falling behind. There can be a bottleneck with regard to large-scale infrastructure or logistics needed for wider deployment, e.g. lack of high voltage grid connections. Furthermore, at higher levels of deployment some technologies might face a system bottleneck where e.g. higher levels of variable renewable energy disrupt their own business model or put too much pressure on the electricity system. There can also be a lack of resources e.g. biomass or rare-earth metals leading to higher production costs. Regulatory barriers (e.g. slow permitting or standard setting) can stifle growth of innovative technologies and products. Also, regulatory instability can deter (long-term) investments, for instance (retro-active) changes to support systems or instruments. Regulatory support might not be adequate through policy makers failing to price in external costs or setting environmental standards for incumbent technologies.

Finally, at the diffusion stage, there might be growing public resistance, in particular for new renewable technologies (and related infrastructure) that take up land. Public acceptance is and will be a

central element of changing the energy system toward sustainable production and consumption. Public resistance to e.g. (landscape or visual pollution of) wind farms or high voltage lines and public and political resistance against storing CO_2 underground occur on a regular basis. This can delay the further diffusion of these technologies or even stall them locally. Without public acceptability and support for changes, a sustainable energy transition is unlikely to be viable. Engineers, policy makers, and project developers tend to misjudge the complexity and causes of public resistance, trying to find the magic bullet to "solve" the lack of public acceptability. Such attempts are likely to be ineffective, or even counterproductive, if they fail to address people's key concerns surrounding energy projects. Public acceptability is often addressed too late and therefore should be incorporated into the planning process from the start, but also be tailored to the specific context and type of project and stakeholders involved. (Perlaviciute et al., 2018)

These issues can be addressed by the following instruments and actions (Reinaud et al., 2016 , Wyns et al., 2019, Wyns and Katchadourian, 2016):

- Setting more flexible standards to allow innovative products or processes reach the market
- Using public procurement to facilitate innovation and create lead markets
- Subsidising new innovative processes and products that are more expensive
- (Carbon) pricing to make incumbent technologies less attractive or offering fiscal support for new technologies
- Financing infrastructure for new processes or technologies
- Removing regulatory barriers e.g. related to permitting
- Tailor made communication and public involvement

In general, when it comes to advancing clean-tech innovation, the development and deployment these technologies is related to managing supply and demand sides which can impede or accelerate the innovation and diffusion of a productive technology (Rothenberg and Zyglidopoulos, 2003). S.S. Erzurumlu and Y.O. Erzurumlu (2013) used three main drivers in their work on analyzing the deployment and diffusion of clean technologies. These are the (internal) operations of companies (mostly related to R&D investment and organization), the market for and marketing of technologies and the regulatory environment. Assessing the presence or absence of three drivers will be part of the sectoral analysis in the next section.

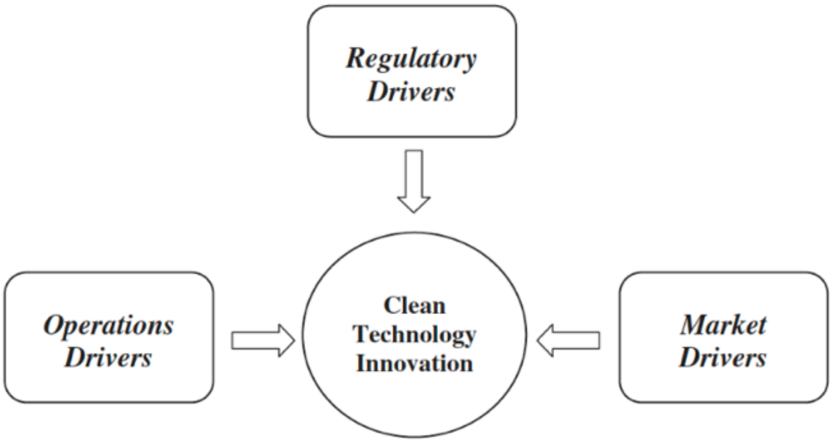


Figure 2 Key drivers of clean technology development and deployment.
Source: (Erzurumlu and Erzurumlu, 2013)

2.3. Sectoral innovation status and R&D challenges in climate-friendly technologies

2.3.1.Introduction

This section will look at the innovation challenges and needs towards achieving net-zero greenhouse gas emissions by mid-century from a sectoral perspective. Focusing only on supply-side technologies (i.e. low-CO_2 innovations for the production of electricity, basic materials or transport technologies) would be too limited, given the importance of demand-side innovation (e.g. new business models, technologies that can significantly alter the demand of basic materials and the use of transport). (Material Economics, 2019 and Creutzig et al., 2017, European Commission, 2018a). Therefore, the analysis of low-CO2 innovation here will cover both the production (technologies) and the technologies and services linked to the demand for these products (e.g. reducing the demand for high carbon products and/or enabling the demand for low-CO2 products). The main sectors considered are the power sector (including storage of electricity) and the (materials-intensive) industrial sectors (steel, chemicals and cement) and indirectly the transport sector in relation to battery and power-to-grid technologies.

For each of the technologies or innovations a short overview is given about its current status and what the main innovation challenges are. These findings are summarized at the end by putting the current state of the technologies inside the innovation typology developed in section 2.1. (i.e. incremental or breakthrough innovations in existing or in new (enabled) markets). This typology facilitates linking the state of technologies with (a combination of) the innovation driver(s) as presented in section 2.2. (Erzurumlu & Erzurumlu, 2013).

Finally, an approach is suggested on how to further the specific innovation needs of the sectors and technologies and how to do this in a coherent manner.

2.3.2. Current state of innovation in the power sector and basic materials industries and related innovation challenges

2.3.2.1. Power sector supply side

In the power sector the most important low-CO_2 supply side (i.e. generation) technologies are:

- Solar: photo-voltaic and concentrated solar power
- Wind: On- and offshore
- Hydropower
- Wave and tidal energy
- Nuclear energy: 3rd, 4th generation fission and fusion
- Geothermal
- CCS for gas/coal fired power
- Bio-based power

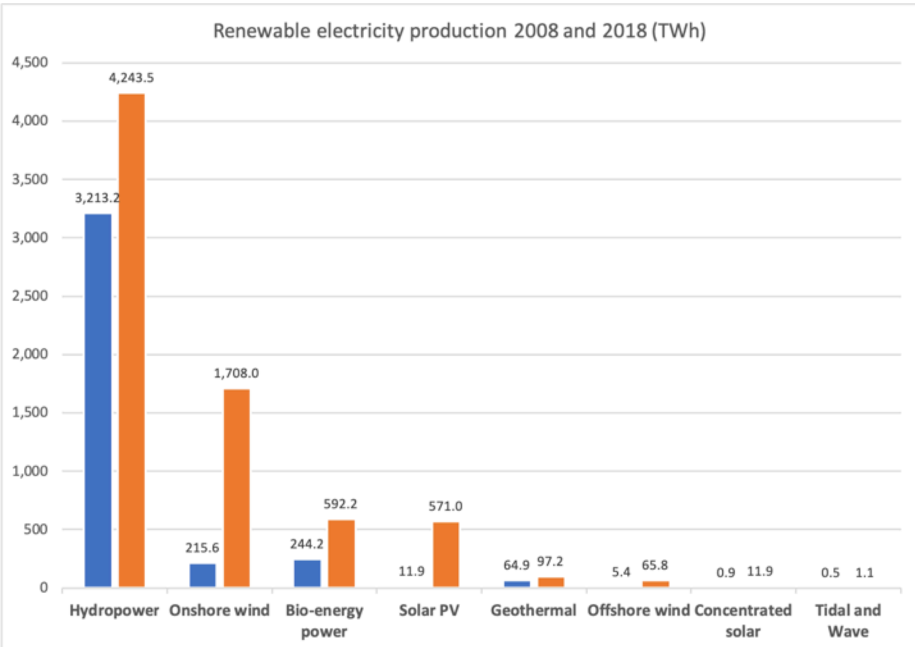


Figure 3 Renewable energy production 2008 (blue) and 2018 (orange) (TWh) ***Source: (IEA, 2018)***

Onshore wind energy can be seen as fitting the definition of a disruptive technology because it is a relative recent technology that has entered an (pre-)existing (power generation) market. Onshore wind energy has become an important though often not yet dominant power generation technology in a number of national markets. In 2018 total electricity production from wind was 1,708 TWh (or around 7% of global electricity production) from installed capacity of 597 GW (IEA, 2018b; World Wind Energy Association, 2019). In many places with good wind resources the technology can now compete with incumbent power production on a cost basis and has become one of the least expensive power generating technologies (per KWh produced) (Lazard, 2018). Technology cost decreases

are partially due to economies of scale and in particular, larger rotor diameters and higher hub heights, which have higher upfront and per unit power costs, but increase power production and decrease costs per unit energy while making better use of the resource and decreasing variability of output. Innovation in onshore wind is now mostly incremental. Key RD&D challenges are fundamental improvements to turbine blade design and manufacturing, as well as materials (component 3D printing and hybrid materials for wind towers) and construction. Other innovations relate to the system level such as enhanced short-term wind forecasts to facilitate the integration of higher volumes, big-data analytics from plant-level measurements, including neural network/ Artificial Intelligence and machine learning (AI) controls (IEA, 2018).

The future challenge of wind-energy will be to secure higher and faster levels of deployment in more places, given its relative low-cost. But also, integration with demand side innovations such as energy storage, demand response and grid management.

Offshore wind energy is starting to see large scale (multiple GW annual) deployment in North-western Europe and other regions (e.g. US and China). Recently subsidy-free offshore wind production has been realised and long-term production price agreements have in some cases reached 50 EUR/MWh or lower, but not everywhere (Lazard, 2018). In 2018 electricity production from offshore wind was 65.8 TWh and around 20 GW installed capacity (IEA, 2018).

Innovations in offshore wind will be both incremental (larger turbines) and more radical, in the form of floating offshore wind-turbines opening up much larger areas in the sea for exploitation and higher capacity factors (De Prada Gil, 2018). Due to the higher deployment rates turbine costs will drop and interconnection and balance-of-system (i.e. all components required for functioning system excluding the power production units) take up a higher share of overall installation costs. Learning on design concepts as well as fundamental technology improvements to power engineering equipment will be necessary.

Soft costs (i.e. costs not related to construction of the turbines) for offshore wind take up a substantial share of total installed costs, and together with interconnection they are a key challenge for further deployment. High throughput manufacturing and standardised designs of floating structures could lower costs in the mid- to long-term. Around a third of the long-term economic potential of offshore wind is at depths over 50m, which will likely require floating offshore constructions (IEA, 2018).

Photo-voltaic energy is transforming power markets in a growing number of economies in particular those with huge solar energy potential, with significant growth expected across the world and in particular developing countries and economies in transition. In regions with high levels of sunshine the technology is cheaper compared to incumbent technologies (e.g. coal-fired power). Utility scale PV can in these regions offer electricity at market competitive prices (Lazard, 2018). In 2018 solar-PV

produced 571 TWh (or around 2% of global electricity production) of electricity from installed capacity of 97 GW (IEA, 2018).

Innovations in PV will be incremental but significantly impact on efficiency improvements and cost reductions. Innovations include high-efficiency cells, improved module optics and capturing long-wavelength photon energy. There is a need to develop further accelerators/incubators to facilitate testing and deployment of more exotic technologies in the pipeline if targets are to reach beyond current generation of crystalline PV. Disruptive innovation related to PV is possible with the integration of PV in building materials (e.g. glass and rooftiles), opening new markets for PV and leading to a broader application of this technology. According to the IEA, solar PV is on track for deployment consistent with its below +2˚C scenario (IEA, 2018).

Concentrated solar power (CSP) has become a mature technology with deployment in a selection of countries with good solar resources (e.g. Chile, Morocco and Spain). Deployment has reached 11.9 TWh 2018 and 4.8 GW installed capacity (2016 figure) (IEA, 2018). CSP is expected to grow by 4.3 GW during the next 5 years. Recent auction results indicate significant cost reduction potential, but technology risks, restricted access to financing, long project lead times and market designs that do not value the energy storage opportunities in CSP form present challenges for further CSP deployment (IEA, 2018).

Tidal and wave energy are still in RD&D phase with a few pilot and demonstration projects having had successful large-scale testing in field environments (i.e. outside of the laboratory). In 2018 tidal and wave energy produced 1.1. TWh. Underwater conditions are complex and varying. Turbulence, wave activity, and depth variations result in unsteady blade loading, causing fatigue. Research in mechanical fatigue is very much needed as this has caused a number of projects to fail (IEA, 2018). Given that the potential of wave and tidal energy is very big (up to 30,000 TWh per year globally (European Commission, N.D.,a)) it will be important to further support fundamental research and pilot and demonstration projects in this area.

Hydropower is a mature technology and has been applied at scale for almost a century and is currently by some distance the most important renewable electricity source. In 2018 hydro-power produced 4243.5 TWh (or around 17% of global electricity production). It seems that global additions of hydropower peaked in 2013 with added capacity in 2018 40% below the level of 2013 (IEA, 2018). Further market penetration potential is limited due to the limited and geographically constrained availability of the resource and possible environmental impacts of large hydropower. In some countries (e.g. China, India and Norway) hydropower forms a significant share of power production. An important ongoing challenge is designing, testing, and validating new ways to improve sustainability and reduce the environmental effects of hydropower generation on e.g. fish populations and ecosystems. Smaller scale hydropower will likely become more important in providing flexibility to accommodate variability in supply (e.g. solar and wind) and demand. (IEA, 2018)

Geothermal energy is a mature technology but applied in a limited number of countries which have the resource easily accessible. In 2018 92.7 TWh was produced with geothermal energy or around 0.4% of global electricity production. Over the last five years, geothermal capacity additions averaged 500 MW per year (IEA, 2018). The main challenge is to make geo-thermal energy cost-effectively available to more regions. In particular drilling costs will have to come down as they account for between 40 and 70% of total capital costs of a geothermal power project (IEA, 2018).

Bio-energy is widely deployed and is the main source of renewable energy in particular in the EU where it was policy-driven. In 2018 bio-energy produced 592.2 TWh electricity (IEA, 2018) or around 2.5% of global electricity production. Further deployment of bio-energy-based power will depend on the availability of adequate and sustainably harvested resources. It is likely that resource constraints will become more important with other sectors such as steel and chemicals in the future making use of biomass as a feedstock. Bio-energy is widely expected to play a future role as a negative emissions technology when coupled with CCS (BECCS).

Carbon Capture and Storage (CCS) (in the power sector) has been researched for more than a decade. However, only a small number of pilot plants is operational, most connected to enhanced oil or gas recovery. An important impediment for deployment is the higher operational cost associated with CCS (IEA 2018). Several technology innovations have been proposed to reduce the costs of CCS and are now being tested at pilot scale. It is likely CCS will play a more important role outside of the power sector for the reduction of industrial CO2 emissions (Energy Transitions Commission, 2018).

Nuclear energy (2nd generation) is a mature technology. Around 11% or 2,563 TWh of the world's electricity was generated by nuclear energy in 2018 (International Atomic Agency, 2019). Current nuclear technology is in the process of being replaced with a 3rd generation of nuclear fission plants but these are facing significant delays and cost overruns, making further deployment uncertain. Further nuclear technology innovation can include addressing R&D gaps to reduce the costs, impact and increase the feasibility of repurposing and extending reactor lifetimes (IEA 2018).

Alternative nuclear technologies (such as molten salt thorium reactors) are being researched but are currently at low TRLs making deployment unlikely before 2040. (Carmack et al., 2017) Similarly it is very unlikely commercial nuclear fusion electricity becomes available before 2050.

2.3.2.2. Power sector: demand side

Next to the supply side (power generation) technologies there are *demand-side technologies* that will be important as a complement to more variable renewable energy sources, for instance to store surplus electricity and to balance power grids. Furthermore, due to expected high levels of electrification in other sectors, grids will have to use technologies that are compatible with large amounts of (variable) renewable energy production. Electricity and energy storage technologies include electro-chemical solid-state batteries, flow batteries, flywheels, compressed air energy storage, thermal

storage, gravitational storage esp. pumped hydro-power and power to hydrogen or other energy-dense gases or liquids. Other demand-side technologies include demand response, innovations to the power grid (smart grid, …) and the integration of other sectors that will electrify (e.g. buildings, industry and transport).

The technology costs for solid state **battery storage** continue to drop quickly, due to the fast and increasing scale-up of battery manufacturing for electric vehicles (EVs) which in turn stimulates deployment in the power sector (e.g. frequency control) (IEA, 2018). Innovation challenges for batteries include the move away from transition metals (such as cobalt), the use of safer (non-flammable or explosive) electrolytes, achieving higher power densities, faster charging rates and overall cost reductions over the battery systems (CCDC Army Research Laboratory Public Affairs, 2019). Addressing these challenges will require continued efforts in basic and applied R&D. Furthermore, electricity storage deployment remains strongly dependent on supportive policy and market frameworks (IEA, 2018 and Zachman, et. al., 2018).

Flow Batteries are batteries where the energy is stored in a electrolyte solution (up to now mostly Vanadium based). They promise longer term storage without losses and quick response times. Flow batteries have not reached wide scale deployment. Long-term performance and reliability still need to be improved. One of the constraining factors is the high cost of Vanadium but engineered molecules for flow batteries (e.g. symmetric Organic Flow Batteries or Polyoxometallate Flow batteries) show promise (IEA, 2018 and Service, 2018).

Flywheel storage is a kinetic energy storage technology using mechanical devices that harness rotational energy to deliver instantaneous electricity. Currently, high-power flywheels are used in many aerospace and in uninterruptable power supply applications with flywheel systems in the kW capacity range. Utility scale storage e.g. for frequency stabilization is under development with pilot and demo projects ongoing (European Commission, N.D.b).

Compressed Air Energy Storage (CAES) uses compressed air (in tanks or caverns) which can be used to power turbines to generate electricity. CAES is another well-developed mature technology offering capacities reaching upwards of 400 MW with discharge durations in the tens of hours (Pinnangudi et al., 2017). The main challenge is to bring the system efficiency of CAES up to 70% e.g. by using the heat generated during compression for heating the cold air during decompression and power generation and hence avoiding gas-based (pre-) heating (EERA and EASE, 2017).

Thermal Energy storage technology captures heat (and cold) to create energy on demand. There are three forms of thermal energy storage. In sensible heat storage a liquid or solid storage medium—such as water, molten salts, sand, or rocks—is heated or cooled to store energy. Latent heat storage relies on the storage medium changing states, for example from solid to liquid. Latent heat storage mediums are often referred to as phase change materials (PCMs). Finally, thermo-chemical storage

uses chemical reactions to store energy. Sensible heat storage is the most common used thermal energy storage technology and is applied at utility scale. The best example is molten salt is used as storage medium e.g. in connection to the production of concentrated solar power (Harvey, 2017).

Pumped Hydro-Power (other gravity-based systems) are based on creating large-scale reservoirs of water at a higher level which can on demand be released to power a turbine. This is a mature technology in use for a long time. Similar technologies not based on water but using e.g. rocks or cement are under development.

CO_2-free hydrogen and storing electricity in energy-dense gases or liquids are promising technologies but not yet applied at large-scale (MW) commercial scale. There is significant and long-time experience of using H_2 in industrial processes (e.g. Haber- Bosch process for ammonia production), but H_2 is also extensively used in refining processes and as a product of coke production in integrated steelmaking. The main process for H_2 production currently used is steam methane reforming (SMR) in particular for ammonia production and for de-sulphuring and hydro-cracking in the refining industry. A likely route for low-CO_2 H_2 production is electrolysis, but alternative routes to low-CO_2 H_2 production should also be considered, including methane pyrolysis, water photolysis and the combination of standard SMR with carbon capture and storage. While alkaline electrolysis H_2 production has been commercially available for a long period the TRLs of other innovative H_2 production processes and in particular their use in production of basic materials (e.g. chemicals and steel) have not reached commercialisation stage but pilot plants are under construction in the EU (Wyns, et al., 2018).

(Smart) grid technologies will be important to facilitate the integration of variable and distributed renewable energy sources on the one hand and energy storage and other demand-side technologies on the other hand. In general, smart grids and related technologies represent the integration of digital technologies with electricity infrastructure such as controls, computers, automation, and new technologies and equipment working together. One specific example is the creation of virtual power plants. It is composed of combining various small size distributed generating units to form a "single virtual generating unit" that can act as a conventional one and capable of being visible or manageable on an individual basis (Saboori et al., 2011). Recent digital innovations such as distributed ledger technology or blockchain show promise in further enabling smart grids and in particular peer-to-peer transactions of e.g. locally produced and/or stored electricity (Mengelkamp et al., 2018).

Smart grid investments did rise by 10% in 2018 but these types of technologies still represent a small share of the total investments in electricity grid infrastructure. There are even signs that investments are slowing down in the areas of microgrids and virtual power plants. Investments in blockchain technology dramatically decreased in 2018 (IEA, 2018).

