Chapter 16: Innovation, technology development and transfer

Coordinating Lead Authors: Gabriel Blanco (Argentina), Taishi Sugiyama (Japan)

Lead Authors: Lawrence Agbemabiese (Ghana/USA), Heleen de Coninck (The Netherlands), El Hadji Mbaye Diagne (Senegal), Laura Diaz Anadon (Spain/UK), Yun Seng Lim (Malaysia), Elena Verdolini (Italy), Jan Witajewski-Baltvilks (Poland)

Contributing Authors: Clara Galeazzi (Argentina), Eriko Kiriyama (Japan), Karolina Safarzynska (Poland)

Review Editors: Nagmeldin Mahmoud (Sudan), Emi Mizuno (Japan)

Chapter Scientists: Muneki Adachi (Japan), Daniela Keesler (Argentina)

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Executive summary

Technology is an integral part of the mitigation of climate change. Since the AR5, disruptive technological innovations have flourished, with the progress of digital technology as the major driver; the changes have influenced all economic sectors worldwide. On the other hand, technology may cause problems too, both social and environmental {16.1}.

This chapter assesses innovation and technological changes in a broad framework, discussing the benefits and hassles of the development and implementation of new technologies aimed at the mitigation of and adaptation to climate change.

What technologies are used, but also how they are used may create social and environmental impacts; whether the consequences are positive or negative will also depend on the context and how policy intervenes *[placeholder uncertainty language]*. In fact, technologies can exacerbate or moderate social and environmental impacts of human activity. Technological development can be explained as both a source and remedy of environmental change {16.2}.

Consequences of technological change include impacts on the labour market and unemployment rates, on soil yields and productivity, on competitiveness and trade, and on distribution of wealth {16.2.1}. These unintended effects require a better understanding in order to reduce the risk of potential responses to climate change {16.2.1.6}.

One of the unintended effects of technological changes, at least in relation to energy efficiency technologies, is the so-called "rebound effect" that occur at different levels of the economy *[placeholder uncertainty language]*. This phenomenon shows that energy efficiency improvements are eroded due likely to a series of economic adjustments in production and consumption processes {16.2.1.4}.

The process of technological innovation must be understood as a process that takes place in "technological innovation systems," which can be thought of as the connected set of actors and institutions that shape innovation processes {16.3}. Processes underpinning innovation {16.3.1} include research and development {16.3.1.1}, learning by doing {16.3.1.2}, knowledge spillovers {16.3.1.3}, technology-related costs unrelated to production techniques {16.3.1.4}, and technology diffusion {16.3.1.5}.

The innovation process has drivers and enablers, but also barriers and constrictions {16.3.2}. These include market incentives, institutional and infrastructural constraints, innovative and absorptive capacity, legal framework and regulation.

One of the key drivers to develop particular technology depends on the market and institutional factors, the most important being the expected size of the market for new technologies, costs of financing and costs of research *[placeholder uncertainty language]*. For instance, a drop in the size of the polluting sector due to climate policy will shift the direction of technological change towards clean goods.

Barriers to accelerated deployment of climate-friendly technologies include the tendency of people and decision makers to discount the future *[placeholder uncertainty language]*. Thus, the extinction of species and ecosystems, the melting of polar ice caps, the leaking of uranium, and the failure to deal with hazardous waste that may occur in the future are giving a diminishing value. Other cognitive, organizational and political barriers also exist and can be identified {16.2.1.10}.

Among infrastructural constraints, the well-established "carbon lock-in" that hinders efforts to implement greenhouse gas-saving measures is worth mentioning *[placeholder uncertainty language]*. Infrastructure and technological lock-in occurs when the economic, institutional and social barriers to switching to an alternative competing infrastructure and technology become prohibitive, effectively perpetuating fossil fuel-based infrastructures and technologies in spite of their known environmental externalities and the existence more sustainable solutions {16.3.2.2}. Technological regimes, that is combination of technologies, rules, and actors that serve societal objectives, are typically resistant to changes due to lock-in effects, but can sometimes be disrupted, resulting in the widespread use of new technologies, changes to actor behavior and institutions.

The extent to which technological innovation in low- and zero-carbon technologies are promoted will strongly contribute not only to reaching a more stringent decarbonisation targets, but also to reaching them sooner {16.4.1} *(robust evidence, high agreement).* One of the key differences across the alternative mitigation pathways is the nature and timing of innovation, technology diffusion and transfer across different sectors of the economy worldwide. Drivers, enablers, barriers and constraints influence the role of innovation, technology development, diffusion and transfer mitigation pathways {16.4}.