Improvement and extension of high voltage transmission of electricity will be important for the expansion of renewable energy sources since it leads to more network interconnections and higher grid stability, but also allows more remote production of renewable energy (e.g. offshore wind and solar energy in desert environments) to be connected. Digital smart-control technologies allow transmission networks to operate at higher capacities, closer to their physical limits. They can also improve management of interconnections among regions and countries. Investments in interconnecting transmission systems increased significantly in 2017, as annual line-kilometers tripled from 2016. (IEA, 2018) Incremental innovation in high Voltage Alternating Current (HVAC) and High Voltage Direct Current (HVDC) systems and technologies is proceeding with new and improved technologies expected to come online in the next ten years. (ENTSO-E, 2018)

The main challenge for the further deployment of smart grids and related technologies is the further implementation of regulatory frameworks (e.g. improved power market designs) that recognise and reward investment in new digital technologies and in other 'non-wire' alternatives to traditional electricity grid extensions (IEA, 2018). In the EU, new market design rules which are currently being implemented should facilitate further developments of smart grids and prosumer markets (Pereira, et al., 2019).

Integration of demand response or demand-side flexibility of sectors outside the power sector will become increasingly important in a renewable electricity-powered economy. Important sectors are the large electricity consumers in industry (which will see higher levels of electrification in the future), electric vehicles (which similarly will see dramatic increase over next decades) and the building sector (electric heating).

On a global scale the end-user level, deployment of demand-side flexibility has been limited and does hence not use the full potential of this resource. It is mostly restricted to large industrial or commercial consumers as well as a number of programmes targeting heating services through night-time tariffs. (IEA, 2018). Around 40 gigawatts (GW) of demand response is in use today through traditional schemes such as arrangements to interrupt service at critical times, or drastically different day- and night-time tariffs, which only amounts to 0.5% of global electricity generation capacity (IEA, 2018).

Digitalisation however is helping to accelerate the development of demand side flexibility with the number of digitally connected energy-related devices growing exponentially (IEA, 2018).

In industry further innovation can help making more capacity available for demand flexibility. The main challenge is to increase the possible output reduction while not endangering continuous processes (Matthews, 2017).

Demand response also has important but lagging potential in electric mobility with several vehicle-to-grid or even vehicle-to-vehicle options that can be deployed (Liu et al., 2013). There are currently

just a few smart charging schemes with leading pilot examples in the Netherlands, Germany and California. While battery electric vehicles only represent a small part of total cars, vans and buses in circulation, the untapped flexibility is already significant. If demand response from electric vehicles were enabled for the total electric vehicle park in operation today around 2 GW of flexibility would be available to the electricity system (IEA, 2018). Further innovation will be required for efficient and standardised bi-directional charging but also, as mentioned before, the integration with digital technologies such as creation of virtual power plants.

Finally, as mentioned above in relation to the development of smart grids, the main challenge for further deployment of demand response is the creation of a facilitating energy market environment.

2.3.2.3. Materials and energy intensive industries production side

In **materials- and energy-intensive industries** (such as cement, steel and chemicals production) the most important process (supply-side) technologies that can enable deep emissions reductions are:

- Energy efficiency improvements and energy savings
- Electrification of heat and of processes
- Use of low-CO_2 hydrogen
- Use of biomass
- Valorisation of CO_2 (CCU and CCS)
- Process integration

Energy-efficiency improvements can reduce CO_2 emissions at a relatively low cost. However, on their own, these measures will generally not lead to deep emission reductions. A global assessment by McKinsey & Co showed an economic potential of 15-20% reduction in fuel consumption in the longer term due to efficiency improvements (McKinsey & Co, 2018). However, such levels of mitigation will be far from sufficient to achieve deep emission reductions let alone net-zero greenhouse gas emissions.

Electrification of industrial heating and of processes will be an important technology to avoid most of the emissions from fossil fuel combustion in industrial processes and can play a role in replacing fossil fuel-based feedstock for processes.

Electrification of heat demand can be applied across most of the basic materials industries. In some sectors such as ceramics, glass and paper production it seems the most promising measure for deep emission reductions. With regard to heat demand, low-temperature heat (e.g. below 300°C) can be relatively easily provided by electric boilers. Other technologies providing heat through electricity include electric arc, infrared, induction, dielectric, direct resistance, microwave and electron beam heating (European Copper Institute & Leonardo Energy, 2018).

One of the main technology challenges relates to the electrification of high temperature (1000°C and higher) furnaces replacing natural gas or other fuels. This will be an essential technology in most of the energy intensive industries (e.g. chemicals, ceramics, glass, cement, ...) to achieve deep emission reductions. In addition, new electrification technologies will need to show significant efficiency improvement to offset the low cost of heating with e.g. natural gas.

Electrochemical processes are currently deployed in the non-ferrous (International Zinc Association, 2012) and ferro-alloys & silicon industries (primary production) and in parts of the chemicals industry (e.g. chlorine production as part of the PVC value chain). Further electrification of processes will only be applicable to some sectors such as steel and chemicals. Examples are steel electrolysis (including high temperature electrolysis), iron ore reduction with plasma (H2). In the chemical industry, the utilisation of electrochemical processes and development of other electricity-based processes (e.g. plasma, microwave, ultrasounds) are part of the options. Most of these innovative processes are early stage and at relative low technology readiness levels. In theory, some of these electrochemical processes could be more efficient (when comparing primary energy use) compared to currently used process technologies, but further optimisation of these processes would be required (Wyns et al, 2018a, 2018b).

CO_2-free H_2 production will play an important role in steel and chemicals transition. Currently most industrial H_2 is produced with Steam Methane Reforming (SMR). Alternative processes to produce H_2 without CO_2 emissions (e.g. electrolysis, CCS) are becoming available for industrial producers but some are still in early stages of development (e.g. methane pyrolysis). Main challenge will be optimisation with the goal of reducing costs and closing the gap with SMR. But also, reduction in the size and space taken up by H_2 production installations together with scaling up the sizes will be important (Wyns et al., 2018a, 2018b).

Biomass (e.g. wood, agricultural and forestry waste and residues) is a key raw material or feedstock for the paper and silicon industries and an increasingly important raw material for the chemicals and refining industries. Biomass is also used as a partial replacement of coal as reducing agent in iron-making (e.g. to transform iron-oxide in hot iron). Many basic and specialised chemicals, including new innovative products can be produced using bio- based feedstock, either as products with identical chemical formulas or as products with similar performance. The paper sector can become an important provider of bio-based chemical feedstock products (e.g. lignocellulose) and of higher value applications like carbon fibres and batteries. Bio- ethanol can become an interesting platform molecule for part of the high value-added chemicals value chain. Some processes (e.g. propylene from biomass) do however require a significant amount more energy compared to fossil feedstock-based routes. Further R&D is likely needed to optimise production of bio-ethanol and of innovative processes that produce basic and/or fine chemicals using bio-based materials (Wyns et al. 2018a, 2018b).

CO_2 utilisation and/or storage can become important future mitigation technologies. However, cost reductions of these technologies will be essential for these to disrupt existing process technologies. In the case of CO_2 utilisations, major barriers exist with regard to the operational expenses (i.e. the ongoing cost of production), in particular related to high energy use (for capturing CO_2 and high H_2 inputs). It is therefore doubtful that Carbon Capture and Utilisation (CCU) will become a mainstream technology for commodity and high value chemicals due to higher costs, but it can break into niche markets for specialties (Wyns et al., 2018a).

For both **Carbon Capture and Storage (CCS)** and Carbon Capture and Usage (CCU), a high purity CO_2 waste stream is essential. This means that high CO_2 concentrated waste streams from (e.g. ammonia production) will be the most interesting routes to consider. Further research in improving current post-combustion CCS technologies will be important.

Cost-competitive access to pure CO_2 streams is important for all CO_2 valorisation routes and applications. Often high purity/uncontaminated sources of CO2 are required. Separation and purification technologies are therefore needed for the valorisation of CO_2 from industrial streams (and from air). The level of purification needed depends on the input stream and the CO_2 valorisation route. A more competitive access to CO_2 from industrial point sources will improve the business case of CO2 valorisation in many cases. This would and require further research into more energy efficient CO2 separation and purification solutions with low capital intensity and operational cost and in adaptation of the level of purification according to the chemical conversion process based on the minimum concentration/maximum impurities of CO_2 streams that the different conversion processes can tolerate (Wyns et al., 2018a).

Another possible focal point for industrial low-carbon R&D is system **integration of different new technologies into a single system**. For instance, the production of olefins from CO_2 will require the integration of CO_2 capture, H_2 and CO_2 transformation to methanol followed by conversion of methanol to olefins. But also, existing fossil fuel-based processes like iron and steel making processes can be modified by the integration of intermediate production steps combined with recycling or better internal use of generated process gases[1]. This integration of intermediate processes results in reduced use of carbon, and thus in reduced CO_2 emissions. Further considerable reduction of CO_2 emissions can be achieved by combining these integrated processes with Carbon Capture and Utilisation (CCU) and/or Carbon Capture and Storage (Wyns et al., 2018a).

[1] Ongoing projects in the iron and steel industry include among others HIsarna, IGAR (Injection de Gaz Réformé), PEM (Primary Energy Melter).

2.3.2.4. Materials and energy intensive industries demand side

It is highly unlikely that a transition to net-zero emissions by basic material producers will be successfully and cost-effectively achieved by only using new production process technologies. **Demand-side innovations** or innovations not directly linked to the production process but relevant in the value chain will have to play an important role in this transition too.

There are also important R&D challenges related to higher materials efficiency and circular use of materials. For instance, demonstrating large scale chemical recycling or recycling polymers (e.g. plastics) back to monomers will be an essential technology for a circular and net-zero economy. Multiple technology options are possible including technologies that will be able to deal with multiple feedstocks (e.g. different plastics types and biomass). Developing new methods to purify steel scrap from contaminants such as copper could increase the yield of high-quality secondary steel. Upcycling concrete waste to new concrete (as opposed to current practices where concrete waste is used in e.g. road foundations) would reduce the need for primary materials in new concrete production, but this is still in the early stages of research. Further improvements in technologies for industrial symbiosis can help with the valorisation of industrial waste streams and hence reduce the need of primary materials. Finally, technologies that allow industrial producers to play an active role in energy storage and demand side management will prove to be essential in the joint transition of the energy and industrial sectors (Wyns et al., 2019).

Not only will the production processes require further R&D, there is a need for innovation across the **value chain**. This includes enhanced use of digital technologies to sort and track materials but also improvements in product design. The latter can involve designing products for disassembly but also simplification of (mixed) materials use and researching higher and different functionality with less materials intensity (Wyns et al., 2019).

There are moreover **key enabling and general-purpose technologies** that can have a broad range of applications. Multi-purpose technologies and innovation can enhance industrial and inter-sectoral symbiosis. Industrial symbiosis is one important example. Industrial Symbiosis can be defined as: "engaging traditionally several separate firms and industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products"- with the key elements thereby being "collaboration", "synergistic possibilities offered by geographic proximity", and "co-located firms" (Chertow, 2000, 2008; Brings Jacobsen, 2006). In essence, industrial symbiosis is the collective management of resource flows (waste or by-products of one production process to be used as the raw materials for another) between businesses and and/or other entities to create a competitive and ecological advantage (Maqbool et. al., 2018). It includes exchanges of materials, energy, water and by-products, and may depend on certain key enabling and general-purpose technologies which can have a broad range of applications. Beyond industrial symbiosis, there are other key enabling and general-purpose technologies and R&D that can have a broad range of applications.

As mentioned above, high temperature heat electrification technologies can be applied across multiple industries. But also, investing in basic research on catalysts (e.g. new materials and physical structure (nano-tech)) can lead to applications in basic chemicals, H_2, Carbon Capture and Utilisation and batteries or other storage technologies. Designing new materials in this area can likely make use or even be the killer application of quantum computing. The establishment of advanced material laboratories making use of state-of-the-art digital technologies (e.g. machine learning and distributed ledger technologies) can accelerate their development. (Wyns et al., 2019)

Innovation for the transition to a climate neutral industry will not only be technological. There is a need to further explore new business models and possibilities of value creation along the value chains. Early identification of new skills needed in a transforming industry will be important so that education and training can adapt in time. New technologies will also require a better way of assessing their climate impact. In this context it is recommended that research in life-cycle accounting (LCA) for GHG emissions take into account the technological changes that are underway in industry and value chains.

As opposed to most climate friendly technologies in the energy sector, most of the above-mentioned industrial climate friendly innovations still have to be proven at commercial, demonstration and even at pilot scale (Wyns et al., 2018).

2.3.3.Mapping the sectoral challenges and possible innovation policy responses

Following the above analysis of technology status and R&D challenges of the different mitigation technologies it is possible to map these to the chosen innovation typology (figure 4). To map the technologies the starting point is the current status of production technologies and the markets (or future markets) they can operate in. Hence, wind- and solar-energy are not treated as disruptive technologies (though they were disruptive at a certain period in time) but as mature incumbent technologies (with the potential to increase market share). In the power market, demand side services such as storage and demand response are treated as (relatively) new markets given their low uptake on global level (though in some power markets these are taken up more).

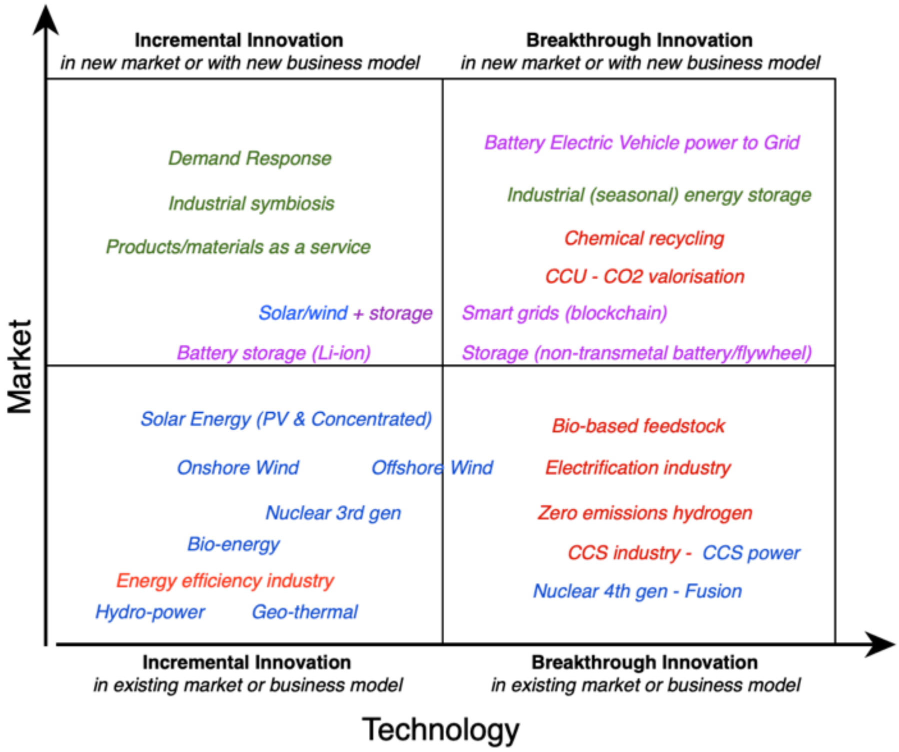


Figure 4 Innovation typology for selection clean technologies. *(blue: electricity production, purple: electricity demand side, red: industry production, green: industry demand side).*

In the energy sector many of the renewable technologies (e.g. solar, wind, bio-power and hydro-power) are mature and hence innovation will be mostly incremental. In industry there still is a need to develop and demonstrate quite a few disruptive or breakthrough processes. The industry and power sector demand-side innovations will develop into new markets with existing technology (architectural innovation) such as new (or relatively new energy) markets for demand response, storage or the use of products as a service. Finally, they can also seek new technologies to better access new markets (e.g. new large-scale storage or circular economy markets) as part of radical innovation.

This typology also helps to link the different technologies with the important factors or drivers that can help them advance. As mentioned in section 2.2 the main drivers are a combination of operational (mostly R&D), market and regulatory, both for the production and demand side (Erzurumlu & Erzurumlu, 2013). Mature technologies will see incremental innovation driven by market forces (competition) and to a lesser extent by regulatory incentives needed in case of market failures (e.g. not internalizing external cost of greenhouse gas emissions and market domination fossil fuel-based incumbent technologies). The disruptive technologies under development will need continued R&D and support for scaling up solutions to pilot and demonstration towards commercialization but also a supportive regulatory context to allow accessing the market dominated by incumbent technologies. Less innovative technologies that want to capture a new market will be driven by regulatory inter-

ventions that enable or even create these new markets. Finally, the radical innovations will require both a regulatory framework (e.g. creation of lead markets) and R&D investment.

Considering the status and type of technologies assessed in this report three main innovation challenges emerge within the context of achieving and accelerating emission reductions towards net-zero emissions by mid-century:

- Facilitating accelerated deployment of (mature) climate-friendly technologies using facilitating regulatory instruments and focused R&D support.
- Accelerating the development of pilot and demonstration projects for low-carbon breakthrough technologies towards commercialization using R&D support and favourable regulatory environment.
- Integration and alignment of supply and demand-side innovations to exploit synergies that can facilitate the transition to net-zero emissions by allowing the emergence of new markets for innovative services and products

Mature technologies such as wind and solar energy will need to see further and accelerated deployment globally to meet climate mitigation goals (IEA, 2018). Furthering deployment will require regulatory interventions to remove barriers. These latter can be related to market failures such as not internalizing the external cost of greenhouse gas emissions or an energy market design that is not adjusted to higher levels of renewable energy deployment, or even to social acceptability barriers. It can also include removing regulatory barriers (e.g. slow permitting) that prevent further deployment of renewable energy (Wyns and Khatchadourian, 2016). Dedicated production support (e.g. feed-in tariffs or premiums) can be used for technologies that at the moment have difficulty competing with incumbent and older fossil fuel-based technologies for which the principle capital investment has been written off. However, such support must be temporary and linked to improving market and technology performance of new technologies. Finally, incremental innovation will be driven by market forces and economies of scale. However, the public sector can as part of an industrial strategy choose to support basic and applied R&D that accelerates cost reductions and/or improvement performance of new climate friendly technologies, e.g. to give domestic technology producers an international competitive advantage.

In particular in the basic materials industry there is a need to, in the short term, scale up innovative climate-friendly technologies towards demonstration and then commercialization. Demonstration is an important stage of the innovation process of low-CO2 process technologies in industry. It is very difficult to anticipate how full-scale systems will operate based only on the performance of smaller-scale prototypes. Innovating companies must therefore carry the cost and risk of building and operating a full-scale, first-of-a-kind demonstration project - a process that often takes several years and substantial sums of capital - before being able to move to a commercial basis (David M. Hart, 2017, p. 4). These costs and risks can make it very difficult or impossible for a single company to shoulder

(Wyns, et al., 2019). This will require dedicated public and private R&D (financing) instruments to be deployed. Furthermore, for these first-of-a-kind disruptive innovations the incumbent product market might not be welcoming given that the new processes have not benefitted from a technology learning curve and hence will see higher production costs (at least initially) (Material Economics, 2019). Therefore, regulatory supporting instruments are relevant as an instrument to ensure market access for these disruptive processes. This can include putting a price on CO2 emissions (e.g. taxation or via emissions trading) but also the use of standards and public procurement or (temporary) production subsidies for new innovative processes (Wyns, et al., 2019).

New markets for products and services will play an important role in the transition to a low-carbon economy. These new markets will in most cases be related to the demand side of climate-friendly technologies. For instance, markets for energy storage, integration of variable renewable energy sources or circular materials. Creating new or lead markets will require (in the beginning at least) dedicated regulatory interventions. Again, these can include a combination of introduction of standards, energy market design reform, use of public procurement for innovation, tax benefits, investments support, use of carbon pricing. (Wyns, et al., 2019).

Finally, from a public policy perspective, there is a need to see the three above-mentioned areas (incremental mature, disruptive new and new markets) as connected. Some of the disruptive technologies will gain maturity and hence see further incremental innovation e.g. through further efficiency improvements. New products and services will facilitate new supply-side technologies to be deployed more and more cost-effectively (e.g. storage, smart grids and demand response supporting renewable energy). But also, in the case of materials production and consumption a value chain approach will be important to ensure better materials efficiency, the use of secondary raw materials (e.g. industrial symbiosis) and circular use of materials (e.g. chemical recycling). Enabling these activities will require a systemic approach to greenhouse gas mitigation. Mission-oriented innovation, aimed at tackling grand challenges, as put forward by Mariana Mazzucato (Mazzucato, 2015, 2018) would be a good example of such systemic innovation. This is further developed in chapter 6.

3. International technology cooperation: Promises and pitfalls

3.1. International technology cooperation and potential value added

This chapter explores the potential value added of international technology cooperation by first discussing the definitions of international technology cooperation. Next it looks at possible channels and stages of cooperation in this area. This is followed by a brief analysis how international technology and innovation cooperation can help address the sectoral innovation challenges identified in chapter 2. The chapter concludes by a literature-based analysis that identifies possible barriers to international technology cooperation.

3.1.1.Definitions of international technology cooperation

Technology transfer is the process of provision of technology developed by one organisation to others for potentially useful purposes. Technology transfer can be divided into five categories (Sudha Rani et al., 2018): international (across national boundaries), regional (between regions or states of a country), cross industry / sector (eg., from NASA space programme into commercial applications), inter-firm (from one firm to another) and intra-firm (within a firm from one location to another).

International technology transfer and cooperation is a highly interdisciplinary subject and is hard to define precisely. The IPCC (2000) defined climate-related technology transfer as “a broad set of processes covering the flows of know-how, experience and equipment for mitigating and adapting to climate change amongst different stakeholders”. In simple terms, international technology transfer and cooperation is the process of transfer of technologies (mostly via the private sector) from one country to another. It can be defined as the transfer of novel technology from country A to country B (Xie et al.,2013). Maskus (2004), defines it as the process wherein a party in country B gains access to country A’s information and successfully absorbs it into their production function. Traditionally, technology transfer and cooperation is viewed from the perspective of the technological divide between developed countries who own the vast majority of the advanced technologies and developing countries who seek access to those technologies (e.g. WTO, 2002; Fu and Zhang, 2011). Some also see it as a means of catching up with industrial and economic development of industrialised countries, and thereby a key tenet of global development cooperation (Sampath, 2012; Roffe, 2012; OECD, 2012).

The term ‘transfer’ in the IPCC definition ((IPCC, 2000, p. 17) encompassed the diffusion of technologies and technology cooperation across and within countries’ therefore ‘comprising of the process of learning to understand, utilize and replicate the technology, including the capacity to choose and adapt to local conditions and integrate it with indigenous technologies’. Yet, others classify three types of technology transfer: North-South, South-South and South-North (Urban and Kirchherr, 2018)[2]. Based on an analysis of 30 years of research, Urban and Kirchherr (2018) note that increasingly, countries like China and India are challenging the North-South technology transfer paradigm especially in terms of climate change mitigation and low-carbon energy (Urban, 2018). For a successful international technology transfer and cooperation, Kirchherr & Urban (2018) estimate that the recipient country not only has received the “hardware” but has also gained the ability to operate, maintain, replicate and innovate it. It can be considered as “mixed” if the recipient country can operate and maintain it but not replicate and innovate it (Urban and Kirchherr, 2018). Experts (Ockwell and Mailett, 2012; and Pueyo et al., 2011) deem technology transfer as failed if the recipient country only receives the hardware.

[2] The authors have used the World Bank (2017) definitions of developing and developed countries.

3.1.2.Stages and Channels of international technology transfer and cooperation

The IPCC (2000) identifies five different stages of technology transfer: (1) identification of needs, (2) choice of technology, (3) assessment of conditions of transfer, agreement and implementation, (4) evaluation and adjustment or adaptation to local conditions, and (5) replication. Pathways for technology transfer vary depending on the sector, technology type and maturity and country circumstances.

International technology transfer and cooperation occur through various established channels which flow across international boundaries, industries, firms and individuals. Sudha Rani et al., (2018) identify three key channels of technology transfer:

i) General Channels – transfer occurs unintentionally and may even carry on without the involvement of the primary source. It generally includes education, study missions, publications, conferences and the like. These are informal channels such as hiring/exchanges of staff (including new university graduates), joint research projects or specific projects related to FDI. In the case of the latter, technology transfer is often only one component of a larger project, rather than a stand-alone objective.

ii) Reverse Engineering – a potent method of technology development by duplication which helps avoid formal transfer of technology process.

iii) Formal Channels – This is a process characterized by intention, planning and consent of the technology owner. The formal channels include a variety of types:
   a) Licensing – The purchase of the rights to use someone else's technology.
   b) Franchise – A form of licensing where the source provides continued support.
   c) Joint Venture – two or more entities come together in a business enterprise in which they share knowledge and technical know-how.
   d) Turn-key project – A country purchases a complete project from an outside source via an agreement. The project is then designed, implemented and delivered ready to operate in which special provisions for training or operational support may be included.
   e) Foreign Direct Investment (FDI) – Usually a corporation or multinational firm which invests some of its resources or decides to produce its products overseas which allows the transfer of technology to another country. The technology however still remains within the control of the firm. Such type of transfer allows for the exchange of technological know-how, training and skills development and knowledge and infrastructure building.
   f) Technical Consortium on Joint R&D project – the collaboration between two or more entities (countries or large conglomerates) to jointly develop technology, advance research and transfer knowledge between participating members.

There exists a role for international cooperation in low-carbon technology development and deployment to address the public goods characteristics of investments in technologies and associated opportunities to free-ride in the context of global climate change mitigation. Such cooperation can help foster rapid technological change, by providing sufficient incentives to undertake investments in currently expensive technologies. This is especially so in the specific case of climate mitigation given that it is harder for individual countries to justify the pursuit of promising underdeveloped

technologies like next-generation solar, biofuel, or carbon capture and storage technologies (Iyer et al., 2016, p.400–411).

There are three factors that are key to climate technology transfer and cooperation: the existence of unexploited markets, socio-economic and environmental benefits, and state and/or donor backed interventions (UNEP, 2019). Market-driven climate technology transfer and diffusion does not happen in a vacuum or automatically. There is a large degree of coordination necessary between public sector and/or donors, financial providers and local recipients to ensure that not only the sale and purchase of technologies is completed but also that capacity building and technical assistance is provided (UNEP, 2019). The role of functioning markets is key to ensuring and securing investments in low-carbon climate technologies. In the absence or weakness of such markets, they need to be created, strengthened and/or expanded through public sector leadership (along with private business leaders) which can generate supply-push and demand-pull action through mission-oriented policies, funding, legal frameworks, other incentives and regulations thereby de-risking commercial opportunities (Mazzucato, 2017).

The Multi-Level Perspective (Geels & Schot, 2007; Geels et al., 2017) suggests that system transition can be driven through three mutually reinforcing processes: increasing momentum of niche innovations; weakening of existing systems; and strengthening exogenous pressures. When aligned, windows of opportunity can be created. The resulting sociotechnical transitions go beyond the adoption of new technologies and include investment in new infrastructures, establishment of new markets, development of new social preferences, and adjustment of user practices. Moreover, there exist five determining features of new technologies when it comes to technology transfer (Tidd, 2006). First, relative advantage or the perceived superiority of a technology over competing or earlier innovations. Second, the compatibility or consistency of the innovation with the requirements of adopters. Third, complexity, which means that easier innovations are adopted faster. Fourth, 'trialability' or the degree to which an innovation can be experimented with. And lastly, the observable benefits of an innovation. There exist various barriers at different Technology Readiness Levels (TRL) which challenge the technology development and diffusion process. In this discussion, we assume that the technology is at TRL 9 (commercial scale).

Several models for international technology transfer also exist which describe and conceptualise the process. These include Calantone et al. (1990), Simkoko (1992), Kumar et al. (1999), Lin & Berg (2001), Malik (2002), Wang et al. (2004), Steenhuis & Bruijn (2005), Waroonkun & Stewart (2008), Mohamed et al. (2010), and Khabiri et al. (2012). These models identify key factors and sub factors impacting the international technology transfer process (example: characteristics of technology providers and receivers, characteristics of the technology, technology transfer environment, learning capabilities, and role of governments and organizations) which have a substantial effect on the suc-

cess of the international technology transfer process. For an excellent scholarly critique of these models, see Hassan et. al., 2015.

There are obvious benefits or value added of technology/innovation cooperation. These include the development of capability in developing nations, pooling of resources, sharing of effort/risks, creating and enhancing access to technology/markets, eventual reduction of costs, and better chances of global climate change mitigation. International technology transfer of innovative technologies is also a known driver of economic growth and development and the large-scale uptake and diffusion of climate technologies is key to achieving the long-term goals of the Paris Agreement and the Sustainable Development Goals (UNEP, 2019). The transfer of technology to developing countries in particular is essential to avoid lock-in in high-emissions systems for decades given these countries find themselves in the process of massive infrastructure development and overhauls (IPCC, 2007).

Technology development and transfer is recognized as an enabler of both mitigation and adaptation in Article 10 in the Paris Agreement (UNFCCC, 2016) as well as in Article 4.5 of the original text of the UNFCCC (UNFCCC, 1992). On the one hand, technology transfer can adapt technologies to local circumstances, decrease financial costs, foster the development of indigenous technology, and develop capabilities to operate, maintain, adapt and innovate on technology globally (Ockwell et al., 2015; de Coninck and Sagar, 2017). On the other hand, technology cooperation could help reduce mitigation cost around the world, and enhance the developing countries efforts in mitigation (Huang et al., 2017a)" (de Conninck et al., 2018).

3.2. Barriers to international technology cooperation

Markets for technology are very different from those of goods and services and face three broad impediments: asymmetry of information, market power and externalities (Johnson & Lybecker, 2009). The asymmetry of information relates to the fact that technology transfers are principally trade in information and ex-ante buyers who lack the ability to fully assess the information can incur transaction costs. Markets play a key role as the price of new technology usually exceeds marginal cost due to first mover advantages of innovators, IP protection, patents and so on. Externalities refer to the partial internalization of the costs and benefits involved. This most often takes the form of uncompensated spillovers and can be addressed not by a general policy measure but on a case by case basis (Johnson & Lybecker, 2009). Another general barrier is the uncertainty of future prices of input (energy, permits) (Jaffe et al., 2001; Wyns et al., 2018).

At the international level, the challenges are broad and abundant. First, the market plays a highly key role. Johnson and Lybecker (2009) demonstrate that incentives to adopt new innovations are greater with market-based tools than with regulatory tools. Economies of scale play an important role in technology diffusion. Market forces can either facilitate or thwart the dissemination of environmental innovations Popp (2003, 2005, 2006). Incentives foster the innovation while R&D helps

improve the potential gains (Popp, 2003). While R&D can address the public good problem only, market policies which address environmental externalities can increase gains (atmosphere and economic welfare) (Johnson & Lybecker, 2009). Large producers in the market will also be able to uptake new low-carbon technologies and exhibit their efficacy (Purvis and Outlaw, 1995). The absence of economies of scale, sufficient R&D and suitable market policies addressing environmental externalities can thus constitute important barriers. In addition, countries with a weak investment climate also inhibit the transfer of low-carbon technologies (OECD, 2011). In most low-to-middle income countries, older or high carbon technologies tend to be affordable and more prevalent, which in turn impedes technology transfer and cooperation of low-carbon climate technologies to these countries (Flamos and Begg, 2010, p.30). Moreover, the lack of a knowledge economy promoted through a process of policy measures and government investment in science, technology and higher education can be an inhibitor (Sachs 2003, p.136).

There is also evidence that the low cost of fossil fuels tends to inhibit low-carbon climate technology transfer while increased fuel prices encourages adoption of fuel saving innovations at industrial facilities in different industries (Johnson & Lybecker, 2009). Government subsidies are one of the reason that natural resources may be underpriced (Arrow et al., 2004), the other two being unclear property rights, and externalities. According to a 1992 World Development Report by the World Bank, amongst 29 of 32 least developing countries (LDCs) surveyed, subsidies had caused the price of electricity, water and fossil fuels to fall below cost (Arrow et al., 2004). When the US sought to phase out leaded gasoline using tradeable permits, there was a growth in more efficient use of resources (Johnson & Lybecker, 2009).

Regulations at the country-specific level can further impede technology transfer and cooperation. Chandrashekar and Basvarajappa (2001) find that for India the process is complicated by institutional and regulatory constraints. They state that “piecemeal and ill-thought out approaches to economic reform and privatization as well as vested interests have often come in the way of the diffusion of pioneering technology”. They also find that security concerns in some cases like nuclear power have impeded trade. The lack of domestic regulations and targets as regards GHG emissions provides no incentive for technology adoption by sectoral actors. It is also important for the host economy to be capable enough to absorb the technology (Sudha Rani et. al., 2018). Chandrashekar and Basvarajappa (2001) find that the lack of downstream infrastructure and technologies, as found in the case of the Indian food processing industry, proves a significant barrier to the development of the industry and its export potential.

Moreover, there is evidence that stronger patent protection encourages FDI and technology transfer of all kinds to mid-level developing and developed countries, but have little to no effect in lowest-income countries (Hall, 2014). Countries which have a stronger absorption capacity of the knowledge and know-how of the technology and provide a certain level of IP protection, are more

favourable to receive foreign technology as foreign companies are more likely to feel that their ownership will be protected (Hall, 2014). However, strong intellectual property rights on carbon abatement technologies do not constitute a significant barrier to developing countries GHG abatement efforts as claimed by developing nations given that IPR-protected technologies are not necessarily more costly than those not covered based on a cost-per-unit-of-carbon-emission-reduction (Rai et al., 2014, p.60). The immaturity of the technology rather than patent protection accounts for the high cost and mature, low-to-medium cost low-carbon technologies that exist at scale are not obstructed by IPRs. Nonetheless, an ineffective IPR regime (uncertainty of patent protection, incomplete enforcement of IP rights) means that the confidence of innovators is lost. Though not specific to developing nations, the uncertainty that exists in these markets is well reflected in the model of Aoki and Hu (1997). They argue that the uncertainty surrounding the scope of patent protection, as well as the incomplete enforcement of IP rights, mean that the effective strength of intellectual property rights are determined by the implementation of the legal system. Given this, they examine how the legal system impacts incentives to innovate. The authors analyze how firms act strategically, using licensing and litigation to prevent infringement and deter imitation. Aoki and Hu's analysis is particularly applicable to areas of new technology. In addition to IP protection in the case of developing nations, it is also essential to safeguard the balance between competition and IP protection with the channel of appropriate policies and legal regimes (Correa, 2007).

At the level of specific technologies, there occur challenges of upfront clarity on cost, risks and benefit-sharing. The Capital Expenditure (CAPEX) and Operating Expenses (OPEX) of new technologies are considerably higher than existing ones and the risks involved are also not clear. The first wave of investors in new climate technologies (before 2030) will face a first-mover disadvantage given that low-CO2 solutions would be priced at a larger CAPEX. Because new technologies are capital intensive, finance thus constitutes a key challenge. Without financial support, the goods produced with the new technology become more expensive and thus diminish the competitiveness of the company (Wyns et. al., 2018, 2019). Challenges extend beyond the CAPEX and OPEX. To install the technology, in many cases either existing installations must be dismantled and refurbished, or a new installation must be created. Brownfield conversion is not a very simple task. Retrofitting brownfield sites with new low-CO2 solutions comes with its own set of added complexity and costs in adapting to the existing wider production system (unless infrastructure upgrades are synchronised). Existing assets might thus also (temporarily) operate in parallel with new processes. Recurring costs can occur in addition in terms of adaptation to the new process.

Moreover, most new technologies especially in the energy intensive sector (low-carbon innovations in the energy and transport sector also rely heavily on industrial products) but also in the transport, power, and buildings sector, are based on electricity or H2. They therefore require large amounts of renewable electricity and green H2 to make a difference to climate efforts. For most of the world,

H2 networks are missing and supply is insufficient. The production of Hydrogen plays an essential role in an industrialised country. “As a highly flexible energy carrier, hydrogen can deliver a holistic – clean, integrated and multi sector– systems approach to energy that will contribute decisively to solving the environmental problem and securing earth’s energy future” (IEA, 2017b). Large amounts of green H2 and cheap renewable electricity will be required to optimize new climate technologies fully.

At the specific industry level, environmental innovation is more likely to occur in industries that are internationally competitive based on factors such as firm size, R&D expenditure, market share, structure of the market, input prices, technology costs, firm ownership, and other institutional factors including policy (Johnson & Lybecker, 2009). Large multinationals also have a higher tendency to adopt innovative low-carbon technologies than smaller firms. Therefore, sectors which have a high concentration of large multinationals rather than a large number of smaller producers, have a greater propensity to adopt (expensive) low-carbon technologies. The first adopters of the technology (which are usually capital intensive and impacted by size and scale economies requiring large investment capital) are also those firms with the highest potential profits (Purvis and Outlaw, 1995). The multinational nature of these firms also ensures that the technology is disseminated internationally.

Suzuki (2015) summarises the key barriers which inhibit low-carbon technology transfer in developing countries into three categories.

Barriers commonly observed among the developing countries.

Barriers	Barriers	Sources
Technological	Limited capacity to assess, adopt, adapt and absorb technological options	Ravindranath and Balachandra, 2009; Painuly, 2001.
	Lack of knowledge of technology operation and management	Doukas et al., 2009; Luken and Rompaey, 2008; OECD/IEA, 2001.
	Lack of skilled personnel/training facilities	Painuly, 2001; Usha and Ravindranath, 2002; Jagadeesh, 2000; IPCC, 2001; Guerin, 2001; Worrell et al., 2001; Flamos et al., 2008; OECD/IEA, 2001.
	Lack of standard and codes and certification	Painuly, 2001; Oliver and Jackson, 1999; IPCC, 2001; Lewis, 2007b; Jagadeesh, 2000; OECD/IEA, 2001; Ölz and Beerepoot, 2010.
Financial	Lack of access to financing	Ravindranath and Balachandra 2009; Painuly 2001; UNFCCC 2003; Worell et al., 2001; Jagadeesh 2000; IPCC, 2001; Thorne 2008.
	Potential lack of commercial viability	Karakosta et al., 2010.
	Lack of financial institutions to support renewable energy technologies, lack of instruments	Painuly, 2001; Jagadeesh, 2000.
Institutional	Uncertain governmental policies	Redd and Painuly, 2004; Painuly, 2001; Worell et al., 2001; Schneider and Hoffman, 2008; Doukas et al., 2009; Karakosta et al., 2010; OECD/IEA, 2001.
	Lack of infrastructure	Painuly, 2001; Thorne, 2008.
	Lack of information and awareness	Kathuria, 2002; IPCC, 2001; Painuly, 2001; Reddy and Painuly, 2004; UNFCCC, 2003; Worrell et al., 2001; Flamos et al., 2008; Karakosta et al., 2010; Luken and Rompaey, 2008; OECD/IEA, 2001.
	Lack of consumer acceptance	Reddy and Painuly 2004; Painuly 2001; Flamos et al., 2008.

Figure 5 Key barriers to low-carbon technology transfer in developing countries *Source: (Suzuki, 2015)*

3.3. Identification of areas where international technology cooperation can offer value added.

In the sectoral analysis in section 2.3. the following areas were identified as important for the further development and deployment of climate friendly technologies:

- Facilitating accelerated deployment of (mature) climate friendly technologies using facilitating regulatory instruments and focused R&D support.
- Accelerating the development of pilot and demonstration projects for low-carbon breakthrough technologies towards commercialization using R&D support and favourable regulatory environment.
- Integration and alignment of supply and demand side innovations to exploit synergies that can facilitate the transition to net-zero emissions by allowing the emergence of new markets for innovative services and products

Furthermore, it is suggested for the public sector to commit to an integrated vision (or mission) and approach to implement the above-mentioned areas.

This section will build upon the finding in section 2.3. and consider recommendations to enhance value added of international technology cooperation.

First of all, it would be recommended to develop innovation missions at an international level e.g. such as the Mission Innovation platform. This allows countries to together focus on key technologies that can enable or accelerate decarbonization in different (e.g. hard to abate) sectors. This could be combined with an international innovation observatory (Wyns et al., 2019) which continuously monitors the status of key innovations needed in the transition to a climate neutral society, a role only partially fulfilled by the IEA (IEA, 2018) at the moment for a selection of sectors and technologies.

Secondly, strategic mapping of innovation capacities and activities in different countries and regions could limit the extent of the innovation 'valley of death'. For instance, countries which are putting a high amount of resources in basic R&D could form partnerships with countries that are investing more in demonstration and deployment of technologies. As such, promising technologies could rise faster on the technology readiness level ladder. Such cooperation will require solid bi-lateral or multi-lateral agreements, in particular with regard to intellectual property sharing or utilization.

With regard to the deployment and diffusion of technologies, increasing the global market opportunities for clean technologies should be key. In this context working together on harmonization of standards (e.g. electric vehicle fast charging or standards that facilitate recycling of plastics) could remove local or regional barriers. Furthermore, regulatory alignment on sectoral policies could remove the fear for first mover disadvantages, where e.g. a local innovative low-CO_2 steel or chemicals producer would be outcompeted by cheaper and CO_2-intensive producers. This approach would go into the direction of so-called bottom-up 'sectoral approaches' (den Elzen and Berk, 2005) in international climate agreements, such as regional or international emissions trading systems. In principle, countries could agree to strive towards equivalent (but diverse) treatment of specific sectors which are both greenhouse gas- and trade-intensive or agree to join or link domestic policies. Regulatory alignment can also be part of technology transfer agreements where transfer of advanced climate friendly technologies is made conditional to the implementation of enhanced climate action in the receiving country as to avoid a distortion of competition. A similar approach can be used in bilateral or multilateral free trade and investment agreements, by including the condition of upwards (i.e. striving towards the most ambitious level of) regulatory alignment for specific trade- and greenhouse gas-intensive industries.

Given the (growing) complexity and internationalization of value chains it is recommended to not only address international innovation challenges at a sectoral level. This includes cooperation on dealing with waste or end-of-life emissions. In particular dealing with plastic waste and the global

plastic and plastic waste value chain could become a priority mission for international cooperation. Other materials intensive sectors that see global trade such as automotive could benefit from more value chain-based approaches as to allow better and higher quality recovery of steel, non-ferrous and precious metals, hence reducing the need for greenhouse gas intensive primary production.

Finally, sub-national international cooperation between large international industrial clusters (often located in harbour areas and having international connections via shipping) could be an additional approach in international clean-tech innovation cooperation (Gosens, et al., 2015).

4. National innovation and technology programmes for GHG mitigation and bilateral cooperation

The EU, US and China are the top three GHG emitters in the world. They are also the top three exporters of low-carbon technology (table 1). The EU ranked at number one in global low-carbon technology exports (USD 427 billion), followed by China (USD 216 billion) and the US (USD 129 billion) (Zachmann et. al., 2018). In terms of low-carbon technology patents too (based on data from the PATSTAT database of the European Patent Office and those filed under the Patents Cooperation Treaty worldwide), the EU, US and China are world leaders. While the EU was the global leader in terms of number of low-carbon patents (2008-2012) with 13,187 patents, the US ranked third with 7,064 (after Japan with 8,682), and China fifth with 1,746 (following South Korea at 2,629) (Zachmann et. al., 2018).