Mitigation pathways highlight the key role of two different types of disruptive technologies: zero-carbon and negative-emissions technologies, some of which are yet not available on the market {16.3.1}, and “general-purpose” technologies, such as digital technologies {16.3.2}, which might contribute to mitigation.

Cost-optimal model scenarios are, in general, too optimistic in terms of timing of action, or technology availability *(robust evidence, high agreement).* Yet, for zero and low-carbon innovation to successfully deploy a large range of non-technical barriers need to be overcome, including stranded assets {16.4.1}, behavioural and acceptance hurdles {16.4.2}.

Institutional, behavioral and social barriers may slow technology diffusion even in the presence of strong climate policies; climate change mitigation will require the redirection and acceleration of technological innovation and national policies play a key role {16.5.1} (*robust evidence, high agreement*). Establishing national innovation systems highlight the importance of national and regional relationships for determining the technological and industrial capabilities and development of a country {16.5.2}.

Public policy instruments can be classified in three broad categories: regulatory instruments, economic instruments, and soft instruments {16.5.4}, but also in “technology push” and “market pull” policies. On the “technology push” side, some of the key policies are directed to R&D, and on the “market pull” side, deployment incentives, efficiency standards, or prices. A systematic assessment of innovation policy found evidence that some of the indirect policy instruments have beneficial impacts but also have negative impacts on outcomes such as distributional outcomes {16.5.6}.

The UNFCCC mechanisms for technology development and transfer have been insufficiently fulfilling the needs of low-emission technologies, in particular in developing countries, but have the potential to support the creation of climate relevant innovation-systems (*robust evidence, high agreement*). International cooperation {16.6} could bring a number of benefits, including information exchange, research activities, consulting, education and training, and access to financial instruments, as well as promotion of domestic industry.

For the first time in the history of the IPCC Assessment Reports, there is a dedicated chapter on innovation, technology development and transfer. The chapter covers the major aspects of these topics by assessing the existing literature with the intention to set the ground for further the discussions.

16.1 Introduction

While nations in the Paris Agreement have agreed on an ambitious climate goal to keep a global temperature well below 2°C, there is an implementation deficit that translates in a GHG emissions gap, which is referred to as the Giga-ton gap. The aggregated NDCs are on the path towards 3°C. Moreover, many nations are not on the path to meet NDC either.

Technology is an integral part of the mitigation of climate change, because it provides a means to alleviate climate change. Since the AR5, disruptive technological innovations have flourished, with the progress of digital technology as the major driver. The change has influenced all economic sectors. On the other hand, technology can cause problems too, such as impacts on the employment.

The chapter begins with a discussion about the implications of Technological Changes in the Context of Sustainable Development (Section 2), follows by an insight of the Fundamentals and Drivers of the technology innovation process (Section 3). Then the chapter discusses the Role of Innovation, Technology Development, Diffusion and Transfer in mitigation pathways (Section 4) and how National and Subnational Innovation Policies and Activities can contribute to this goal (Section 5). The chapter closes with a discussion on the current status and the potential of International Cooperation (Section 6).

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16.2 Technological Changes in the Context of Sustainable Development

Humans share a basic need for survival, safety and the freedom to pursue personal and collective goals generally associated with ‘the good life.’ Humanity’s evolution has witnessed discovery and diffusion of knowledge about the world and of innovative ideas, practices and tools – from the most primitive to the most sophisticated technologies. Technological change has always been implicated in human efforts to meet our needs as expressed in socio-cultural, political, economic dimensions. In the mid-20th century, a modern concept of ‘development’, formalized in a speech at the United Nations by President Roosevelt, was presented as the solution to the persistent problems of ‘under-developed areas’ – poverty, disease, illiteracy, and the like. The UN and other development agencies took up the challenge of implementing programmed transformations of primitive communities to more advanced societies wherein the good life, supported by modern technologies, could be guaranteed. Technology transfer was considered a central component of these programs.

The failures of the conventional development model and its associated technological systems to deliver on its promises have been well documented. An alternative ‘sustainable development concept,’ announced in 1987 by the Bruntland Commission has engaged the attention of scholars, policy makers and the general public in every country over the past several decades. A fundamental position on which all seem to agree is that the conventional development model is incommensurable with the sustainable development approach. While it meets – to a limited extend – “…the needs of the present,’ it severely compromises ‘the ability of future generations to meet their own needs.’ (UN General Assembly, 1987, p43). Calls to abandon it as a guiding principle for further technological development abound. This section highlights recent contributions to the sustainable development discourse as it relates to technological change. It focuses on the persistent misalignments of multiple technological transitions at niche, regime and landscape level and sustainable development goals. Emerging opportunities and examples for accelerating transitions to sustainable technologies for sustainable development are explored.