Table 1 Sum of exports (Billion USD) and number of patents of low-carbon technologies.
Source: Extrapolated from (Zachmann et. al., 2018)

Country/Region	Sum of exports in billion USD (2008-2012) of low-carbon technologies	Number of patents (2008-2012) of low-carbon technologies
EU	427	13,187
US	216	7,064
China	129	1,746

This suggests that all three (EU, US, China) recognize the economic advantages of a transition to a low-carbon economy given that these technologies have come about due to policy-changes (Zachmann et. al., 2018). An in-depth overview of their respective innovation regimes and specific policies can help inform and understand the progress made domestically towards decarbonization through innovation and how national programmes can inform recommendations for international govern-

ance/cooperation. In addition to the North–North technology interaction, the choice of the EU and the US for assessment is obvious given that technology transfer and cooperation has principally ensued from developed countries/nations towards under-developed, developing countries. China is therefore an interesting case study as it allows us to explore the growing dynamics of South-South and South-North technology transfer. As discussed in Chapter 3, international technology transfers are increasingly happening between countries of the South. China therefore makes a compelling case-study candidate.

4.1. Selected national programmes

This section provides an assessment of national technology and innovation programmes in the EU, US and China. For each, it will be endeavoured to assess the core of their efforts, how programmes can frame, promote or hinder technology development, commercialization and diffusion.

4.1.1.EU

Research activities undertaken by the EU (outside the coal and nuclear fields) began in the 1970s when the then European Economic Community (EEC) adopted the first community research programmes. The legal basis for EU policy on research and technological development (RTD) is provided by Articles 179 to 190 of the TFEU. Innovation policy in its inception was closely linked to EU industrial policy as shown in Article 173 of the Treaty on the Functioning of the European Union (TFEU), which states that ‘the Union and the Member States shall ensure that the conditions necessary for the competitiveness of the Union’s industry exist’. In 1983, the first framework programme (FP1), the main instrument of the Union’s RTD policy, was adopted. Research and innovation activities also feature in 1986 Single European Act, and the 1993 Treaty of Maastricht which transformed the FPs into financial tools for EU research activities. The EU multiannual FPs have since underscored research, technological development and innovation.

Horizon 2020 is the EU’s 8th FP (2014-2020) with a budget of nearly EUR 80 billion and the first programme to integrate research and innovation. A comparative assessment of the EU’s FPs can be found below.

Table 2 Comparative assessment of the EU's FPs. ***Source: (Mako et al., 2016)***

	Green Paper (1995)	Lisbon I (2000-2005)	Lisbon II (2005-2008)	Lisbon III (2008-2010)	Horizon 2020
Elements of broad-based innovation concept	Fully applied broad-based approach	A slight shift from linear towards systemic approach appears only in 2003[20]	Public procurement as a tool to boost innovation	No significant changes compared to Lisbon II	Top 6 priorities: social innovation; design-driven innovation; demand-side innovation policies; public sector innovation; public procurement of innovation; workplace innovation
Elements of narrow innovation concept	In terms of proposed policy measures, it remains technology-oriented: importance of technological innovation, scientific, explicit and individual knowledge-base, the STI mode of innovation	Strategic objective is to raise the share of R&D expenditures in the GDP from 1,9% to 3% by 2010	Focus is on R&D expenditures, green economy, strong industrial base and on innovation-friendly environment, explicit reference to market failure approach	Increase investment in R&D, innovation and education. Develop clean technologies for cars and construction. High-speed internet for all	Innovation statistics remained science and technology-focused
Measurement		Establishment of the European Innovation Scoreboard: no indicators on non-technological innovation and on Job Quality			5 key indicators[21] and the creation of Innovation Union Scoreboard and Summary Innovation Index
Sector prioritised	Innovation is important in low-tech sectors, in private and public segments of services	No sectoral focus	Promotes innovation in the services	Green economy, car manufacturing and constructions	Health and social service, green economy, public sector
Interrelation of Innovation and Job Quality	Recognised but poorly developed, more focus put on quantitative dimension of employment	Exclusive focus on quantitative dimension of employment, although improving working conditions	'Better jobs' dropped from the agenda		Job quality is of high priority again, though not in direct relation with innovation

Innovation policy in the EU is the interface between research and technological development policy and industrial policy. It comes under the Innovation Union launched by the European Commission in October 2010 and is one of the 7 flagship initiatives of the Europe 2020 strategy for smart, sustainable and inclusive growth. The Innovation Union plan has over 30 action points and has three objectives:

- make Europe into a world-class science performer,
- remove obstacles to innovation like expensive patenting, market fragmentation, slow standard-setting and skills shortages,
- revolutionise the way public and private sectors work together, notably through Innovation Partnerships between the European institutions, national and regional authorities and business.

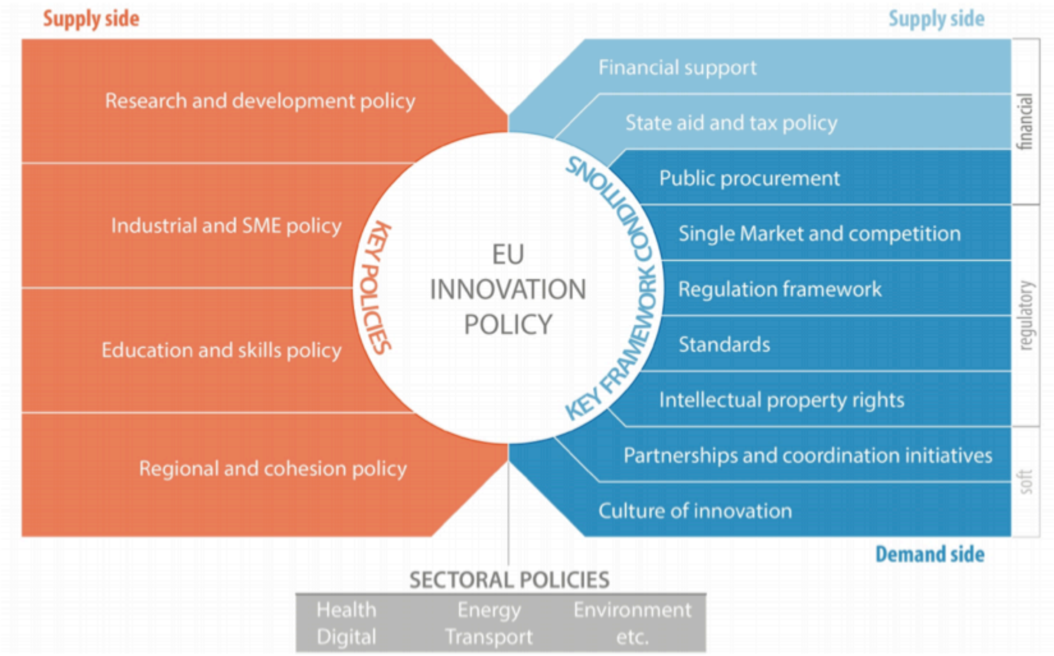


Figure 6 EU Innovation Policy Mix. ***Source: EPRS data in (European Parliament, 2016)***

Table 3 EU Competences for each component of the EU innovation policy mix.
Source: (European Parliament, 2016)

Key policies	Fund	Regulate	Promote
R&D policy	✓✓	✓	✓✓
Industrial and SME policy	✓	✓	✓
Education and skills policy			✓✓
Regional and cohesion policy	✓✓		✓✓
Key framework conditions	**Fund**	**Regulate**	**Promote**
Financial support	✓✓	✓	✓
State aid and tax policy		✓	✓✓
Public procurement	✓	✓	✓✓
Single Market and Competition		✓✓✓	✓
Regulation framework		✓	✓✓
Standards		✓	✓✓
IPR		✓✓✓	✓
Partnerships and initiatives	✓✓	✓	✓✓
Culture of innovation			✓

Source: EPRS ✓: Potential action or low competence ✓✓: Important feature ✓✓✓: Strong competence

The Innovation Union has set an EU-wide target of investing 3% of EU GDP in R&D by 2020 which could create 3.7 million jobs and increase annual GDP by EUR 795 billion by 2025. The EU innovation policy mix interacts with the policy mixes developed at national and regional level. Each of these levels of governance may establish policies and instruments depending on their competences. Table

3 above offers an overview of the EU's powers with regard to the various policies and instruments that are part of the European innovation policy mix.

It aims to improve conditions and access to finance for research and innovation and create a genuine single European market for innovation which would attract innovative companies and businesses through measures such as patent protection, standardisation, public procurement and smart regulation. The Innovation Union also aims to stimulate private sector investments. The Innovation Union seeks to create a European research area which would create coherence between EU and national research policies.

Several instruments have been introduced to measure and monitor the situation across the EU and the progress being made:

- A comprehensive Innovation Union Scoreboard (European Commission, 2019) based on 25 indicators and a European knowledge market for patents and licensing. The European Innovation Scoreboard (EIS) is a Commission instrument developed under the Lisbon Strategy to provide a comparative assessment of the innovation performance of EU Member States;
- A Regional Innovation Scoreboard (RIS), which classifies the EU's regions into four innovation performance groups, similarly to the Innovation Union Scoreboard. There are 41 regions in the first group of 'innovation leaders', 58 regions in the second group of 'innovation followers', 39 regions are 'moderate innovators' and 52 regions are in the fourth group of 'modest innovators'. This provides a more accurate mapping of innovation at local level;
- The Innobarometer, an annual opinion poll conducted among businesses and the general public on attitudes and activities relating to innovation policy. The Innobarometer survey provides policy-relevant information which is not available from other sources.

There are other instruments which are part of the EU's innovation policy such as cohesion policy which targets at least 80% of the European Regional Development Fund (ERDF)'s resources at national level to innovation, prioritizing competitive SMEs and a low-carbon economy. The EU ERDF along with the European Social Fund (ESF) are two key programmes supporting innovation at the regional level. Other such funds include the EU programme for the Competitiveness of Enterprises and SMEs (COSME): successor of the Competitiveness and Innovation Programme (CIP), designed to support innovation among SMEs, other research funds such as the Euratom Research and Training Programme (EUR 1.6 billion), the International Thermonuclear Experimental Reactor (ITER EUR 2.9 billion) and the Research Fund for Coal and Steel (EUR 319 million) (European Parliament, 2016).

The European Strategic Energy Technology Plan (SET Plan) is a key Research & Innovation (R&I) instrument to accelerate the development and deployment of low-carbon technologies focusing on the energy system. The plan coordinates EU and national research efforts in financing the most impactful technologies and promotes research and innovation efforts across Europe (EU level, EU

countries, companies, research institutions) by supporting in the EU's transformation to a low-carbon energy system. The broad SET Plan comprises of a Steering Group, the European Technology and Innovation Platforms, the European Energy Research Alliance, and the SET Plan Information System (SETIS).

The Set Plan identifies 10 actions for research and innovation based on an assessment of the energy system's needs, addresses the whole innovation chain (from research to market uptake, and tackles both financing and the regulatory framework), fosters a more effective interaction with EU countries and stakeholders and measures progress via overall Key Performance Indicators (KPIs) like the level of investment in research and innovation, or cost reductions (European Commission, N.D., d). Nine European Technology and Innovation Platforms (ETIPs) were created to support the implementation of the SET Plan and promote the market uptake of key energy technologies by pooling funding, skills, and research facilities.

Various financial instruments and institutions such as banks, insurance companies, asset managers, credit and sustainability ratings, pension funds, socially responsible investments, bonds, are also active in greening the economy. The European Investment Bank for instance helps finance energy projects by providing companies with loans and other financial instruments. EIB funds have helped not only finance innovative technologies (Arcelor Mittal example in Wyns et al., 2018) but have also helped upscale technology deployment. In renewables alone, EIB lending increased from EUR 0.5 billion per year in 2004 to EUR 6.2 billion per year in 2010. The EIB also finances low-carbon technology deployment in third countries.

Finance plays a key role in the EU innovation framework. The 'InnovFin – EU Finance for Innovators' initiative, an initiative launched by the Commission, in cooperation with the European Investment Bank Group (EIB and EIF), under Horizon 2020 helps improve access to loans for R&D projects and launch demonstration projects. 'InnovFin – EU Finance for Innovators' covers the entire value chain of research and innovation in order to support investments from the smallest to the largest enterprises. The 'Investment Plan for Europe' will seek to unlock public and private investments in the 'real economy' to the sum of at least EUR 315 billion over a three-year fiscal period. EFSI is one of the three pillars of the 'Investment Plan for Europe' and aims to overcome current market failures by addressing market gaps and mobilising private investment. It helps to finance strategic investments in key areas such as infrastructure, research and innovation, education, renewable energy and energy efficiency, as well as risk financing for SMEs. Under Horizon 2020, the European Institute of Innovation and Technology (EIT) was created in 2008 as a one-stop shop for innovation in a number of areas. The EIT has resulted in providing support to more than 1250 ventures, the creation of more than 600 new products and services and 6100 jobs, more than 40 innovation hubs across Europe and more than EUR 890 million in investments raised by EIT ventures (European Institute of Innovation and Technology, N.D.).

An EU Innovation Council, launched in 2015 as a pilot scheme, aims to support top-class innovators, start-ups, small companies and researchers developing high-risk, breakthrough innovations with the potential to create new markets and boost jobs, growth and prosperity in Europe and scale up internationally (European Commission, N.D.,c). The EU ETS innovation fund is the main instrument to bridge the pilot/demonstration to commercialisation gap that will make available around EUR 10 billion for the demonstration of breakthrough technologies in the energy and industrial sectors in the period 2020-2030. The fund solves many issues that hampered its predecessor (NER300), in particular the lack of upfront financing. The fund will provide project developers early access to capital, even before the construction of the demonstration technology and will also cover part of the (possibly) higher OPEX compared to incumbent technologies. Moreover, the fund will allow blended finance with other EU financing instruments (e.g. Invest EU). Finally, the set-up of the innovation fund contains support at an early stage for the development of project proposals (Wyns et al., 2019).

Other instruments used to support innovation include state aid (to support R&D feasibility studies, research infrastructure, innovation activities and innovation clusters), tax policy (best practices), venture capital, regulations, standards, IPR and procurement. All these together, in addition to numerous other initiatives, make up the innovation policy in the EU.

The EU’s answer to innovation-led growth has transpired through mission-oriented R&D - the new direction adopted by Horizon Europe (Mazzucato, 2018). With such a mission oriented R&D approach, the EU recognizes that innovation not only has a rate but also a direction which when harnessed, can in turn harness the power of R&D to achieve societal and economic goals (Mazzucato, 2018). Such innovation-led growth would ergo not only be more sustainable but also equitable. In the EU therefore, there is a well-developed innovation and environmental policy structure at the supranational level, complementing member state innovation and environmental policy structures of differing strengths. However, it is yet too early to say whether an innovation-based growth model is solidly in place especially as compared to China (Section 4.1.3 below).

4.1.2.US

In contrast to the EU, the environmental and eco-innovation policy system in the US is extremely fragmented. Such a system has been described as a Silicon Valley model – whereby a vertically disintegrated industry allows new entrants, specialising in particular components, to insert themselves at various points in the value chain (Owen, 2017). At the national level, the Environmental Protection Agency (EPA) is the primary body responsible for developing and enforcing environmental regulations based on the National Environmental Protection Act (NEPA) of 1969 – the cornerstone of the current US environmental legislation. The EPA for instance oversees policies such as The Clean Power Plan - one of President Obama's signature environmental policies now repealed by President Trump - which required the energy sector to cut carbon emissions by 32 percent by 2030 (Gibbens, 2019). However, this environmental regulation is based on a tripartite system of the Congress (Sen-

ate and House of representatives) or the Legislative branch, which passes relevant laws in addition to a number of formal and informal controls, the Executive branch consisting of governmental authority on environmental issues represented by the EPA as well as other departments with environmental competencies, and the Judicial Branch which arbitrates on relevant issues.

The fragmentation of competencies on environment protection in the US comes from the fact that both chambers of Congress each have ten different committees dealing with environment. Key committees are spread across the House of Representatives, Senate and Executive Branch while no less than 13 key US federal departments hold relevant responsibilities. Knigge and Bausch (2006) explain a threefold distribution of power in the US on environmental policy-making determined by the Constitution and judicial decisions: federal level, state level and local level.

At the subnational level, some of the most important initiatives include GHG inventories, climate change action plans, GHG reporting and registries, carbon cap or offset requirements for power plants, vehicle emission standards, appliance efficiency standards, green pricing programmes, public benefit funds, portfolio standards and regional initiatives (Knigge and Bausch, 2006). Certain States like California or Massachusetts play a dominant role in the overall global scientific impact of the country (European Commission, 2017).

In terms of innovation policy, Atkinson (2014) describes it as a triangular concept based on the business environment, regulatory environment, and innovation environment. The business environment consists of market and firm structure and behaviour, the system for financing business, and related social and cultural factors affecting how business operates. In the business and financing system, the US has pioneered venture capital with focus shifting to upstream investments in the last 15 years. “While the business environment plays the key role in determining innovation success, government policy plays a powerful enabling (or detracting) role, particularly through the broad areas of trade, tax and regulatory policy that shape the innovation environment” (Atkinson, 2014). Atkinson (2014) estimates the innovation system in the US to be less sophisticated than those of others. However, there exists targeted support for mission-oriented research (USD 140 billion R&D funding in 2013) to federal labs and curiosity-directed research through university funding. Federal labs consist of around 100 government research labs who focus on in particular defense, energy and health issues. University research labs are supported through a number of agencies, including DOD (Department of Defense), DOE, and NIH. What is interesting is that there are a number of policies in place to transfer technologies from the federal and research labs to the marketplace since the Stevenson-Wydler technologies act of 1980. The retention of IP rights by universities further helps incentivize the commercialization of research.

The US government also supports innovation in business. For example, the Obama administration launched a National Network for Manufacturing Innovation (NNMI) inspired in part by the German Fraunhofer centers and that brings together firms, universities and several government agencies in a

unique public-private partnership. These centres (four in total) focus on spawning commercial innovation and competitiveness. However, there isn't enough funding for this industry-oriented research initiative (South Korea spends 89 times as much on the same, while Germany spends 43 times more) (Atkinson 2014). There also exist industry clusters (more at the state and local levels) and mechanism which underpin industry collaboration with academic institutions of excellence such as MIT, Caltech, Stanford etc. Although there has been little effort made by the US to acquire foreign technology - given it has long been at the head of cutting edge technology - there are several policies and programmes in place which help diffuse technology and promote technology adoption, for example in the agriculture and manufacturing sectors. The Manufacturing Extension Partnership (MEP) programme for instance which is overseen by the National Institute of Standards and Technology and administrated by over 60 regional centers, helps firms with energy efficiency amongst others (Atkinson, 2014).

While the fragmentation of US eco-innovation and environment policies is clear, by avoiding over-centralisation, innovation policy seems to have benefitted the US given a number of funding agencies with differing missions and priorities (Owen, 2017). The vibrant private sector, in particular the support to innovative new entrants has also been of great support to science-based innovation. Moreover, the entrepreneurial role of the universities makes technology development and transfer more productive. However, US performance in the manufacturing sector has not been very great as evidenced also by the paucity in innovation funding mentioned earlier. In recent years however, under the Trump administration, there has been a significant amount of regression in the US in terms of climate policy-related innovation.[3]

4.1.3. China

China has made significant efforts to rein in its GHG emissions through its National Program on Climate Change, its Work Plan for Controlling Greenhouse Gas Emissions during the 12th Five-Year Plan Period, its Comprehensive Work Plan for Energy Conservation and Emission Reduction for the 12th Five Year Plan Period, its 12th Five Year Plan for Energy Conservation and Emission Reduction, the 2014-2015 Action Plan for Energy Conservation, Emission Reduction and Low-Carbon Development, and the National Plan on Climate Change (2014-2020) (UNFCCC, 2015b). China has also taken significant steps to modify its industry and energy structures through energy efficiency improvements and decarbonization strategies such as the establishment of carbon emission trading pilots in 7 provinces and cities and low-carbon development pilots in 42 provinces.

China has invested heavily in its Innovating Low-Carbon Development Growth Pattern which features low-carbon pilots in provinces and cities; low-carbon cities (towns) pilots as well as low-carbon

[3] For an excellent analysis, see Frank Jotzo, Joanna Depledge & Harald Winkler (2018)

industrial parks, low-carbon communities, low-carbon business and low-carbon transport pilots; carbon emissions control research; and the facilitation of the emergence of low-carbon cities with rational space distribution. It has also sought to build research on and establish carbon emission accreditation system, to carry out low-carbon certification pilots and promotion of low-carbon selected products.

China's innovation policy has been described as innovation mercantilism as it pursues its goal of becoming an innovation leader. As much policy making in China goes, innovation and environment policies are extremely top-down. Chinese authorities have made a deliberate, holistic plan and long-term commitment to the local adaptation and development of various low-carbon technologies (WRI, 2010). Atkinson and Foote (2019) describe China's path to innovation leadership as a four-staged strategy: (i) transfer of foreign technology mainly through FDI, (ii) diffusion and upgradation of the technology, (iii) efforts to assimilate, adapt and improve the technology to the eventual development of indigenous technology, and (iv) enabling Chinese firms to become independent innovators.

In 2006, therefore, China enacted the "National Medium- and Long-term Program for Science and Technology Development (2006–2020), which had the objective to master 402 core technologies. Other plans have been put in place: the Five-Year Plan for Science and Technology, the Five-Year Plan for National Informatization, a National Cybersecurity Strategy (which calls for 80% domestic market share of high end computer machines by 2025, 70 percent for robots and robot core components; 60 percent for big data; 60 percent for IT for smart manufacturing; and 50 percent for industrial software), and the Made in China 2025 Strategy (Atkinson and Foote, 2019).

Atkinson and Foote (2019) write, "no other government in history has done more to promote an innovation-based economy than China". Chinese government has already announced that it aims to become a world leader in AI by 2025. Since the late 1980s, the Chinese government has been promoting the formation and development of national science and technology industrial parks (STIPs) of which there are around 54 (2008 data) (Zhang and Sonobe, 2011). An example of this is the Chinese policy which made China into a global wind energy leader (Table 4 below).

Table 4 China's energy policy development as regards wind power.

Table 10. China energy policy relevant to wind

Tier	Wind Energy Policy
First tier	Provide general direction and guidance, including speeches by state leaders and the Chinese government's general standpoint on the global environment
	• 2003 Renewable Energy Promotion Law • 2005 Renewable Energy Law • Amendments to Renewable Energy Law, 2010
Second tier	Specify goals/objectives and development plans, with a focus on rural electrification and renewable energy–based generation technologies
	• 1996 Ride the Wind Program • 2003 Rural Energy Development Plan for Western China • 2006 Medium to Long-Term Development Plan on Renewable Energy • 2006 11th Five-Year Plan for Renewable Energy • 2007 National Plan for Renewable Energy Development • 2007 International Science and Technology Cooperation Program on New and Renewable Energy
Third tier	Provide practical and specific incentives and managerial guidelines, aimed at reaching the goals and objectives set by the second-level policies
	• 2006 Management Regulations on Electricity Generation from Renewable Energy • 2006 Notice on Management Requirements for Wind Power Construction • 2006 Provisional Management Measures on Construction Land Usage and Environmental Protection of Wind Power Stations • 2006 Interim Measures for Renewable Energy Development Special Funds • 2008 Tariff Adjustments for High-Power Wind Turbines and its Key Components • Circular on Preferential Tax Policy Issues for Developing the Western Region

Source: Li, 2006; NDRC Website

Beyond science-based innovation, China also has global champions to rival US' Apple, Google, and Amazon. While Apple and Samsung hold 18.2% and 18.7% of the global smartphone share respectively, Chinese smartphone makers—Huawei, Xiaomi, and Oppo—together hold 32 percent of the global market. Huawei alone controls 28% of the global telecommunications equipment market thanks to its over USD 11.5 billion annual R&D spending - the fifth in the world. China's Alibaba too has emerged as one of the world's top ten retailers. In 2016, China's high-speed rail car producer CRRC had over two-thirds of global deliveries while China BOE Technology Group is one of the most sophisticated producers of liquid crystal displays (LCDs).

China spends 2.13% of its GDP on R&D (mostly government spending), a figure higher than the EU's and 76% of US levels. China's R&D spending has in fact increased from USD 6.8 billion in 1998 to USD 39 billion in 2008. China's R&D spending is between 15.6% (2017 figures of the Chinese National Innovation Index 2016-2017) and 21% (2015 figures of the Science, Research and Innovation Performance of the EU) of the world total (European Commission, 2018b). The Chinese Academy of Sciences for instance operates over 104 institutes.

The Chinese government has successfully capitalised on public-private and industry-academia synergies to bring together multi-sector expertise in order to develop and diffuse innovation (WRI, 2010). In 2016, the U.S. Patent and Trademark Office (USPTO) had granted 11,000 - or 8% - of US patents to China (a figure higher than any other country), while in the same year, the USPTO had issued 45% of

patents in the ICT field to Chinese firms, higher than the 34% issued to US firms! In 2016, Chinese patents issued by the USPTO were as high as 6.6 percent for sustainable energy (alternative energy, energy storage, smart grid, and pollution mitigation), 5.4 percent for alternative energy (e.g., bioenergy, solar, wind, nuclear, fuel cells, hydropower, wave/tidal, geothermal, and electric vehicles), and 11 percent for energy storage (e.g., batteries, compressed air, flywheels, superconducting magnets, ultracapacitors, hydrogen, and thermal) of the patents granted to Americans. Looking closer, the number of patents by percentage of U.S. patents stood at 17.3% for battery technology, 10.2% for wind technology, 6% for solar energy patents and 3.3% for nuclear energy in 2016. As of 2018, China also produces 227 of the world's top supercomputers, compared to 109 for the United States.

Innovation policy in China can be described as assertive mission-oriented, developed through a multitude of national-level and sector-wide laws, policies, and regulations. However, these policies have also been market-oriented in ensuring that necessary technologies, in particular low-carbon ones, are scaled-up, commercialized and a domestic/international market is created to drive down the costs (WRI, 2010). There have been strong criticisms of Chinese IP theft from foreign firms. But despite foreign pressure on the Chinese government to curb innovation theft, there is a growing domestic innovation economy. China's can therefore be described as an innovation-based growth model.

4.2. Existing technology/innovation cooperation between EU, China, US

4.2.1. EU-China[4]

The EU and China are strategic partners and have an elaborate science and technology cooperation in place. In December 1998, the EU and China signed a Science and Technology Cooperation Agreement overseen by the EU-China Joint Steering Committee on Science and Technology Cooperation which governs bilateral science and technology cooperation. The EU-China 2020 Agenda for Strategic Co-operation, adopted at the 2013 Summit, is currently the defining document for the bilateral relationship which addresses the broad headings of peace and security, prosperity and sustainable development and people-to-people exchanges, and contains extensive reference to the pivotal role of research and innovation cooperation in the overall EU-China relations. Other agreements in place include the EU-China Innovation Cooperation Agreement between the European Atomic Energy Community (Euratom) and the Government of the People's Republic of China for Research and Development (R&D) Cooperation in the Peaceful Uses of Nuclear Energy (RD-PUNE) (since August 2008) and EU-China Space Cooperation Dialogues. Since the signature of the RD-PUNE agreement in 2008, China has become one of the principal nuclear research interlocutors for Euratom. Cooperation on climate innovation in particular spans broad climate-related scientific research and cooperation on

[4] This section is based on European Commission, 2018b.

technology innovation, including the development and deployment of low greenhouse gas emission technologies such as carbon capture, utilisation and storage (CCUS), and adaptation solutions.

At the 19th EU-China Summit that took place on 2 June 2017 in Brussels, two new research and innovation related documents were signed - a Joint Statement on flagship initiatives and co-funding mechanisms, and a Framework Research Arrangement between the European Commission Joint Research Centre (JRC) and the Chinese Academy of Sciences (CAS).

The EU and China also have in place a dedicated High-Level EU-China Innovation Cooperation Dialogue (ICD) since 2012 which has the ambition of raising the level and intensity of research and innovation relations with China by providing a forum for discussing respective innovation policies and systems, addressing framework conditions and launching new joint Research and Innovation (R&I) initiatives. It includes initiatives in the areas of food, agriculture and biotechnologies, environment and sustainable urbanisation, surface transport, safer and greener aviation, and biotechnologies for environment and human health; translated into a number of topics for cooperation with China under Horizon 2020.

At the 2015 Summit and ICD, the EU and China reached a breakthrough agreement on the setting up of a Co-Funding Mechanism (CFM) for research and innovation cooperation. The CFM gets funding from China's ministry of Science and Technology (MOST) to the tune of EUR 26 million and EUR 100 million from the EU on an annual basis for joint projects under Horizon 2020 and seeks to improve framework conditions, notably reciprocal access to science, technology and innovation resources, and to promoting open access to publications and research results. China is a key partner in science and technology and actively participates in EU initiatives such as Horizon 2020. A budget of up to EUR 100 million is reserved for cooperation with China in Horizon 2020. Until October 2018 Chinese entities have participated 337 times to 158 signed grants of collaborative in Horizon 2020, Marie Skłodowska-Curie Actions (MSCA) and European Research Council (ERC) actions, receiving EUR 3.1 million of direct EU contribution while EUR 33.8 million is the non-EU budget of Chinese beneficiaries. China through its National Natural Science Foundation (NSFC) also collaborates with the EU's European Research Council via an Implementing Arrangement signed on 29 June 2015.

The EU and China are also partners of the ITER multilateral cooperation project on fusion research and participate, within the Generation IV international Forum, in the research and development activities of the Sodium Fast Reactor and the Very-High Temperature Reactor. China is a leading actor in fusion energy research, a full member party of ITER and the only country with plans to build a new fusion machine complementary to ITER in the next decade, the so-called Chinese Fusion Engineering Testing Reactor (CFETR). There are 111 on-going activities, involving 18 European and 21 Chinese entities. Under the RD-PUNE-Fusion, cooperation will be intensified via the Technology Management Plan (and the associated Project Plans) notably in the areas of Joint development of the Chinese Fusion Engineering Testing Reactor (CFETR) and of the European Demonstration Fusion

Power Reactor (DEMO) design (Materials testing and qualification, Breeder Blanket development, Other technologies necessary for the realization Materials testing and qualification, Systems integration and assessments, Plasma Scenario development, Safety and socio economic studies and assessments) and the undertaking of joint operation of major research infrastructures in support of future ITER operation (Physics and technology of long pulse operation, Heat exhaust, plasma-wall interaction and divertor optimization, model validation, Disruption mitigation, Training activities on ITER operations, other experiments relevant to the design and definition of CFETR and EU DEMO). On fission, Euratom continues to encourage the participation of Chinese entities with specific targeted actions on international cooperation in fission R&D between Euratom and China. An effective dialogue on the strengtheningof cooperation in mid-term perspectives on nuclear safety, decommissioning and waste management via programmatic discussion is ongoing. In the longer term, China will likely continue to be a strategic partner for the EU in peaceful use of research cooperation also due to Chinese boosting nuclear energy programmes.

The EU and China collaborate on climate-related scientific research and technology innovation, including the development and deployment of low-carbon technologies (and adaptation solutions). For instance, the Horizon 2020 project CHEERS (Chinese-European Emission- Reduction Solutions) launched in October 2017 involves three Chinese partners with the aim of demonstrating large-scale decarbonisation of industry, offering a considerable potential for retrofitting industrial combustion processes. Sustainable urbanisation and in particular its environmental aspects is a major socio-economic area of cooperation for both China and Europe with emphasis on green urban mobility and sustainable electrification. The project PIANO ("Policies, Innovation, And Network for enhancing Opportunities for China-Europe water cooperation") was initiated in 2018 as a strategic cooperation partnership, which had developed a Strategic Research and Innovation Agenda (SRIA). In the transport sector, cooperation with China in 2018-20 focuses on transport impact on urban mobility, green aviation, sustainable electrification, air quality, and freight transport systems. In the field of clean energy research, cooperation focuses closely on Carbon Capture and Storage (CCS). Twinning workshops on Concentrated Solar Power were also organised with the Chinese Ministry of Science and Technology. In Horizon 2020, Chinese participation has also focused on hydrogen safety for energy applications.

Internationally, the EU and China collaborate closely on clean energy R&D in Mission Innovation (see Section 5.2.5).

4.2.2. EU-US[5]

Research and innovation cooperation between the EU and the US is governed by the 1998 Agreement for Scientific and Technological Cooperation, overseen by the Joint Consultative Group (JCG).

[5] This section is based on (European Commission, 2017)

In addition to the JCG, EU-US scientific cooperation takes place under the auspices of the EU-US Space Dialogue, the Transatlantic Ocean Research Alliance, the Energy Council and the Transatlantic Economic Council. EU-US S&T cooperation focuses on research and innovation priority areas like: Marine and Arctic Research, Bioeconomy, Research Infrastructures, Health research, Transportation Research (including Aviation), and Nanosafety and regulatory research / materials research.

Cooperation between the US and European Research Infrastructures is well consolidated. The US is involved in the activities of CERN and other major European initiatives such as Common Language Resources and Technology Infrastructure (CLARIN ERIC), and the Square Kilometre Array (SKA) telescope, both identified as Landmarks on the European Strategy Forum on Research Infrastructures (ESFRI) roadmap.

Bottom-up project participation is also a strong feature in EU-US cooperation. The EU and the US collaborate on research within the Horizon2020 framework in which the US is the leading 3rd country participant (both in participation and funding). By October 2017, U.S. entities participated 864 times in 653 signed grants of Horizon 2020, receiving 27.3 million euros of direct EU contribution and 15.8 million euros in the non-EU budget of U.S. beneficiaries. As concerns collaborative actions of Horizon 2020, U.S. applicants have a success rate of 18.0% (as compared to 16.5% for non- associated countries and 14.7% overall). Regarding the Horizon 2020 Marie Sklodowska-Curie Actions (MSCA), U.S. entities have participated 671 times (301 in Individual Fellowships (IF), 201 in the RISE, 144 in the ITN and 25 in the COFUND programme). A total of 250 U.S. researchers have participated in MSCA actions. Moreover, US entities received 1.7 million euros ERC grants of Horizon 2020, making it the country of nationality of the highest number of ERC non-ERA grantees by October 2017. The basis for cooperation in the ERC is the Implementing Agreement signed between the Commission and the US National Science Foundation on 13 July 2012.

The EU and the US also collaborate in various sectoral areas such as transportation research, nanosafety and materials research, energy cooperation and so on. In 2013, the US and EU signed an Implementing Arrangement (February 2013), covering Cooperative Activities in the Field of Research, Development, Technology, and Innovation Applied to all Modes of Transport. A steering group has been established to implement the agreement and cooperation areas include transport infrastructure, traffic management, road safety, urban freight logistics and others. A milestone in this area of cooperation has been the launch in 2013 and 2015 of Interoperability Centres for smart grids and e-vehicles by the Joint Research Centre and the US Department of Energy, followed by cooperation established under the auspices of the Transatlantic Economic Council. New global rules and standards are advanced jointly in Aviation by the US Federal Aviation Administration (FAA) and the European Aviation Safety Agency (EASA) since the supply chain is transatlantic.

In nano safety and regulatory research, cooperation with the US is of special importance and is implemented through the Communities of Research as well as government-level cooperation in the

OECD working party on manufactured nano-materials (in particular through the NanoReg initiative, started already under FP7 and followed by further activities in H2020). A reinforcement of EU-US raw materials cooperation took place via the signing of an Implementing Arrangement between DG JRC and the US Geological Survey. Specifically, the cooperation will cover Earth Sciences, Climate and Land Use Change, Ecosystems, Energy and Minerals, Environmental Health, Natural Hazards and Water.

With regard to fission research cooperation, nine US entities participated in ten fission projects under the Euratom FP7 research programme focusing on various aspects of radiation protection, severe accident management and radioactive waste management. Presently six entities participate in six projects under the Euratom Programme, complementing Horizon 2020, focusing on the history of nuclear energy, education and training, materials, innovative small modular nuclear reactors, emergency preparedness and emergency response and core monitoring techniques. The cooperation in the field of fusion research encompasses around 315 ongoing collaborative activities, involving 27 US research institutions and 19 European fusion labs under the bilateral Fusion Cooperation Agreement legal framework, aimed at supporting ITER and long-term DEMO developments. Potential new areas of future S&T cooperation include the domain of Research Infrastructures, green aviation, Future Internet and Advanced Wireless Platforms.

4.2.3. US-China[6]

The US and China have a longstanding relationship in Science and Technology (S&T) cooperation. 2019 marks the 40th anniversary of the U.S.-China Agreement on Cooperation in Science and Technology (S&T), which has advanced cooperative research in diverse fields, including fisheries, earth and atmospheric sciences, basic research in physics and chemistry, a variety of energy-related areas, agriculture, civil industrial technology, geology, health, and disaster research. Other agreements fostering U.S.-Chinese collaboration the Agreement on High Energy Physics (1979), the Protocol on Nuclear Physics and Fusion (1983) and the Fossil Energy Protocol (2000). In 1998, DOE's Office of Energy Efficiency and Renewable Energy assisted in the design and construction of a high- performance, energy-efficient demonstration building for the Agenda 21 Commission and has since assisted in the LEED application to the U.S. Green Building Council, leading to the building being the first in China to be designated LEED Gold. Both partners have also established a USD 150 million Clean Energy Research Center in November 2009 as a home for joint research consortiums of research institutions, universities and industry participants from both countries, with an initial focus on clean coal, clean vehicles, and building energy efficiency. The DOE and the Chinese Academy of Sciences also signed an agreement in January 2011 to facilitate and promote cooperation in research and development in a broad range of energy sciences.

[6] This section is based on (Obama White House Archive, N.D.)

To facilitate and strengthen collaboration between U.S. and Chinese scientists and engineers, in 2002, the Ministry of Science and Technology (MOST) and National Science Foundation (NSF) signed the U.S.-China Cooperative Arrangement for the Summer Institute in China Program. Since then, in May 2006, the NSF has established a Beijing office to facilitate and strengthen such collaboration.

The US National Institute of Standards and Technology (NIST) has also signed a number of collaborative arrangements with several Chinese governmental and academic institutions, and one formal protocol with the Chinese Academy of Sciences in the fields of chemistry, physics, materials science, and engineering measurement. NIST has hosted close to 1,000 Chinese scientists and engineers since 1980 through its Foreign Guest Researcher Program. Similarly, collaboration between the US National Oceanic and Atmospheric Administration (NOAA) and the China Meteorological Administration (CMA) has spanned decades with the former helping the CMA modernize. NOAA and CMA laboratories have also cooperated for almost thirty years to measure greenhouse gas (GHG) concentrations leading to a shared understanding of global changes in GHGs.

Cooperation on agriculture science and technology is also extremely structured. In December 7 2002, the United States and China signed a protocol on cooperation in agriculture science and technology, which calls for cooperation between the Chinese Ministry of Science and Technology and the U.S. Department of Agriculture's (USDA's) Agricultural Research in areas such as agricultural biotechnology, natural resource management, dairy production, food safety, agricultural products processing, water-saving agricultural technology, and bioenergy. Moreover, the U.S. Forest Service and the Chinese State Forestry Administration regularly engage in cooperative ventures including the establishment of demonstration sites in a variety of forest ecosystems across China with a focus on community-based protection and restoration.

Since 1999, the U.S. Fish and Wildlife Service (FWS) has provided USD 1.1 million for conservation efforts in China, including training and conservation practices. In October 2010, the EPA and MEP signed a Memorandum of Understanding on Scientific and Technical Cooperation in the field of environment, supporting collaborative efforts to tackle shared challenges posed by air pollution, water pollution, pollution from persistent organic pollutants and other toxic substances, hazardous and solid waste, and the development, implementation, and enforcement of environmental law. The US has also sought to help China to decarbonize the industrial sector. In 2006, the EPA introduced U.S. Superfund and Brownfields cleanup programs to MEP providing China with long- term cleanup assistance using U.S.-developed technology to reduce dioxins emissions from cement kilns and to implement China's first-ever non-thermal PCB soil remediation project. In 2007 China shut down five of its six remaining plants for production of chlorofluorocarbons (CFC) and halons and both partners continue to work together through the Montreal Protocol framework to encourage the use of safer substitutes to CFCs and halons and help China meet its growing demand for refrigerants.

The US and China collaboration therefore seeks economic growth and prosperity through policies that promote innovation. What is essential for the US is that such cooperation is conducted on terms that are fair and equitable to all and respect the principles of non-discrimination, intellectual property rights protection, market competition, and ensuring no government interference in technology transfer. In recent times, the Trump administration has called out China for technology 'theft' and demands the country to strengthen intellectual property protection and stop forcing the transfer of technology.

4.2.4.Conclusion

The EU, US and China are global innovation hubs in their own right. The deep cooperation that is visible in EU-US, EU-China and US-China relations shows the potential for increasing their participation and cooperation in global climate mitigation efforts (Aldy et al., 2003; Barrett, 2003; Barrett and Stavins, 2003; Buchner and Carraro, 2005; Newell, 2008; De Coninck et al., 2008) (W. Jin / Technological Forecasting & Social Change 102 (2016) 357–372). Greater coordination of climate technology innovation and R&D amongst the EU, US and China would greatly help advance and commercialise the most potent of low-carbon technological innovations. Internalising the positive technology externality can take place via international platforms such as Mission Innovation (described in the next section).

5. International governance of (climate) technology

5.1. Introduction

Two questions guide this section. The **first question** is: Does existing international (governance of) climate technology and/or innovation address barriers and create sufficient value added?

Barriers to international technology and/or innovation cooperation (see section 3.2) are, among others: competition / anti-trust rules and the protection of Intellectual Property Rights (IPRs), lack of upfront information on cost-, risk- and benefit-sharing for both the public and the private sector, incompatible R&D conditions and a lack of agreement on the sharing of risks and/or costs by the private sector, political factors and a lack of necessity felt by the public sector to step in, etc. International technology and/or innovation cooperation can create value added by means of, among others, pooling resources, sharing effort/risks, providing access to specific technology/markets, etc.