16.2.1 Consequences of technological change: co-benefits, synergies and trade-offs

16.2.1.1 Economics impacts on the labour market and unemployment

Most of the literature addressing the impact of green technological change on the labour force market is focused on the USA, with only a few studies looking at the UK. Results are contradicting. Some studies find that the employment effect is negligible (Morgenstern et al. 2002; Cole and Elliott 2007; Martin et al. 2014) while others find negative and modestly large effects concentrated in energy-intensive industries (Greenstone et al. 2012; Kahn and Mansur 2013). At the aggregate level, the empirical evidence points to the conclusion that the costs associated with job losses at the aggregate level resulting from stricter environmental policies are significantly smaller than the benefits (Vona 2019). Furthermore, job losses are concentrated in specific areas, sectors and social groups that have been hit hard by the great recession and international competition (Vona 2019). Overall, the 'job-killing' argument associated with stricter environmental policies is amplified by localized contextual effects, such as peer pressure, already struggling communities in difficult economic situations, and, importantly, tightened government budgets. In this context, the ability to compensate workers and citizens who are 'left-behind' can contribute to increasing the political acceptability of stringent mitigation policies (Vona 2019).

16.2.1.2 Competitiveness and trade

The evidence regarding the impact of decarbonisation on economic competitiveness is mixed (Jaffe et al. 1995; Kozluk and Zipperer 2015). Some studies, particularly focused on the US, conclude that environmental regulation caused a productivity slowdown (Gollop and Roberts 2002; Gray and Shadbegian 2003; Greenstone et al. 2012), and that such slowdown is a consequence of a displacement of "productive" investment by environmental regulation. Other studies suggest that environmental regulation leads to increases in productivity (Berman and Bui 2001; Alpay et al. 2002). The impact of environmental policy on competitiveness strongly depends on whether firms are able to innovate and what kind of less polluting technologies they are able to introduce. Specifically, innovations increasing firms' resource efficiency in terms of material or energy consumption per unit of output have a positive impact on profitability. Conversely, innovations which do not improve firms' resource efficiency are not associated with positive effects on profitability (Rexhäuser and Rammer 2014) The academic evidence regarding the impact of more stringent environmental regulation on trade, which is another key indicator of competitiveness is also mixed. Trade-related impacts of environmental policies provide insights on what decarbonisation may mean for exporting as well as importing countries. In particular, as exemplified by the so called "pollution haven hypothesis", policy-induced industry relocation would result in an increase in net imports of dirtier goods from countries with laxer environmental policies, to the detriment of both the importers' competitiveness and the overall efforts of reducing anthropogenic emissions. The debate on the existence of such pollution haven effects has however yet to be settled with a definitive answer. The difference in results emerging from the literature generally depend on the study methodology. In particular, ex-ante analyses and results from computable General Equilibrium models suggest that the trade impact related with technological innovation may be large. Yet, the results of empirical analyses fail to agree on whether environmental policies produce any trade-related impact.

16.2.1.3 Distribution of wealth

In the case of developed economics, for instance, the development of new low carbon technologies and business models raises concerns regarding the distributional impact of the energy transition. Key developments such as the implementation of Mobility as a Service, which is seen as a key levers to increase energy efficiency in the transport sector, will change the ability for different user classes to access transport and mobility modes. Elderly and disables users, for instance, may face high barriers to the use of these technologies.

16.2.1.4 Energy efficiency improvements and rebound effects

Improvements in energy efficiency are an important component of the strategy to reduce GHG emissions, especially in carbon-intensive sectors with limited zero-carbon technological options. For instance, the (IEA 2014) forecasts that energy efficiency improvements can reduce energy demand and CO_2 emissions by 25% and 50% by 2050, respectively.

Yet, the engineering savings that are theoretically achievable following an efficiency improvement are not likely to be fully realized. Back in 1865, the economist William Stanley Jevons claimed in that ‘‘technological efficiency gains actually increased the overall consumption of coal, iron, and other resources, rather than saving them’’ (Gossart 2015; Westergård 2018).

Indeed, a large literature argues that energy efficiency improvements are likely eroded due to a series of economic adjustments in production and consumption processes (Greening et al. 2000) (Barker et al. 2009) (Barker et al. 2007) (Barker et al. 2009). Hence, an X% increase in energy efficiency will not translate in an X% reduction in the demand for energy. This is due to the fact that after the efficiency improvement, the energy intensive good is relatively cheaper than other goods. Therefore, the demand for energy and energy intensive goods (inputs) and their complements will increase vis-a-vis that of relatively more expensive non-energy intensive substitutes.

In the USA, estimates of this “rebound effect” a transportation are in the range of 5-30% (Greene 1992; Jones 1993; Greene et al. 1999). In Europe, estimates are somewhat higher estimates, ranging from approximately 15% in the UK, 24% in Italy and 37% in France (Orasch W. Wirl 1997) to 55% - 65% in Germany (Orasch W. Wirl 1997)(Frondel et al. 2012) In residential heating, whose estimates of the direct rebound effect range between 15-55%, which significant differences across countries (Nesbakken 2001).

Case studies to determine the magnitude of the direct rebound effect abound and show different results. Typically the diminished gains fall within a range of 10-30% of expected gains for consumer end-uses in developed countries (Greening et al. 2000; Sorrell et al. 2009), larger direct rebound effects can be expected for developing countries – a limited amount of empirical evidence suggests 40-80% (Sorell 2007).

A study by Greene et al (1999) on Fuel Economy Rebound Effect for U.S. Household Vehicles estimates a direct rebound effect of 20% of the potential energy savings from vehicle fuel economy improvements as traveled miles increased (Greene et al. 2016).

A study by Barker et al. (Barker et al. 2009) on the rebound effect on transport, residential and services buildings and industrial sectors in the US, estimates a total rebound effect of 31% by 2020 rising to 52% by 2030 (Barker et al. 2009).

Other study shows that between 1982 and 2012, while final energy intensity in France decreased by one third, final energy consumption increased by 15%, from 134 to 154 Mtoe. The transportation sector also witnessed important energy efficiency gains. For example, the fuel consumption of a medium-range car dropped from 8.3 to 6.7 l/100 km between 1990 and 2012, and CO_2 emissions of new average cars also dropped from 175 to 124 gCO_2 /km. In the same period, the mileage per medium range car remained stable at around 13,000 km/y. These results should have delivered energy savings to the French economy, but the exact opposite happened: the final energy consumption of road transportation increased from 32 to 36 Mtoe, and its CO_2 emissions increased by 10%. Despite energy efficiency improvements, overall energy consumption and pollution increased, notably because the number of cars increased from 24 to 32 million, providing evidence of a rebound effect (Nässén and Holmberg 2009).

Considerations on rebound effects are particularly important with respect to the diffusion of digital technologies (see section 16.2.1.5 Short- and long-term technology rebound effects / direct and indirect rebound effects

A particularly important reason for concerns related to information and communication technologies (ICT) which are bound to affect the efficiency of energy use. Therefore, they may give rise to important rebound effects of all kinds (energy, time, and knowledge-related), notably because ICT are general purpose technologies that can generate high resource savings throughout the entire economy and society. A company using energy-efficient servers will reduce its data storage costs, which will enable it to buy more servers and to use them more intensively, directly impacting its electricity bill (Gossart 2015). Rebound effects caused by ICT miniaturization are exemplified by the case of Switzerland, where between 1990 and 2005 the average physical mass of a mobile phone was reduced by a factor of 4.4, while the total mass of all phones in Switzerland increased by a factor of eight, because the number of users exploded (Gossart 2015).

Using China as a case study, ICT sector is far from being environment friendly while considering its embodied carbon impacts, which are several times greater than the direct impacts. This is because ICT sector can induce significant amounts of emissions through its requirement for carbon-intensive intermediate inputs from non-ICT sectors. The fast growth of embodied emissions in ICT sector is driven by the large-scale expansion of final demand for ICT products, although improvements in upstream production efficiency have largely slowed the growth (Zhou et al. 2019).

Macro-level rebound effects are more difficult to ascertain empirically and model-based estimates vary widely. Methodologies are subject to criticism and the evidence remains inconclusive.

Technological change generally produces a number of improvements, of which the energy efficiency gain is just one among other benefits. These benefits can give the demand for the improved technology a boost and lead to economy-wide rebound effects higher than 100%. As a consequence, a technology that leads to efficiency gains on the micro level might actually lead to efficiency losses on the macro level (Gossart 2015).

In terms of policy, prevention of the rebound effect requires an emission-constraining framework and an appropriate policy design and policy mix are key to avoiding undesired outcomes such as additional rebound effects and environmental trade-offs, suggesting that energy efficiency technologies alone are not enough to foster energy savings (Gossart 2015) (Font Vivanco et al. 2016).

16.2.1.5 Short- and long-term technology rebound effects / direct and indirect rebound effects

The rebound effect appears at different space and temporal levels usually referred to as direct, indirect and economy-wide. The direct effects of improved energy-efficiency decrease the effective price of an energy service, and lead to an increase in consumption of that service. The indirect effects in which energy-efficiency improvements lead to changes in demand for other factors of production, and the economy-wide effects, in which the cumulative impact of numerous energy-efficiency improvements throughout the economy reduce energy prices, which in turn should increase aggregate energy demand and economic growth (Barker et al. 2007).