The **second question** of this section is: How do the existing international institutions that govern climate technology / innovation address the sectoral needs with regard to climate technology / innovation (identified in sections 2.3 and 3.1 above)? The sectors considered are four crucial ones for tackling climate change: the power sector, the energy-intensive industries sector, the land transport

sector, and the international transport (aviation focus only[7]) sector. The sectoral needs can be divided in three categories, namely those pertaining to: 1) research, development and demonstration (RD&D); 2) market entry; and 3) market transformation. **Sectoral needs in the RD&D category** are: a) public R&D expenditure to help generate private R&D investments; b) dedicated R&D into cleantech including the innovation ecosystem (research, technology providers, companies, public sector, …); c) dedicated R&D agencies with focus on cleantech and innovation missions; d) public sector support of / participation in risk sharing to bring basic R&D to demonstration level; e) an advantageous fiscal regime for private R&D in cleantech innovation. **Sectoral needs for market entry (ME)** are: a) financial or fiscal support for new technologies to compete (e.g. subsidies for renewables, electric vehicles, …); b) public procurement for innovation (e.g. environmental targets in tendering criteria for infrastructure); c) public sector assistance with setting up infrastructure for new technologies (e.g. charging stations for electric vehicles). **Sectoral needs for market transformation (MT)** are: a) sectoral or economy-wide legislation that forces the uptake of (mature) clean technologies (e.g. emission standards, CO_2 price, subsidies, ….); b) facilitation of the roll out of supporting infrastructure. To answer the two questions of this section, we make use of case studies on international institutions in the area of climate technology / innovation (see also Table 5, Table 6, and Table 7).

5.2. Case studies

The case studies below analyse 17 international institutions that govern climate technology / innovation. They introduce the institution's main characteristics to make clear to what extent the institution addresses barriers, creates value added, and/or identifies sectoral needs, or not.

We have included only those international institutions that fully focus on technology and/or innovation or those that include key elements that focus on technology and/or innovation. As in previous reports (Hermwille et al., 2017; Rayner et al., 2018), we do not aim to be exhaustive and include the most salient institutions in the area only. The institutions covered are: the UNFCCC technology mechanism and framework, the World Intellectual Property Organisation (WIPO), the World Trade Organization (WTO), the International Energy Agency (IEA), Mission Innovation (MI), the Breakthrough Energy Coalition (BEC) and Breakthrough Energy Ventures, the G20, the Clean Energy Ministerial (CEM), the International Renewable Energy Agency (IRENA), the Global Environment Facility (GEF), the Major Economies Forum (MEF), the United Nations Industrial Development Organisation (UNIDO), the Low Carbon Technology Partnership initiative (LCTPi), and a few international sectoral initiatives with key elements on technology/innovation that were already included in a previous COP21 RIPPLES report (Rayner et al., 2018), namely the Cement Sustainability Initiative (CSI), the Transformative Urban Mobility Initiative (TUMI), and the Air Transport Action Group (ATAG).

[7] Potentially there are others in the maritime sector, as noted in Rayner et. al., 2018.

5.2.1. UNFCCC Technology Mechanism

In 2010, the Conference of the Parties (COP) of the UNFCCC established the Technology Mechanism (TM) to accelerate and enhance climate technology development and transfer. The TM consists of the Technology Executive Committee (TEC) and the Climate Technology Centre and Network (CTCN). It serves the Paris Agreement (UNFCCC, 2019b). Thus far, the TM has shown that the interests of developed and developing countries with regard to technology transfer are not aligned on various issues, such as: intellectual property rights, what constitutes an enabling environment for technology transfer, and how technology transfer under the UNFCCC should be funded (de Coninck & Sagar, 2017, pp. 262–263).

The text in the UNFCCC Paris Agreement (2015) on the TM focuses on the early stages of the technology cycle (RD&D. In addition, access to technology and the development of endogenous capacities and technologies are included as areas for further work (de Coninck & Sagar, 2017, p. 265). Article 10 paragraph 4 of the Paris Agreement established a 'Technology Framework'. The framework guides the work of the TM in promoting and facilitating enhanced action on technology development and transfer in order to support the implementation of the Agreement. The details are being elaborated (UNFCCC, 2019a). The hope is that it will connect the UNFCCC's financial mechanism and its TM. An underfunded TM would hamper implementation of developing countries' nationally determined contributions, as this implementation is dependent on technology transfer (de Coninck & Sagar, 2017, p. 264).

5.2.1.1. Technology Executive Committee (TEC)

The TEC is the TM's policy arm. It helps countries in identifying policies that accelerate the development and transfer of climate technologies. Its functions are to: provide an overview of countries' climate technology needs and analyse policy and technical issues related to climate technology development and transfer; recommend actions to promote climate technology development and transfer; recommend guidance on policies and programmes; promote and facilitate collaboration between stakeholders; recommend actions to address barriers to climate technology development and transfer; seek cooperation with stakeholders and promote coherence across technology activities; and catalyse the development and use of climate technology road maps and actions plans (TT:CLEAR, 2017). The TEC follows six 'modalities' in conducting its functions: analysis and synthesis, policy recommendations, facilitation and catalysing, linkage with other institutional arrangements, engagement of stakeholders, and information and knowledge sharing (UNFCCC, 2019a). It resembles the UNFCCC's Expert Group on Technology Transfer (EGTT), which existed from 1992 until 2010. An improvement in comparison with the EGTT is that the TEC is open to observer organisations, which can comment on its agenda items and participate in task forces (de Coninck & Sagar, 2017, p. 261).

The TEC meets at least twice a year and reports its annual technology-related recommendations to the COP each year. For 2017, for example, the thematic priority areas identified by the TEC were: adaptation; climate technology financing; emerging and cross-cutting issues; innovation and research, demonstration and development (RD&D); mitigation; and Technology Needs Assessments (TNAs) (UNFCCC, 2017). For adaptation, the TEC worked on South-South cooperation and triangular cooperation on relevant technologies. For climate technology financing, the TEC continued its work on enhancing collaboration with the Financial Mechanism, the Green Climate Fund, the Global Environment Facility, and the Standing Committee on Finance. For emerging and cross-cutting issues, the TEC started to consider the issue of development and enhancement of endogenous capacities and technologies. For innovation and research, development and demonstration, the TEC highlights ways in which national and international actors may enhance financing of climate technology RD&D activities. For mitigation, the TEC hosted a thematic session on sustainable urban development and a thematic dialogue on industrial energy efficiency and material substitution in carbon-intensive sectors. For technology needs assessments, the TEC produced guidance on how the results of the TNAs can be developed into projects and implemented (UNFCCC, 2017).

In addition, the TEC further implements the technology transfer framework and works to accelerate cooperation to achieve the Paris Agreement's objectives (especially Article 10 on technology). The TEC consists of 20 technology experts representing developed and developing countries. It works closely with the CTCN on technology development and transfer. It also engages with entities including the Adaptation Committee, the Global Environmental Facility, the Green Climate Fund, the Standing Committee on Finance and the Executive Committee of the Warsaw International Mechanism for Loss and Damage. The TEC calls for inputs and invites stakeholders to take part in TEC meetings, task forces, workshops, thematic dialogues, expert meetings and side events.

De Coninck and Bhasin argue that the TEC has not been able to live up to initial expectations. It has failed to become "the go-to place for technological advice and a trusted source of information on technology development and transfer for developing countries." The reasons seem to be a lack of resources and the fact that most TEC members are UNFCCC negotiators, which makes it hard to discuss practical issues and brings back the same deadlocks as in the negotiations (de Coninck & Bhasin, 2015, p. 457).

In 2001, Parties to the UNFCCC created the Technology Transfer Framework. It comprises five key themes to increase and improve the transfer of environmentally sound technologies and know-how. The five key technology themes are: technology needs and needs assessments; technology information; enabling environments for technology transfer; capacity-building for technology transfer; and mechanisms for technology transfer. In 2007, four sub-themes were added: innovative financing; international cooperation; endogenous development of technologies; and collaborative research

and development (UNFCCC TT:CLEAR, 2019b). Since 2010, the TEC implements the Technology Transfer Framework.

5.2.1.2. Climate Technology Centre and Network (CTCN)

The CTCN is the TM's implementation arm. It serves as a "landing base for national, regional, sectoral and international technology networks" (Kangas, Ollikka, & Weaver, 2016). It provides technical assistance to developing countries, creates access to information and knowledge, and fosters collaboration among climate technology stakeholders (UNFCCC TT:CLEAR, 2019a). The core service of the CTCN is responding to requests for technical assistance submitted by the National Designated Entities (NDE) of developing countries. The CTCN is hosted by the United Nations Environment Programme (UNEP) and the United Nations Industrial Development Organization (UNIDO). It is also supported by 11 institutions with expertise in climate technologies.8 It is rather small: in 2017, the Climate Technology Centre (CTC) consisted of one Director, five professional staff and two administrative staff (UNFCCC, 2017).

An interested Party to the UNFCCC can nominate an NDE. NDEs serve as National Focal Points for CTCN activities, manage requests and proposals from national stakeholders submitted to the CTCN, and manage the submission of technical assistance requests. NDEs identify priority technology and capacity-building needs in line with national needs and design collaborative programmes with the CTCN (CTCN, 2015). NDEs in Annex I countries contribute to the CTCN by making available relevant information and tools and engaging institutions in their countries. NDEs in Non-Annex I countries participate in designing and updating their national development and climate strategies. They work closely with ministries (finance, planning, environment, energy, science and technology) to reflect priorities in their requests to the CTCN. They should make consultations and collect proposals and suggestions from government, the private sector, civil society and academia (CTCN, 2015).

If the CTCN Climate Technology Manager categorises a request for assistance as a "quick response", it can be addressed rapidly and directly by the Climate Technology Centre (CTC) selecting the most qualified consortium partner. This type of request can involve up to approximately USD 50,000. If the request is categorized as "response project" because its cost would be approximately between USD 50,000 and USD 250,000, it is normally treated by the Climate Technology Network soliciting bids for providing technical support (CTCN, 2015).

The CTCN is more independent from the UNFCCC than the TEC. However, its Advisory Board still consists mainly of UNFCCC negotiators (de Coninck & Bhasin, 2015, p. 457). The CTCN started as a rather experimental initiative (de Coninck & Sagar, 2017). It has not undertaken a lot of activities to

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[8] The consortium partners are: Asian Institute of Technology, Bariloche Foundation, Council for Scientific and Industrial Research, Deutsche Gesellschaft für Internationale Zusammenarbeit, DNV GL, Energy Research Centre of the Netherlands, Environment and Development Action in the Third World, National Renewable Energy Laboratory, Energy and Resources Institute, Tropical Agricultural Research and Higher Education Center, World Agroforestry Centre.

facilitate R&D cooperation yet. Like the TEC, the CTCN suffers from a lack of funding. It relies primarily on contributions from donors. Structural funding is required for the CTCN to live up to its expectations (de Coninck & Bhasin, 2015, p. 458; de Coninck & Sagar, 2017, pp. 261, 271).

5.2.2.World Intellectual Property Organization (WIPO)

The WIPO is a United Nations agency for services, policy, information and cooperation on intellectual property (IP). In March 2019, it had 191 member states. WIPO's mission is to guide the way to an international system for intellectual property that brings creativity and innovation for the benefit of humanity. The WIPO Convention established WIPO in 1967. About 250 non-governmental organisations and intergovernmental organisations have official observer status at WIPO's meetings (WIPO, 2019b). WIPO provides a policy forum to shape rules on IP, global services to protect IP and resolve disputes, technical infrastructure to connect IP systems and share knowledge, capacity-building and cooperation programmes, and information on IP.

On climate change, WIPO hosts a multi-stakeholder platform to promote the innovation and diffusion of green technologies (e.g. renewable energy technologies, energy efficiency technologies, or clean transport, agriculture and forestry technologies). This platform is called WIPO GREEN. WIPO also provides information, analysis and expertise to promote green technology innovation and diffusion (WIPO, 2019a). WIPO GREEN functions as a marketplace, connecting technology owners with individuals or companies who want to commercialise, license or access/distribute a green technology in another way. It has a database that includes technologies at all stages of development, thereby increasing the transparency of the market for green technologies (WIPO, 2019c).

Some propose more radical solutions than WIPO GREEN, though, arguing that the WIPO, WTO and UNFCCC should put together a Joint Declaration on Intellectual Property and Climate Change. Like that, conflicts over intellectual property and climate change could be tackled in three key arenas in a coordinated manner: intellectual property law, trade law, and climate law (Rimmer, 2014). A WIPO Global Green Patent Highway that fast-tracks intellectual property applications relating to green technologies and harmonises national green patent fast-track programs would be another option to make a step forward (Lane, 2012).

5.2.3.World Trade Organization (WTO)

The WTO is relevant with respect to the trade of renewable energy and other low carbon technologies. Preferential trade agreements could play a facilitative role in promoting the deployment of renewable energy. Their potential is currently not being exploited, according to some analysts (Lewis, 2014; Morin & Jinnah, 2018). In 2014, a group of 14 countries, including the United States, EU, China and Japan, started to negotiate an "Environmental Goods Agreement" to reduce tariffs and trade barriers on low-carbon technologies (Van de Graaf and Colgan, 2016). In 2019, the number of coun-

tries has increased to 46, yet the negotiations are slow and seem to have lost some of the initial momentum (Meyer, 2016; WTO, 2017).

5.2.4. International Energy Agency (IEA)

The IEA (1974) is an autonomous intergovernmental organisation under the OECD. Its members are 30 of the 35 OECD countries (plus, Chile which has been an accession country since 2010). In addition, it has working relationships with several non-OECD countries: Brazil, China, India, Indonesia, Morocco, Singapore, and Thailand are associated countries (see also Heubaum & Biermann, 2015). The IEA's aim is to provide reliable, affordable and clean energy to its members and beyond. At the outset, the IEA was founded as a 'buyers club' to counter the Organisation of Petroleum Exporting Countries (OPEC) and secure oil supplies (Dubash & Florini, 2011). Over the years, the IEA has widened its portfolio, which now includes all energy sources (Heubaum & Biermann, 2015). "[T]he IEA is the closest we currently have to a World Energy Organization" (Van de Graaf, 2013, p. 107).

Recently, the IEA has launched an extensive "Clean Energy Transition Programme". It aims to leverage a global energy transition beyond IEA member countries, in particular in emerging economies (IEA, 2017a). Today, the IEA's main value added is to make available information on all types of energy markets and technologies. "This information function has become the hallmark of the IEA's day-to-day functioning" (Van de Graaf, 2017, p. 595). The World Energy Outlook (WEO) and Energy Technology Perspectives (ETP) reports provide energy market analysis and projections. These function as a key benchmark for decision-making for both public and private actors. However, the IEA's scenarios have been criticised for skewed predictions and underestimating the uptake of renewable energy (Creutzig et al., 2017; Muttitt, 2018). But, "the IEA was hardly the only organization that got it wrong" (Heubaum & Biermann, 2015, p. 232).

Besides its information provision function, the IEA has established various Technology Collaboration Programmes (TCPs) to ease cooperation (on research, development and demonstration) among experts in governments, international organizations, non-government entities, businesses and industries, such as on renewable energy technology deployment (2005-17), climate technology (2003-17), and hydrogen (still in operation). The TCP on Renewable Energy Technology Deployment provided a cross-cutting and policy-focused platform which aimed to accelerate the deployment of renewables, enhance international cooperation on policies, best practices and market instruments, and support deployment of renewable energy technologies (IEA, 2019c). The TCP on climate technology provided a framework to accelerate technology transfer and capacity building relating to clean technologies. It aimed to bridge the gap between investors and clean energy projects in need of financing through the Private Financing Advisory Network (IEA, 2019c).

The IEA also develops international energy technology roadmaps and provides analysis on a technology-specific basis to indicate needs in terms of technology development, legal/regulatory, finan-

cial, and public engagement/outreach. It has developed seven roadmaps already, on solar PV, concentrating solar power, wind energy, CO2 capture and storage, electric vehicles, nuclear power and cement sector sustainability. In addition, at the time of writing, roadmaps are in preparation on energy efficiency in buildings, smart power grids, biofuels, geothermal energy, and vehicle efficiency. The IEA provides such analysis for key non-member countries too (a.o.4 Brazil, China, India, Indonesia, Russia, and South Africa), namely cost-benefit modelling, scenario assessment, and technology roadmaps at the national level (Benioff et al., 2010; IEA, 2016, 2019c). The IEA created an International Low-Carbon Energy Technology Platform (Technology Platform) in 2010. The Technology Platform serves as an engagement tool among IEA member and partner countries, the business community, and international organizations to promote clean technology and reduce GHG emissions. The Technology Platform focuses on sharing best practices on clean energy technology and building partnerships via 'Dialogue workshops', guiding development and implementation at the national/regional level with 'How2Guides', and collaborating with partner countries to foster deployment of low-carbon energy technology (IEA, 2019b).

Several IEA Energy Technology Perspectives (ETP) reports (IEA, 2019a) and Technology Roadmaps (IEA, 2019d) focus on the energy intensive sector. In addition, via its Technology Collaboration Programmes (TCPs) IEA members and stakeholders can collaborate by sharing research on breakthrough technologies, fill existing research gaps, build pilot plants and carry out deployment or demonstration programmes along any technology-related activity in the energy intensive industry sector that supports energy security, economic growth, environmental protection and engagement worldwide (IEA, 2016). The Industrial Energy-Related Technologies and Systems (IETS) is a TCP established in 2005 with the aim "to foster international co-operation among OECD and non-OECD countries for accelerated research and technology development of industrial energy-related technologies and systems". The IETS co-operative activities include "scientific research, technology and systems research and development, demonstration and deployment, technology and systems foresighting, technology and systems assessment of policies and consequences, and dissemination of information" (IETS, 2018).

5.2.5. Mission Innovation (MI)

Mission Innovation (MI) is an international institution with a technology-neutral innovation-oriented focus. MI is a global initiative of 23 countries[9] and the EU with the aim of making clean energy technology widely affordable. It was announced on November 30, 2015 at UNFCCC COP 21. Over a period of five years, MI members seek to double their R&D investments in clean energy. MI tries to encourage private investors to commercialize the early-stage clean energy technologies that emerge

[9] The Governments of Australia, Austria, Brazil, Canada, Chile, China, Denmark, Finland, France, Germany, India, Indonesia, Italy, Japan, Mexico, Netherlands, Norway, Republic of Korea, Saudi Arabia, Sweden, the United Kingdom of Great Britain and Northern Ireland, the United Arab Emirates, and the United States of America.

from government R&D programs. MI members also provide, annually, information on their clean energy RD&D efforts so as to promote transparency, to help identify collaborative opportunities and help improve the investment decisions of the private sector (Mission Innovation, 2015, 2019a; Sanchez & Sivaram, 2017).

The MI members build roadmaps and tools to help understand where research, development and demonstration (RD&D) is happening, where gaps and opportunities exist, and how RD&D can be accelerated. They pursue joint research among themselves and/or through public-private partnerships. MI has partnered with the World Economic Forum to facilitate engagement between leading businesses and MI members. The collaboration brings together the private sector's business expertise and the public sector's strategic clean energy research investments. MI members cooperate on eight innovation challenges, on: smart grids, off-grid access to electricity, carbon capture, sustainable biofuels, converting sunlight, clean energy materials, affordable heating and cooling of buildings, and renewable and clean hydrogen. The innovation challenges are aimed at accelerating RD&D in the selected clean energy technology areas, as global calls to action (Mission Innovation, 2015, 2019a).

5.2.6. Breakthrough Energy Coalition (BEC) and Breakthrough Energy Ventures (BEV)

The Breakthrough Energy Coalition (BEC) was launched at UNFCCC COP 21 alongside MI. It is a group of investors that seeks to drive clean energy innovation by investing in early-stage technology development. The investors are financial institutions with large amounts of capital to finance large projects, global corporations that produce/consume large amounts of energy, and private investors who can take risks and are patient (Breakthrough Energy, 2019b). Breakthrough Energy Ventures is a patient and flexible investment fund to bring clean energy innovations that have the potential to significantly reduce greenhouse gas emissions to the market faster (Breakthrough Energy, 2019c). In December 2017, the BEC announced pilot partnerships with five MI members. This represents a new way of engaging in public-private partnerships to catalyse more investment (Mission Innovation, 2019b). It invests in new clean energy technologies related to electricity, transportation, agriculture, manufacturing and buildings (Breakthrough Energy, 2016). The Bill & Melinda Gates Foundation is part of Breakthrough Energy Ventures. It is funding innovations related to climate change mitigation and adaptation, such as climate smart agriculture technologies and clean energy technologies (Cheney, 2018; Gates, 2016). Other Breakthrough Energy Ventures investors are for example the Laura & John Arnold Foundation, The Children's Investment Fund, Richard Branson, founder of Virgin Group, and Michael Bloomberg, CEO of Bloomberg (Breakthrough Energy, 2019a).

5.2.7. Group of 20 (G20)

A G20 call for the phase-out of inefficient fossil fuel subsidies dates back to the 2009 summit in Pittsburgh (Dubash & Florini, 2011). Various scholars have called for a stronger role of the G20 in

global energy governance (Goldthau, 2017; Roehrkasten, Thielges, & Quitzow, 2016). Since 2017, the G20 seems to be more active in the area. In that year, the German G20 Presidency emphasised the topic of energy transition (University of Toronto, 2018).

At the 2018 G20 summit in Argentina, Energy Ministers met to promote the role of energy to support sustainable development. The Argentinian G20 Presidency advanced work on topics like energy transitions, energy efficiency, renewable energy and energy access. In the G20 Energy Ministers Communiqué of 15 June 2018, the G20 Energy Ministers state that they are committed to lowering greenhouse gas emissions by means of increasing innovation on clean energy systems, and that they are supportive of energy transitions. They consider innovation a key driver of the transitions process and declare that they "will encourage and facilitate research, development demonstration and deployment (RDD&D) of innovative, cleaner and efficient energy technologies". They also aim to "encourage greater cooperation in developing, sharing and applying best available technologies, and […] encourage multilateral development banks and finance institutions to facilitate investment, and technology transfer" (University of Toronto, 2018) .