Case studies to determine the magnitude of the direct rebound effect abound and show different results (see Box 16.1). Typically the diminished gains fall within a range of 10-30% of expected gains for consumer end-uses in developed countries(Greening et al. 2000; Sorrell et al. 2009), larger direct rebound effects can be expected for developing countries – a limited amount of empirical evidence suggests 40-80% (Sorrell 2018). A study by Greene et al (1999) on Fuel Economy Rebound Effect for U.S. Household Vehicles estimates a direct rebound effect of 20% of the potential energy savings from vehicle fuel economy improvements as traveled miles increased. (Greene et al. 2016).

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Box 16.1 Selected Cases of Direct Rebound Effects

A study by Barker et al. (2009) on the rebound effect on transport, residential and services buildings and industrial sectors in the US, estimates a total rebound effect of 31% by 2020 rising to 52% by 2030. (Barker et al., 2009).

The transportation sector witnessed important energy efficiency gains. In France, the fuel consumption of a medium-range car dropped from 8.3 to 6.7 l/100 km between 1990 and 2012, and CO2 emissions of new average cars also dropped from 175 to 124 gCO2 /km. In the same period, the mileage per medium range car remained stable at around 13,000 km/y. These results should have delivered energy savings to the French economy, but the exact opposite happened: the final energy consumption of road transportation increased from 32 to 36 Mtoe, and its CO2 emissions increased by 10 %. Thus, despite energy efficiency improvements, overall energy consumption and pollution increased, notably because the number of cars increased from 24 to 32 million, providing evidence of a rebound effect (Nässén & Holmberg, 2009).

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16.2.1.6 Links to adaptation and sustainable development

A growing literature explores the existence of trade-offs and synergies between climate mitigation and (sustainable) development (Combes Motel et al. 2014) including the SR1.5 of the IPCC. Among them are studies that show the aggregated impact of mitigation for multiple sustainable development dimensions, often linked to disciplinary models covering specific SDGs in more detail (Grubler et al. 2018; McCollum et al. 2018a; Rogelj et al. 2018).

Significant synergies are identified between:

- Climate mitigation and air pollution; these synergies generally with the stringency of the mitigation policies (Smith et al. 2018; Klimont et al. 2017; Shindell et al. 2017)

On the contrary, trade-offs emerge with respect to:

- Climate mitigation and food production. For instance, technologies such as biofuel productions compete with the food sector for land, and raise food security concerns (Smith et al., 2014). Climate policies need to be drafted together in a portfolio of policies including measures in the food sector to avoid negative impacts for global food security (Hasegawa et al. 2018).

- Mitigation and access to clear water. For instance, use of water-intensive energy technologies generate stress on local water availability.
- Climate mitigation and increasing energy access. For instance, scenario studies which quantify the interactions between climate mitigation and energy access indicate that stringent climate policy which would affect energy prices could significantly slow down the transition to clean cooking fuels, such as liquefied petroleum gas or electricity

The trade-offs and synergies differ between developed and developing countries.

16.2.1.7 Unintended Effects

The literature on climate change mitigation and adaptation efforts has drawn attention to unintended effects arising primarily from the inherently systematic nature of the challenge (Ingwersen et al. 2014). Several studies have contributed new understanding of the mechanisms by which modest gains in material and energy efficiency can cause large increases in consumption – the so-called consumption rebound effect. Besides immediate consequences such as increased generation of material waste and environmental pollution, the effect tends to propagate in the form of ever-widening ripples of social and negative externalities, political-economic inequalities and other consequences that were not anticipated by initiators. Such disproportionately large impacts have been captured in several studies, inspiring calls for new planning frameworks that recognize and make provisions for reducing or eliminating unintended costs of “localized gains” (Laurenti et al. 2016).

16.2.1.8 Specific challenges in emerging economies and least-developed countries

For emerging economies and, especially, least developed countries, unintended consequences of mitigation and adaptation efforts have raised concerns. There is growing evidence that these can compound pre-existing development challenges in situations where response strategies and mechanisms are non-existent or notoriously weak (Vajjarapu et al. 2019).

In the case of mitigation efforts in developing countries, attention has been drawn to the unintended impacts of pursuing relatively expensive low-carbon energy options that end up exacerbating age-old problems of energy poverty and inequality. The literature recognizes that commentary on these challenges should not be interpreted as a rejection of a mitigation agenda in developing countries. Rather, “…until developing countries' most severe concerns can be appropriately addressed, attention should be focused on measures that promote human well-being while saving emissions” (Jakob and Steckel 2014). As China and other emerging economies have demonstrated in recent years, climate mitigation and adaptation efforts in developing countries can coexist with the promotion of clean technology development and green infrastructure expansion meeting basic needs (Du, 2015).

As elaborated in sub-section 16.6 of this chapter, international cooperation to facilitate the transfer and uptake of climate technologies in developing countries can play a central role in promoting mitigation initiatives while addressing pre-existing development challenges (Ockwell et al. 2015). A growing body of research emphasizes the critical role of intermediaries in this regard (Zanello et al. 2016).

16.2.1.9 Acceptability and social inclusion in decision-making

A recently recurrent theme in the clean technological change discourse is social inclusion in the technological change process. Recognition of the need to build a stronger theoretical foundation to guide knowledge development and policy in these areas has motivated several pioneering efforts (cite as many of the most well-known ones). These share a common concern about the central issue of social inclusion for socially relevant innovation. A valuable contribution in this regard argues that social innovation be understood as "agent-driven positive responses" to societal needs for innovative, sustainability-focused technologies. A recent study of cultural underpinnings of successful technology adoption suggest that "societies in which culture naturally leans towards awareness and acceptance of paradox tend to be more socially innovative" (Periac et al. 2018).

A strand of this literature covering green economy theory and practice observes that green consumer behavior "…can induce industries to develop green production methods and convert wasteful patterns of consumption into green consumption patterns. Practice of green consumption relies on the self-sanction concept in individuals. Personal self-concepts (the most significant of which is green consumption self-efficacy), personal outcome expectation and social sanction all have a significant influence (Lin and Hsu 2015) (Sathye et al. 2018).

16.2.1.10 Communication and information diffusion

The development and rapid expansion of modern information and communications technologies (ICT) has impacted the lives of people worldwide. The least developing countries have witnessed some of the most dramatic effects, especially in the voice telephony and data subsectors where technological leapfrogging has enabled them by-pass traditional 'land-lines' to sophisticated, widely available mobile solutions. These revolutionary transitions are opening up hitherto inaccessible knowledge systems to individuals, businesses and government entities, catalysing innovations such as e-commerce, e-learning and e-governance. In the case of education, ICTs are enabling instructors and learners to design highly customized solutions matching the context and needs of users – matching content accessibility to user profiles in innovative high impact, low cost ways (Fonseca et al. 2018).

However, studies of ICT-society relations suggest that the potential of ICTs as enablers of social inclusion and knowledge diffusion is matched by significant challenges that are coming under focus. The 'digital age' has, on the one hand, been hailed as opening up new channels and platforms for building public awareness of, and access to, knowledge, skills and other resources for realizing the long-held vision of social change for people, of people and by people. On the other, the advent of ICTs has been criticized as reinforcing prior socio-economic divisions while deepening inequalities among and within societies at local, national and international levels. On balance, the literature points to a universalization of technological devices and a continuously evolving is underway in terms of communication and knowledge capacity (Hilbert 2014). The exponential growth in proliferation and access to big data, machine learning and artificial intelligence appears bound to influence the pace, direction and impact of technological change and applications in ever more dramatic ways during and beyond the current decade.

16.2.1.11 Cognitive, organizational and political barriers to accelerated deployment of climate-friendly technologies

The literature has produced valuable insights on barriers to action on sustainable development. A recent case study of the US has explored the cognitive, organizational and political barriers to action on climate friendly technologies and policies (Bazerman, 2009). The core challenge is how to deploy these solutions at a rapid enough rate and on sufficiently large scale by surmounting cognitive, organizational and political barriers.

Cognitive barriers include:

- ***A tendency of people and organizations to discount the future***. The literature demonstrates that decision makers "far too often use extremely high discounting rate regarding the future. In practice, this means focusing on or overweighting short-term considerations when making decisions. The consequences of overdiscounting the future comprise a wide array of environmental problems. Ackerman and Heinerling (year) link the discounting of the future to species extinction, the melting of polar ice caps, leaking of uranium, and failure to deal with hazardous waste.

- ***Existence of positive illusions about the future***. Such illusions tend to be sustained by perceived benefits such as enhancement of self-esteem, increasing commitment to action. But studies also show that positive illusions reduce the quality of our decision-making and play a role in preventing us from taking action in time (Bazerman, 2009). Two particularly powerful illusions identified in the literature are: unrealistic optimism – the tendency to believe that one's future will be better and brighter than that of other people, and delusions of control – the view, often mistaken, that we can control uncontrollable events. In the climate change domain, this type of positive illusion manifests in the common expectation that scientists will create technologies to solve the problem (Bazerman, 2009).