In February 2019 the G20 Energy Transitions Working Group (ETWG) held its first meeting. The ETWG focused among others on innovation possibilities in the energy sector. Greater energy data transparency was also addressed. Technologies discussed were, among others, liquified natural gas and other new gas technologies, renewables and storage technologies, and cleaner use of fossil fuels. In June 2019, the first joint energy and environment ministers meeting on Energy Transitions and Global Environment for Sustainable Growth will take place under the Japanese G20 Presidency (International Energy Forum, 2019).

5.2.8.Clean Energy Ministerial (CEM)

The Clean Energy Ministerial (CEM) is a high-level forum that aims to accelerate the transition to a global clean energy future. Its members are 25 countries (Australia, Brazil, Canada, Chile, China, Denmark, Finland, France, Germany, India, Indonesia, Italy, Japan, Korea, Mexico, Netherlands, Norway, Russia, Saudi Arabia, South Africa, Spain, Sweden, United Arab Emirates, the UK and US) and the European Commission. The CEM promotes policies and programmes that advance clean energy technology and shares lessons learned and best practices. It focuses on three policy goals: improving energy efficiency, enhancing clean energy supply, and expanding clean energy access. Its three main activities are: first, policy dialogue at ministerial meetings (annually, since 2010) to accelerate the pace with which clean energy policies are adopted; second, public-private partnerships to encourage industry, government and civil society to cooperate globally; and third, clean energy initiatives and campaigns that are action-driven, with the aim to increase the deployment of clean energy technologies and policies (Clean Energy Ministerial, 2019c).

There are CEM initiatives on: power system transformation, efficient equipment and appliances, carbon capture, utilization and storage, clean energy policy, electric vehicles, lighting and energy access, energy interconnections, energy management, investment and finance, nuclear innovation, smart grids, solar and wind energy, sustainable cities and towns, and women in energy (Clean Energy Ministerial, 2019b). There are (short-term) CEM campaigns on: power system flexibility, distributed generation in strategic regions, scenarios for the energy transition, gender diversity and women in the clean energy sector, nearly zero energy buildings, lighting, electric vehicles, energy management, renewables, power plant flexibility, and cooling (Clean Energy Ministerial, 2019a).

5.2.9. International Renewable Energy Agency (IRENA)

IRENA deals exclusively with renewable energy governance. It is an intergovernmental organisation that aims to support countries in their transition to a sustainable energy future. It also serves as a platform for international cooperation, hosting various initiatives and facilitating projects, and as a repository of knowledge on renewable energy related to policies, technology (including quality, standards and patents) and finance (IRENA, 2019a). IRENA has established several international initiatives: clean energy corridors, a coalition for action (to promote renewable energy uptake), the global geothermal alliance, a parliamentary network, renewable energy roadmaps (focusing on finding possible technology pathways for renewable power, heating, cooling and transport), renewables readiness assessments (a country-led collaborative tool to scale up renewable energy in a particular country by bringing various stakeholders together), and SIDS lighthouses (a framework that supports small island developing states to transform to a renewables-based energy system) (IRENA, 2019a). In March 2019, there were 160 IRENA members (countries and the European Union) and 23 states in accession (IRENA, 2019c). IRENA was founded in 2009 (IRENA, 2019b).

Müller (2016, p. 252) states that IRENA has become a "leading political entrepreneur" on renewable energy by building a global knowledge base on the topic "to exert power over knowledge". Key IRENA publications are its comprehensive renewable energy statistics and technology specific roadmaps. Another key tool is the renewable readiness assessments for countries in which IRENA brings together national entities (ministries, regional entities, financial institutions, as well as corporate and civil society stakeholders) and sends transnational knowledge brokers to the country to identify gaps in the existing technological and administrative environment and develop concrete action plans to overcome these gaps (Müller, 2016). IRENA also developed several relevant regional initiatives, such as the Africa Clean Energy Corridor (ACEC), the Clean Energy Corridor for Central America (CECCA), the West Africa Clean Energy Corridor (WACEC) and the Small Island Developing States (SIDS) Lighthouse Initiative.

IRENA also provides access to funding for projects and assists with finding investors. It has created several platforms to support the roll-out of renewable energy technology projects. Those are: the IRENA/ Abu Dhabi Fund for Development (ADFD) Project Facility (a joint financing facility for devel-

oping countries), the IRENA sustainable energy marketplace (a virtual platform to connect project owners, investors, services providers and technology suppliers), the IRENA project navigator (to provide practical guidance to assist the development of projects), and the IRENA global atlas (an online geographic information platform that maps data and assesses resources on renewables) (IRENA, 2019d).

5.2.10. Global Environment Facility (GEF)

The GEF provides funding to climate technology development and transfer activities through the UNFCCC Poznan strategic program on technology transfer. Supported developing countries are enabled to undertake technology needs assessments, develop technology pilot projects, and implement climate technology projects. The GEF provides support to the UNFCCC's climate technology centre and network (CTCN) and public-private partnerships too (UNFCCC, 2019a). In 2018, the GEF made clear that in GEF-7, the seventh replenishment (of financial contributions by donor countries) cycle from 2018 until 2022, "partnership[s] with the private sector to promote technology innovation and deployment will be a key priority" and that "investments in the energy sector for climate change mitigation will focus on continuing to promote innovation for sustainable energy breakthroughs in four key areas: decentralized renewable power with energy storage; electric drive technologies and electric mobility; accelerating energy efficiency adoption; and cleantech innovation" (GEF, 2018).

In addition, the GEF, together with UNIDO and Cleantech Open, has set up a Global Cleantech Innovation Programme (GCIP) for Small and Medium-sized Enterprises (SMEs). The aim of the programme is to enhance cleantech start-ups in the participating developing countries and to enhance the local ecosystem and policy framework for entrepreneurship. Participating countries are: South Africa (the first country to join after a successful pilot in 2011), Malaysia, Armenia and India, Pakistan, Thailand, Turkey and Morocco. The programme focuses on seven specific technology groups: renewable energy, energy efficiency, chemicals and advanced materials, waste, water efficiency, green buildings, transportation (Cleantech Open, 2013; UNIDO, 2019a, 2019b).

5.2.11. Major Economies Forum on Energy and Climate (MEF)

US President Barack Obama launched the MEF on Energy and Climate 28 March 2009. It was an initiative of the US State Department. It was intended to facilitate dialogue among key developed and developing countries to achieve successful outcomes in the UNFCCC, in the first place at COP 15 in Copenhagen in December 2009. The MEF had 17 participating members, namely: Australia, Brazil, Canada, China, the EU, France, Germany, India, Indonesia, Italy, Japan, Korea, Mexico, Russia, South Africa, the UK and the US. Denmark, as the Presidency of UNFCCC COP 15, and the UN were invited too. It met regularly (a few times a year) until the 2015 UNFCCC COP 21 negotiations in Paris (U.S. Department of State, 2017).

In 2009, the MEF developed a portfolio of 10 Technology Action Plans (TAPs) to advance global co-operation on clean energy technologies. The TAPs identified measures that advance innovation, facilitate information sharing, and accelerate deployment. They identified measures and opportunities for both individual countries and collaborative action across countries. The TAPs covered advanced vehicles, bio-energy, building energy efficiency, carbon capture and storage, high efficiency and low emissions coal, industrial energy efficiency, marine energy, smart grids, solar energy, and wind energy (MEF, 2009).

5.2.12. United Nations Industrial Development Organization (UNIDO)

UNIDO is the UN's specialised agency for industrial development (to reduce poverty), inclusive globalisation and environmental sustainability (UNIDO, 2019e). In 2018, UNIDO had 168 member states. Its mission is to "promote and accelerate inclusive and sustainable industrial development" in its member states (UNIDO, 2019e). UNIDO's four programmatic priorities are: "creating shared prosperity, advancing economic competitiveness, safeguarding the environment, and strengthening knowledge and institutions." Its four enabling functions are: "(i) technical cooperation; (ii) analytical and research functions and policy advisory services; (iii) normative functions and standards and quality-related activities; and (iv) convening partnerships for knowledge transfer, networking and industrial cooperation" (UNIDO, 2019e).

Over time, UNIDO's programs have targeted industrial energy efficiency including policy and development standards, capacity building, training and awareness-raising, technology demonstration and upscaling (Matteini, 2015). UNIDO has also set up knowledge sharing platforms for its member states, such as the Vienna Energy Forum (VEF) (UNIDO, 2019c). Examples of UNIDO projects are: global agribusiness development, the Low Carbon Low Emission Clean Energy Technology Transfer (LCET) programme – which involved the deployment of technologies like micro hydropower, solar energy and waste-to-energy in Africa (UNIDO, 2014) –, and the ECOWAS regional centre for renewable energy and energy efficiency (ECREEE) (UNIDO, 2019d). With regard to the environment, UNIDO focuses on three topics: resource-efficient and low-carbon industrial production, clean energy access for productive use, and implementation of multilateral environmental agreements (UNIDO, 2019c).

5.2.13. Low Carbon Technology Partnership initiative (LCTPi)

Led by the World Business Council for Sustainable Development (WBCSD), the Low Carbon Technology Partnerships initiative (LCTPi) consists of more than 200 companies (e.g. the Coca Cola Company, ENGIE, Ernst & Young, Michelin, Siemens, Starbucks, Statoil, Unilever) and (coalition and implementation) partners (e.g. Clean Energy Ministerial, SE4ALL, UNEP, World Bank) that are committed to accelerating the transition to a low-carbon economy. It was launched in 2015 at UNFCCC COP 21 in Paris. LCTPi offers a collaborative platform for businesses and policymakers to scale up deployment of business solutions to a level and speed consistent with limiting global warming to below 2°C.

LCTPi manages six key projects: REscale (renewable energy), Climate Smart Agriculture, Natural Climate Solutions (forestry and land use), Emobility, Transforming Heavy Transport (freight and logistics operations via air, sea and land) and New Energy Solutions (to decarbonise the energy system). It focuses on research, development, demonstration and deployment. For some technologies/sectors it focuses on deployment only (namely renewables, buildings and climate smart agriculture), while for others it focuses on RD&D (namely CCS, chemicals and cement). It also engages in training and capacity building and finance through various initiatives and has developed platforms for stakeholder engagement (WBCSD, 2019a).

5.2.14. Cement Sustainability Initiative (CSI)

The Cement Sustainability Initiative (CSI) is a transnational sustainability programme by major cement producers. It is comprised of 24 such producers, which are active in more than 100 countries and account for around 30 percent of the world's cement production (WBCSD, 2012). CSI members plan to reduce their CO2 emissions by 20 to 25 percent by 2030 compared to business as usual (LCTPi, 2016). At the outset, CSI's main deliverables were: to develop a climate mitigation strategy, to develop relevant tools (integrated in projects) for the cement industry to reduce its emissions, and to share information on the emissions of their members, including targets and progress towards these targets. *Getting the Numbers Right* is a database that reports the CO2 emissions of the cement sector worldwide (WBCSD, 2016). On 1 January 2019, CSI's work was transferred from the World Business Council for Sustainable Development to the Global Cement & Concrete Association (WBCSD, 2019b).

CSI has also made efforts to create an action plan to enhance energy efficiency in the cement industry; to scale up the use of high quality alternative fuels and raw materials in the production process, including waste from other sectors; to reduce the clinker content in cement in order to minimise the energy intensive part of the production process; to develop new types of cement with reduced net CO2 emissions over their full life cycle; to engage the full value chain in minimising emissions; and to evaluate new green technologies such as carbon capture, sequestration and utilisation (CCSU). In 2009, CSI and the IEA together developed a cement industry technology roadmap, the first sector-specific report of its kind, which offered the industry a trajectory to halve its CO2 emissions by 2050 (House of Commons Environmental Audit Committee, 2013).

5.2.15. Transformative Urban Mobility Initiative (TUMI)

The German government launched the Transformative Urban Mobility Initiative (TUMI) in 2016. It brings together 11 institutions on sustainable mobility, including city networks and think tanks, such as the Asian Development Bank, UN-Habitat, ICLEI (the leading global network of cities, towns and regions), the World Resources Institute, C40 Cities, and GIZ (the German Development Agency). TUMI tries to modify policy and investment decisions in order to achieve sustainable urban mobility.

TUMI's main activities are: providing capacity building to developing country leaders and technical and financial assistance to support innovation. TUMI also supports 1 000 urban "changemakers" who plan and implement modern mobility concepts, and facilitates innovative pilot activities in cities worldwide. The German development bank KfW committed itself to providing USD 1 billion to sustainable urban transport projects via TUMI (TUMI, 2019).

5.2.16. Air Transport Action Group (ATAG)

The Air Transport Action Group (ATAG) is an association that brings all players in the global air transport industry together. Its aim is to promote the sustainable growth of the industry in order to benefit society globally (ATAG, 2019c). It has about 50 members. Its founding partners are: Airports Council International (ACI), Airbus, ATR, Boeing, Bombardier, Civil Air Navigation Services Organisation, CFM International, Embraer, GE, Honeywell Aerospace, International Air Transportation Association, Pratt & Whitney, Rolls-Royce, and Safran (ATAG, 2019c). It works among others on sustainable aviation fuels and stimulates industry collaboration (among others by organising a Global Sustainable Aviation Summit) to reduce aviation emissions in other ways. It pushes for the development and implementation of new technologies, of which cleaner fuels are an example (ATAG, 2019a). ATAG has also created a website that provides information on the measures that the aviation industry is implementing to reduce its impact on the environment (ATAG, 2019b).

5.3. Conclusions

5.3.1. Overview tables based on case studies

Overview Table 5 below shows which barriers the 17 studied international institutions in the area of climate technology/innovation address and which kind of value they add. The barriers to international technology and/or innovation cooperation included are: competition / anti-trust rules and the protection of Intellectual Property Rights (IPRs), lack of upfront information on cost-, risk- and benefit-sharing for both the public and the private sector, incompatible R&D conditions and a lack of agreement on the sharing of risks and/or costs by the private sector, political factors and a lack of necessity felt by the public sector to step in, etc. The value added of international technology and/or innovation cooperation included in Table 6 below is: pooling resources, sharing effort/risks, and providing access to specific technology/markets.

Table 5 Overview of Barriers Addressed and Value Added

Institution	Barrier addressed					Value added			
	Competition / anti-trust issues + IPR protection **(public. +private.)**	Lack of info on cost / risk / benefit sharing **(public + private)**	Incompatible R&D conditions **private sector** + lack of agreement on sharing of risks/costs **private sector**	Political barriers **(public)** + no clear **public sector** need felt to step in	Other **(public + private sectors)**	**Pooling resources**	**Sharing effort / risk**	**Providing access to tech / market**	**Other**
TEC		☑							☑ Info sharing (analysis, recommendations) Stakeholder engagement
CTCN		☑			☑ address technological barriers			☑	☑ Access to information, stakeholder collaboration
WIPO	☑ WIPO Green	☑		☑ policy forum to shape rules, dispute resolution				☑	☑ capacity-building, providing information, connecting tech supply and demand
WTO	☑ Negotiations on tariffs reduction								
MI		☑	☑	☑ involves national governments in rule setting, implementation		☑ via TCPs	☑ via collaboration platforms, TCPs	☑ via Low-Carbon Energy Tech Platform	☑ access to finance via TCP on climate technology (2003-17), tech analysis
BEC		☑	☑ address lack of financing from private sector in middle stage	☑					☑ double R&D investments ☑ involve private sector finance ☑ accelerate RD&D
G20			☑ address lack of investment in tech development (public.-private)	☑ address lack of investment in tech development (publ.-private)					☑ bring in patient and flexible investment for clean energy innovation = public-private

Institution	Barrier addressed					Value added			
	Competition / anti-trust issues + IPR protection (**public. +private.**)	Lack of info on cost / risk / benefit sharing (**public + private**)	Incompatible R&D conditions **private sector** + lack of agreement on sharing of risks/costs **private sector**	Political barriers (**public**) + no clear **public sector** need felt to step in	Other (**public + private sectors**)	**Pooling resources**	**Sharing effort / risk**	**Providing access to tech / market**	**Other**
CEM		☑ data transparency encouraged	☑ address lack of investment + tech transfer	☑ address lack of investment+ tech transfer					☑ encourage cooperation in developing, sharing and applying tech; facilitate investment and tech transfer; encourage energy data transparency
IRENA		☑	☑ address lack of public-private cooperation.	☑ address lack of public-private cooperation.		☑	☑	☑	☑ action-driven initiatives / campaigns to increase the deployment of tech and policies
GEF		☑	☑ address lack of public-private cooperation, lack of financing, lack of integrated action plans	☑ address lack of public-private cooperation, lack of financing, lack of integrated action plans		☑	☑	☑	☑ action-driven initiatives + platforms to increase the deployment of renewable energy tech and policies; repository of knowledge on tech, policy, and finance
MEF			☑ Address lack of funding for innovation and tech transfer + lack of partnerships with private sector	☑ Address lack of funding for innovation and tech transfer + lack of partnerships with private sector		☑ (for developing country)	☑ (for developing country)	☑ (for developing country)	☑ Cleantech Innovation Programme for SMEs in **developing countries**
		☑		☑		☑	☑	☑	☑ Facilitate information sharing
UNIDO		☑ (via knowledge sharing)	☑ address lack of standards, tech demonstration			☑ (focus on developing country)	☑ (focus on developing country)	☑ (focus on developing country)	☑ analysis and research, policy advisory, training, awareness raising and capacity building for developing countries

Institution	Barrier addressed					Value added			
	Competition / anti-trust issues + IPR protection (**public. +private.**)	Lack of info on cost / risk / benefit sharing (**public + private**)	Incompatible R&D conditions **private sector** + lack of agreement on sharing of risks/costs **private sector**	Political barriers (**public**) + no clear **public sector** need felt to step in	Other (**public + private sectors**)	**Pooling resources**	**Sharing effort / risk**	**Providing access to tech / market**	**Other**
LCTPi		☑ via platforms for business and policymaker interaction	☑ (for CCS, chemicals and cement)			☑	☑	☑	☑ also engages in training, capacity building and provides financing
CSI		☑ by means of cement sector cooperation	☑			☑ (in cement sector)	☑ (in cement sector)		☑ engaging the full value chain in minimising emissions; sharing emissions data; R&D efforts
TUMI				☑ barriers in developing country. to realise innovation in transport –> rules, capacity to lead, finance for pilot projects					☑ capacity building for developing country leaders; tech and financial assistance for innovation, including pilots
ATAG		☑ lack of coordination. of business players (here in aviation sector)				☑	☑		☑ sharing and publishing information on aviation sector efforts to reduce emissions

Note: Barriers to international technology and/or innovation cooperation (amongst others) are:

- *For both the public and the private sector - competition / anti-trust rules and the protection of Intellectual Property Rights (IPRs), lack of upfront information on cost-, risk- and benefit-sharing,*
- *For the private sector - incompatible R&D conditions and a lack of agreement on the sharing of risks and/or costs*
- *For the public sector: political factors and a lack of necessity felt by to step in/*

Table 6 Sectors Addressed. This table shows which sectors the 17 institutions address. The four sectors included are the power sector, the energy-intensive industries sector, the land transport sector, and the international transport (aviation) sector.

Institution	Power Sector	Energy-intensive industries	Land transport sector	International transport sector
TEC				
CTCN	☑	☑	☑	☑
WIPO Green	☑	☑	☑	☑
WTO				
IEA	☑	☑	☑	
MI	☑		☑ (sustainable biofuels, hydrogen)	
BEC	☑	☑	☑	☑
G20	☑			
CEM	☑		☑	
IRENA	☑		☑	
GEF	☑	☑	☑	
MEF	☑	☑	☑	
UNIDO	☑	☑	☑ (a few projects only)	
LCTPi	☑	☑	☑	☑
CSI		☑		
TUMI			☑	
ATAG				☑

Table 7 Needs Addressed. In terms of sectoral needs, we take into account the needs highlighted at the start of this section for RD&D (5x), market entry (ME) (3x) and market transformation (MT) (2x). This table shows which of these needs the 17 institutions address, and how.