- ***A tendency to be biased in a self-serving manner, a well-known symptom of egocentrism***. Itself related to positive illusions mentioned earlier, this phenomenon refers to the tendency to make self-serving judgements regarding allocations of blame and credit, leading in turn to differing assessments According to Messick and Sentis (Year), we tend to first determinate importance our preference for a certain outcome on the basis of self-interest, then justify the preference on the basis of fairness by changing the importance of attributes affecting what is fair.

Organizational barriers refer to the failure to deploy sensible policies supportive of sustainable production and consumption technologies. Bazerman (2009) identifies two of the most important barriers in this regard. The situation in the US is instructive. For the most part, "the U.S. government is not structured in a way that would allow it forcefully confront the nation's current energy challenges" (Bazerman, 2009). Employees also often lack training in methods needed to implement effective strategies to implement sustainable energy technologies that have been developed. An important part of the structural problem has to do with the way in which any organization affects how well it collects, processes and uses information. "A common problem is that organizational "silos" – storehouses of information and resources that only certain people can access – prevent governments from acting in time. Another is compliance mindset adopted by government employees that attenuates the creative search for more economically and environmentally efficient technology choices that might deviate from established standards. These mindsets that develop in government employees are the results of behavior through force of habit, which in turn creates resistance to change arising from years of rejection of contribute to institutional inertia (Bazerman, 2009).

Political barriers to acting in time refer to the failure of government to pass meaningful and sufficient campaign finance reform laws, resulting in the perpetuation of a system in which money corrupts the potential for an intelligent decision-making process on energy policy. "Well funded and well-organized special interest groups – concentrated constituencies intensely concerned about a particular issue – have disproportionate influence on specific policies at the expense of millions who lack a strong voice on that issue" (Bazerman, 2009). In the United States, these groups representing the automotive, coal, and oil industries have succeeded in distorting energy policies and keeping the country from implementing sustainability-focused policies and will continue trying to do so. The often stall reforms by calling for more thought and study or by simply donating enough money to the right politicians so that wise legislation never even comes to a vote. Their efforts effectively turn Congress and the president away from the challenge of making wise energy decisions" (Bazerman, 2009).

16.3 The technology innovation process: Fundamentals and drivers

This chapter adopts the definition of technology as the subset of knowledge that includes the full range of *devices, methods, processes, and practices* that can be used “to fulfil certain human purposes in a specifiable and reproducible way,”(Brooks 1980) or “ a means to a purpose” (Arthur 2009). It also adopts a broad definition of innovation as the “process by which technology is conceived, developed, codified, and deployed (Brooks 1980)”, recognizing that new technologies build on existing ones (Scotchmer 1991; Arthur 2009). In other words, innovation involves inventing and discovering new ideas building on prior knowledge *and* realizing them at large scale affecting how we live and work (Greenstone, M; Looney 2011).

Given these definitions of technology and innovation, the process of technological innovation must be understood as a process that takes place in “technological innovation systems,” which can be thought of as the connected set of actors and institutions that shape innovation processes (Bengt-Ake and Lundvall 1992, Nelson 1993). Innovation activities take place in a number of interconnected and non-linear stages (including research, development, demonstration, niche markets, diffusion and phase out (Wilson et al. 2012) and through a set of functions (Hekkert, MP; Suurs, RAA; Negro, SO; Kuhlmann, S; Smits 2007). The research and development stages have also been described as a cycle of discovery (usually scientific understanding) and invention (of a concept), indicating that neither of those two components of innovation always occur first (Narayanamurti, V; Odumosu 2016).

The temporal dimension of technological innovation can be usefully understood from a multilevel characterization of innovation systems (Geels 2002). Using an example, the multi-level conception of innovation systems implies that, at any given moment, particular societal objectives, such as the availability of reliable and affordable energy services, are addressed through a particular combination of technologies, rules, and actors, forming a “regime” (e.g., the dominant fossil fuel system) (Anadon et al. 2016b) and shaped by the “landscape” of social trends and large spatial patterns, such as the geopolitics and economics of the coal industry. New technologies within regimes (e.g., high-efficiency wind turbines) are generally initially developed within local “niches” (Geels 2002) of conducive practices and contexts, such as local and regional markets with targeted policies to advance renewable technologies (Anadon et al. 2016b). Such regimes are typically resistant to changes or new technologies emerging from niche markets in a process commonly known as technology lock in (Unruh 2000), but can sometimes be disrupted, resulting in the widespread use of new technologies, changes to actor behaviour and institutions, and even the transition to a new regime (e.g., meeting energy goals through a fully renewable system). We discuss the roles of lock-ins in section 16.3.2.2.