	RDD1	RDD2	RDD3	RDD4	RDD5	ME1	ME2	ME3	MT1	MT2
TEC									☑ (Indirect – advises on legislation)	
CTCN									☑ (Creates access to info)	☑ (Tech advice + fosters collaboration)
WIPO					☑ WIPO Green helps over-come IPR issues	☑ WIPO Green supports market entry too				
WTO						☑ Tries to re-duce tariffs and trade barriers				
IEA			☑ Helps with research sharing + pilot plants, etc.					☑ Advises on tech + market instruments	☑ Advises on policies	☑ Advises on tech + market instruments
MI	☑ Aim to double public R&D invest-ment	☑	☑	☑						
BEC+ BEV	☑ private invest. in R&D	☑ Ibid.								
G20		☑ RD&D support (weak)				☑ Supports fin. institut. to play greater role (weak)				
CEM						☑ Promotes policies such as subsid.		☑ Tries to put right policies in place	☑ Ibid.	
IRENA						☑ Promotes policies for RE + helps with access to funding (joint fin. facility)		☑ Develops action plans	☑ Supports policy change + creates action plans	

	RDD1	RDD2	RDD3	RDD4	RDD5	ME1	ME2	ME3	MT1	MT2
GEF				☑ Funding for clean- tech development + pilots		☑ Funding for deployment of tech in develop-ing country		☑ Supports SMEs in develop-ing country		☑ Supports developing country with tech transfer
MEF								☑ Via Tech Action Plans (2009)		☑ Via Tech Action Plans (2009)
UNIDO				☑ Tech demon-stration support		☑ Via its tech transfer program for deployment		☑ Support for SMEs: enhance policies		☑ Support for SMEs: enhanc-ing policies
LCTPi				☑ Public-private support for RD&D		☑ Public-private support for deployment				
CSI		☑ Cement sector RD&D efforts								
TUMI				☑ Supports innov. pilot activit.		☑ Finance for innovative. tech.		☑ Tries to modify policy + investment. for sustainable urban mobility		☑ Tries to modify policy + investment. for sustainable. urban mobility.
ATAG		☑ R&D for sust. aviation fuels							☑ Tries to promote sus-tainable sectoral policies	

Table Key					
Sectoral needs in the RD&D category.		**Sectoral needs for market entry (ME)**		**Sectoral needs for market transformation (MT)**	
RDD1	public R&D expenditure to help generate private R&D investments	ME1	financial or fiscal support for new technologies to compete (e.g. subsidies for renewables, electric vehicles, …)	MT1	sectoral or economy-wide legislation that forces the uptake of (mature) clean technologies (e.g. emission standards, CO_2 price, subsidies, ….)
RDD2	dedicated R&D into cleantech including the innovation ecosystem (research, technology providers, companies, public sector, …)	ME2	public procurement for innovation (e.g. environmental targets in tendering criteria for infrastructure)	MT2	facilitation of the roll out of supporting infrastructure
RDD3	dedicated R&D agencies with focus on cleantech and innovation missions	ME3	public sector assistance with setting up infrastructure for new technologies (e.g. charging stations for electric vehicles)		
RDD4	public sector support of / participation in risk sharing to bring basic R&D to demonstration level				
RDD5	an advantageous fiscal regime for private R&D in cleantech innovation				

5.3.2. Conclusion on how international institutions address barriers and offer value added

With regard to **barriers addressed**, we find that out of the 17 institutions we selected, only the WTO to a limited extent tries to address barriers related to competition and anti-trust issues, and only WIPO, via WIPO Green, tries to address the issue of IPR protection. Lack of information on cost, risk and/or benefit sharing is addressed by no less than 13 out of 17 institutions. This is the barrier that the institutions we analysed in this section address most. Incompatible R&D conditions and/or a lack of agreement on sharing costs or risks in the private sector are addressed by 10 out of the 17 institutions studied in this section. The same number of institutions addresses political barriers and the lack of a public sector feeling of necessity to act. One other type of barrier we found, addressed by the CTCN, is: technical problems on the road to diffusion of new technologies in developing countries (CTCN). On the basis of these results we can argue that the 17 institutions together address all barriers quite well, except for the competition and IPR barrier.

With regard to **value added**, we find that 9 institutions help with pooling resources, with sharing effort/risk, and with providing access to technology and/or the market, and all institutions except the WTO (= 16) add value in other ways too. These other ways are: sharing information (analysis, recommendations) and engaging stakeholders (TEC), providing access to information and making stakeholders collaborate (CTCN), providing capacity-building, information, connecting technology supply and demand (WIPO), providing access to finance via TCPs on climate technology (2003-17) and providing technology analysis (IEA), doubling R&D investments, involving private sector finance and accelerating RD&D (MI), bringing in patient and flexible investment for clean energy innovation (public-private) (BEC), encouraging cooperation in developing, sharing and applying technology, facilitating technology transfer, and encouraging energy data transparency (G20), organising action-driven initiatives and campaigns to increase the deployment of technology and policies (CEM), preparing action-drive initiatives and platforms to increase the deployment of renewable energy technology and policies, and providing a repository of knowledge on technology, policy and finance (IRENA), supporting a Cleantech Innovation Programme for SMEs in developing countries (GEF), facilitating information sharing (MEF), providing analysis and research, policy advisory, training, awareness raising and capacity building for developing countries (UNIDO), engaging the full value chain in minimising emissions, sharing emissions data, and R&D efforts (CSI), providing capacity building for developing country leaders, and technological and financial assistance for innovation (including pilot projects) (TUMI), engaging in training, capacity building and providing financing (LCTPi), and sharing and publishing information on the aviation sector's efforts to reduce emissions (ATAG).

With regard to the **sectors addressed** by the 17 institutions we studied, we found that, on the one hand, three institutions address all four sectors we selected, namely the CTCN, WIPO Green, and the LCTPi. On the other hand, the WTO and TEC do not address any of the four sectors (albeit the WTO has implications for the sectors), and CSI, TUMI, ATAG (the three sectoral institutions) and the G20 address one

sector only. Of the sectors we looked at, most of the 17 institutions focus on the power sector and the land transport sector (12x). Nine institutions focus on the energy intensive industries sector. The least addressed sector of the four is the international transport sector (by 4 out of the 17 institutions only). This latter sector deserves more attention from international governance.

In terms of **sectoral needs**, we took into account the needs highlighted at the start of this section for RD&D (5x), market entry (ME) (3x) and market transformation (MT) (2x). Table 4 above shows that the 17 institutions address the needs on RD&D, ME and MT relatively equally: they addressed RD&D needs 11 times, ME needs 11 times, and MT needs 10 times. If we look at the 10 needs individually, then we see that 'using public procurement for innovation' in the ME category is not addressed by any of the 17 institutions. The need to create an advantageous fiscal regime for private R&D in cleantech innovation in the RD&D category is only addressed once (by WIPO), and the need for public/private R&D expenditure and for dedicated R&D agencies is addressed by two institutions each only (MIC and BEC+ BEV and IEA and MI respectively). The other needs are addressed by 5[10], 6[11], 7[12] or 9 institutions. The highest score of 9 belongs to the need for financial/fiscal support for new technologies to compete in the ME category (WIPO, WTO, G20, CEM, IRENA, GEF, UNIDO, LCTPi and TUMI). A highest score of 9 institutions addressing the need out of a total of 17 institutions is rather low. In addition, some of the institutions try to address a need and only manage to do so in an indirect or weak manner, which is not effective enough. On the basis of these findings we can conclude that the 17 institutions do not address the various sectoral needs that we selected to a high/sufficient degree. In particular, the need to use public procurement for innovation, the need to create an advantageous fiscal regime for private R&D in cleantech innovation, the need for public/private R&D expenditure, and the need for dedicated R&D agencies could be addressed more by the institutions.

6. Options and priorities for the European Union (and its member states) for unilateral, bilateral and multilateral low-carbon technology development and diffusion

6.1. Domestic technology and innovation policies

For the EU the main innovation-related priorities do relate to addressing the sectoral innovation needs (chapter 3), given that deep greenhouse gas mitigation in these sectors will be essential to meet the long-term greenhouse gas target of the EU and its Member States . However, these priorities need to be

[10] Dedicated R&D into cleantech including the innovation ecosystem is addressed by MI, BEC+BEV, G20, CSI and ATAG.
[11] Sectoral or economy-wide legislation that forces the uptake of (mature) clean technologies is addressed by TEC, CTCN, IEA, CEM, IRENA, and ATAG.
Facilitation of the roll out of supporting infrastructure is addressed by CTCN, IEA, GEF, MEF, UNIDO, and TUMI.
[12] Public sector assistance with setting up infrastructure for new technologies is addressed by IEA, CEM, IRENA, GEF, MEF, UNIDO and TUMI.

seen in the broader context of how low-carbon technology development can generate economic co-benefits such as technological leadership and export markets of EU technologies and know-how. The three important challenges, that differ between sectors, as mentioned in chapter 3 are:

- Accelerating the deployment and hence technology learning curves (incremental innovation) of mature technologies.
- Enabling key technologies to cross the 'valley of death' towards demonstration and commercialisation.
- Aligning supply and demand side innovations to enable systemic changes in the economy that assist with economy-wide transition to net-zero emissions.

Mature technologies such as solar (PV) and wind-energy will likely see further cost reductions due to increased deployment and hence the benefit of technology learning curves and incremental innovation. For the EU it will be important to further facilitate the deployment of these technologies in order to benefit from lower costs down the road. Securing a growing domestic market for climate friendly technologies will be important for EU-based companies that are involved in the construction, exploitation, maintenance and R&D of these technologies because it gives them access to a local growing market which is an important factor in industrial growth. A strong domestic industry in this area increases the likelihood of EU companies gaining market share in markets outside of the EU and reduces the risk of becoming dependent on technologies and know-how developed outside of the EU (Lund, 2009). Hence supporting further deployment of climate friendly technologies in the EU should be seen as part of an industrial strategy.

For some sectors, in particular the energy- and material-intensive industries, the priority will be to develop and more importantly demonstrate the commercial viability of new climate-friendly technologies. This implies focused and adequate R&D support for technologies that need to cross the 'valley of death' towards demonstration and commercialization. Sectors with longer investment cycles (e.g. steel, cement and chemicals) will need to see the most promising breakthroughs reach the commercialization stage over the next decade to allow for wide scale deployment between 2030 and 2050 and hence an adequate contribution to an economy-wide net-zero emissions goal by 2050.

The third challenge, 'aligning supply- and demand-side innovations to enable systemic changes', is more complex and consists of diverse groups of technologies along the same or different value chains. For instance, an increased deployment of variable renewable energies will be increasingly matched by new demand-side technologies and services such as storage of energy and demand-side management. It will also require improvements in current electricity infrastructure and intelligent grid management. For basic materials production it is similarly essential to enable deeper connections to the value chains for achieving material use efficiency gains and circular material use. Net zero emissions in materials production will furthermore require infrastructure for e.g. carbon capture and storage or utilization, new

zero-emissions energy carriers such as renewable electricity, hydrogen and biomass. Innovations that allow better linking of material, energy and waste flows between companies, industrial sectors and other parts of the economy will also be critical vis-à-vis achieving cost-effective deep greenhouse gas reductions. The advanced use of digital technologies (e.g. distributed ledger technologies) will be enabling factor in the establishment of new business models, for instance related to circular materials use or delivering materials as a service. Finally, also in the transport sector such an integrated approach to innovation will be essential. Electric vehicles will have to be integrated in a zero-CO2 electricity system, which will require adequate charging infrastructure but also the possibility of battery electric vehicles to deliver power to the grid. EU innovation support for electric mobility should continue to focus on key parts of the value chain, in particular development and production of battery technologies in order to to keep up with other parts of the world that have more advanced battery industries. Further innovation in digitization will be important for the transition of mobility. This relates to advancing self-driving vehicles but more importantly the development of mobility as a service, as opposed to e.g. car-ownership, to maximize efficient use of public transport infrastructure.

Addressing the above-mentioned (mission-oriented) challenges will require that the traditional market failure justification for policy intervention be complemented with a more active market creating justification. According to Mazzucato (Mazzucato, 2015) the market failure framework is problematic for addressing societal challenges. It cannot explain and justify the kinds of transformative mission-oriented investments that in the past picked directions, coordinated public and private initiatives, built new networks, and drove the entire techno-economic process, which resulted in the creation of new markets, not just in the fixing of existing ones. The market failure approach is hence more useful for describing a steady-state situation in which public policy aims to put patches on existing development trajectories provided by markets, but not to dynamically create and shape new trajectories, such as achieving net-zero greenhouse gas emissions over a period of 30 years.

How can the EU move towards such a market-shaping and mission-oriented innovation framework? The following elements can be considered in this regard (Reinaud, 2016, Wyns et al, 2019, Material Economics, 2019):

- Providing long-term clarity in terms of the direction which innovation should move
- Setting of integrated policy priorities
- Using a broader set of innovation instruments to bridge the innovation valley of death and for the creation of lead markets for new products and/or services
- Providing infrastructure for and directing finance towards transformational technologies or practices
- Implementing innovation along value chain, including the creation of new value chains, in particular to promote materials efficiency and circularity

- Accelerating coordination with local and national authorities
- Develop and integrated governance system

The public sector can provide a clear direction in which the actors involved in innovation should move. This can be achieved by fixing medium or long-term targets but also by defining innovation missions (e.g. climate-neutral steel production) (Mazzucato, 2015, Mazzucato, 2018). This commitment by the public sector implies adequate and long-term support to e.g. research institutes and the private sector responsible for implementing such innovation missions.

Setting integrated priorities in policy making will be important to cover the broader innovation value chain and to avoid policy conflicts (Reinaud et al., 2016). For instance, expected electrification of transport and of industrial processes will need to be integrated or coupled with the transition to renewable energy sources (Wyns et al., 2019). It is also relevant to consider greenhouse gas mitigation actions and necessary innovation across key value chains by avoiding overly narrow sectoral innovation goals (Material Economics, 2019). For instance, by including end-of-life emissions of products within the scope of primary production innovation. Finally, other policy areas that are often at the core of greenhouse gas mitigation can be integrated and streamlined furhter from an industrial policy perspective. This can for instance be integration of enhancing industrial competitiveness with climate and trade (Reinaud et al., 2016) e.g. as part of future free trade and investment agreements or existing trade defence instruments.

Innovation instruments will need to be aligned better and where needed new instruments should be deployed. While supporting basic R&D has been an important role of the public sector, a large-scale economic transition such as drastically reducing greenhouse gas emissions will require innovation policies beyond but aligned with basic research (Mazzucato, 2018). This can include financing instruments (such as the new EU Emissions Trading System (ETS) innovation fund (European Commission, N.D., e) or the European Investment Bank's (EIB) innovfin (EIB, N.D.,)) that help innovations bridge the 'valley of death' towards large scale demonstration and commercialization. But equally important is ensuring a streamlined innovation system that covers the whole innovation process from invention to market. In this context it will be important to also develop or use market-pull innovation instruments that allow the creation of lead markets for climate friendly processes and products.

Further innovation (risk sharing) instruments to finance large-scale demonstration installations and create lead markets (market pull) for new products and services (Reinaud et al. 2016). The instruments to achieve the latter include (green) public procurement, the use of standards (or adjustment of existing standards to allow new products market entry) (Wyns et al. 2019).

Embedding sectoral innovations (e.g. in industry or transport sector) will need a public investment programme that finances or facilitates financing for supporting infrastructure. Hence, the EU and its

member states will need to link sectoral innovation with infrastructure needs, map these and roll out a long-term programme to roll them out. This will require the use of existing EU wide (and national) financing institutions such as the EIB (Material Economics, 2019, Wyns et al. 2019).

The supply- and demand-side innovations must be linked by implementing climate friendly innovations along the value chains. This can include the creation of new value chains and related business models. In particular in the areas of materials efficiency and circular economy this approach will be important. Excluding the value chains from climate-friendly innovations risks leaving the necessary technological breakthroughs solely with incumbent producers which can lead to a lock-in into existing processes using more expensive mitigation technologies as opposed to value chain innovations which can use a broader spectrum of actions. (Material Economics, 2019)

Innovation and industrial policies are not a unique EU competence. These areas are also covered by national (and subnational) competences and instruments (e.g. R&D tax breaks). It is hence important for the EU to align its innovation missions and implementing actions with those of the national and local authorities (Wyns et al., 2019). This can include technical and regulatory assistance and knowledge and best practice sharing. Furthermore, the early stage design of new EU innovation frameworks should be coordinated and aligned with national innovation systems as to allow for different programmes to maximise possible synergies (Reinaud et al., 2016).

Finally, given that the previous elements touch upon much more than pure innovation instruments (e.g. finance, regulation, infrastructure), and upon competences shared between the EU and its Member States, it is necessary to provide more integrated and coherent governance. This would allow for fostering collaboration between different levels of governance and pooling of resources through co-financing. It will also help coordination of different competences beyond innovation but necessary to successfully bring innovations to the market and enhance the consistency and effectiveness of instruments. Finally, new monitoring instruments such as innovation dashboards that use metrics to assess the state of innovation missions and broader (socio-economic and environmental) goals that are set out. These can help with timely adjustments of instruments that are underperforming (Wyns et al. 2019, Reinaud et al., 2016).

6.2. Options to enhance the EU's international technology and innovation framework

Next to enhancing domestic innovation and technology policies for climate change mitigation, the EU can also further instruments and policies that have an impact beyond its borders. To outline possible elements of an international climate innovation strategy for the EU, first the main drivers to further engagement in this area will be explored. Next some boundary conditions or criteria are put forward for the EU to engage while minimising the risk of losing economic competitiveness or how higher levels of EU engagement in international climate innovation can be a benefit for the EU itself.

Generally speaking, the main principles for setting out an international collaboration strategy on science and technology should be based on an assessment that contains elements that are directly in the specific domestic (economic) interest of the EU itself but also indirectly, by helping the EU advance on its interests in a global context.

International science and technology cooperation can help the EU by accessing complementary scientific and innovative strengths that currently lie outside the EU. This can be important in the area of battery research and applications thereof in the automotive sector, where the EU is lagging behind compared to other parts of the world (Beuse, et al., 2018). This is especially important if there are important gaps in the EU's technology competences. Furthermore, such enhanced international cooperation can lead to further economic valorization through better access to global markets and infrastructures. Strengthening the EU's technological capacity through international cooperation can hence help improve its competitiveness. Strengthening R&D cooperation involves ensuring that Europe is attractive as a region for lead markets, pilots and demonstration, infrastructure for testing and technology verification (Schwaag Serger and Remoe, 2012).

Beyond the direct economic benefits that might arise from enhanced international science and technology cooperation, the EU can use it as a means to reach other policy ends in an international context. Ensuring that the world addresses global challenges such as climate change adequately is an important example of such a policy end. In particular, in the context of the Paris Agreement where actions by countries are nationally determined a focus on stronger bilateral and multilateral cooperation on R&D can help accelerate national climate action through better access to (better) technologies or by making technologies cheaper. This is in particular relevant for developing countries with lower science and technology capabilities. The EU can use its enhanced role in such cooperation to create better and stable diplomatic relationships and hence have more diplomatic leverage within international climate negotiations (Boekholt, P., Cunningham, P., Edler, J., Flanagan, K. , 2009).

However, higher levels of international engagement on R&D by the EU can pose risks. Countries not engaging in ambitious climate policies might use the ensuing R&D benefits to create a bigger competitive advantage e.g. through the use of more efficient technologies, thereby closing technology gaps while still avoiding stricter climate regulations. This could further erode the EU's competitive edge in some areas. There is also a risk that EU-funded intellectual property gets diffused without honouring licensing agreements, for example, and hence creates economic leakage out of the EU.

These risks can be minimized by considering the following actions. The EU can take the lead in key projects addressing some of the grand societal challenges relevant to addressing climate change such as chemical recycling of plastics to avoid plastic waste in the natural environment while reducing greenhouse gas emissions at the same time, where a global effort is beneficial for everyone or challenges that need pre-competitive R&D and where IP issues might be less. The EU should furthermore look to

take leadership in international projects and platforms which aim to set global standards and norms (Negev et al., 2018). This would allow the EU's leadership in certain clean technologies to take advantage of possible market opportunities that arise from the introduction of bi-lateral or multilateral agreements on standards and norms. It would also allow the EU to have a stronger influence in regulatory areas linked to these standards. The EU can in this context continue to advocate for a harmonization of international rules and practices related to intellectual property rights or at least in international R&D projects and programs where the EU takes up a leading role (e.g. through financing). Finally, the EU can consider strengthening the strategic link between international R&D cooperation and trade e.g. by requesting reciprocity in access to public procurement and by striving to the removal of trade barriers for climate friendly products (Schwaag Serger and Remoe, 2012).

What are the practical steps the EU can take to implement an international innovation strategy that both helps international climate change mitigation and assists the EU in achieving its domestic climate goals while preserving or enhancing its international competitiveness?

First of all, the EU can mainstream (forthcoming) mission-oriented innovation (i.e. innovation tackling grand challenges) into its international R&D programmes. The strategic use of these programmes should be informed by internal auditing of the EU's science and technology strengths, weaknesses and possible innovation gaps. The EU could hence better design its bilateral cooperation and involvement in international partnerships based on where these initiatives can benefit the EU's R&D environment. The assessment must also address innovation from basic R&D to commercialization to see if technologies at lower TRL can be scaled up with EU support or vice versa where EU research at lower TRL levels can be easier deployed towards higher levels or bigger scale outside the EU. The EU can also link its domestic R&D support to requirements or restrictions on the use of EU-funded IPR outside the EU. For instance, EU-funded R&D and resulting IPR cannot be used or commercialised outside the EU unless there is a bilateral agreement in which partner countries promise to apply specific standards and regulations (to avoid competing against the EU with EU funded technology) and by strict adherence to IPR and licensing rules.

Furthermore, the EU can be more opportunistic in getting access to the best research(ers) in the world by making Horizon Europe open to participation for non-EU institutions and researchers, in partnership with EU research institutions. This would allow EU researchers to work with the best brains in the world, wherever they are located and hence facilitate knowledge transfer to the EU (Schwaag Serger and Remoe, 2012).

Finally, international cooperation on climate friendly R&D can be used more strategically by using a variable geometry in bi-lateral and multilateral cooperation. Hence, prioritise working with partners that share the same or similar political goals towards dealing with climate change or use the differentiation as an instrument to strengthen diplomatic links in the areas of energy- and climate transition (Schwaag

Serger and Remoe, 2012). The EU's climate technology cooperation could hence, next to climate finance, become a more political instrument in the EU's external relations.

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