Measuring the activities related to technological innovation in areas relevant for climate change mitigation and adaptation is essential to design and evaluate policies at all levels. But because of the multiplicity of actors, stages, and processes that contribute to innovation identified above, there is no single metric that can capture it(see table 1).

The Organization for Economic Cooperation and Development (OECD) has worked to establish international guidelines for collecting and interpreting innovation data since 1997 (OECD 2005), but on most topics (and most certainly in topics related to climate change mitigation and adaptation), there is no easily or globally available and comparable data. There has been significant work developing a set of quantitative metrics that, collectively, can help get a picture of innovation in a particular *energy* technology or set of energy technologies. These energy innovation metrics are divided into inputs (e.g., R&D investments into solar power), outputs (e.g., number of solar patents) and outcomes (Freeman, C; Soete 1997) (e.g., fraction of electricity generated with solar panels) and are listed in Table 16.1. None of the many metrics listed in Table 16.1 is used in all quantitative assessments of innovation, mainly because depending on what aspect of innovation is being studied, different metrics become more important. For example, a particular country may be interested in developing home grown technologies and may focus on inputs to energy innovation if they have not much experience, while other regions may be more interested in accelerating the deployment on the ground in the short term and may then focus on outcomes.

In the output category, patents counts and patent citations (assessing the importance of a patent by how many citations it receives after being released) are the most widely used indicator for the research and development stage of innovation, mainly because this is one method that firms use to protect their inventions, which means that patents are systematically registered by government bodies, are broken down by technological fields, and are available for long time series (Archibugi and Pianta 1996) (unlike other output metrics, which are not widely available across countries and technologies) and also because work links patents to positive firm level outcomes (Griliches, Z; Pakes, A; Hall 1987). At the same time, patents are not perfect indicators because not all inventions are patented (or patentable), different firms and sectors have different propensity to patent (Archibugi and Pianta 1996), and patents are biased toward industrialized countries (given that the quality and accessibility of the patent system may differ) (Basberg 1987). Nonetheless, much of the research assessing the relationship between particular policies and outputs in the innovation process relies on patents.

Overall, to obtain a full understanding of the innovation dynamics in a climate or energy related technology or sector, often complementary qualitative assessments of innovation processes are needed (Gallagher, KS; Holdren, JP; Sagar 2006). Qualitative assessments become very important for example for adopting an adaptive strategies and supporting learning demonstration projects(Chan, G; Goldstein, AP; Bin-nun, A; Anadon, LD; Narayanamurti 2017).

Table 16. 1 Commonly used quantitative innovation metrics, organized by inputs, outputs and outcomes. From Gallagher et al. (2011), based on (Gruebler, A; Aguayo, F; Gallagher, KS; Hekkert, M; Jiang, K; Mytelka, L; Neij, L; Nemet, G; Wilson 2012) and (Gallagher, KS; Holdren, JP; Sagar 2006) and (Sagar and Holdren 2002).

	Metric	Description	Issues
Inputs	R&D expenditure	• Public, private, or total expenditure on R%D (e.g., real $) • Can also include expenditure on demonstration projects (i.e., RD&D) • Expressed either in absolute terms or as 'R&D intensities' normalized for total output (GDP), production, investment, etc.	• Data on public R&D expenditure typically available; time series data allows trends to be analysed • Private R&D data, particularly in nonlisted companies, can be difficult to obtain; if available data are often highly aggregated so difficult to isolate expenditures specific to energy R&D.
	Investment	• Public, private, or total investment in innovation (e.g., real $) • Includes R&D expenditure (see above) but also investments in demonstration, early deployment, and diffusion • Narrow investment metrics can also be normalized (e.g., early stage venture capital as % of total venture capital)	• Similar issues to R&D expenditures (see above) but broader categorization of investment can avoid disaggregation issues (e.g., of aggregated investment figures in corporate accounts) • Investment data tend to under-represent later stage innovation activities (see text) and conflate R&D and demonstration stages • Some database compile private investments into specific technology sectors by investor type (e.g., venture capital, private equity); but investment targets are usually start-up companies rather than innovation per se, and

	Metric	Description	Issues
			databases mainly cover industrialized markets
	Human resources	• Number of scientists and engineers engaged in R&D • Can be weighted by education (e.g., highest degree attained) or type of training • Expressed either in absolute terms, by sector or per capita	• Use as a proxy for ‘tacit’ knowledge embodied in labor input to innovation process • Simplified metric does not account for quality or efficiency, not difference in research infrastructure or capita equipment (so difficult to assess R&D labor productivity) • As with investment metrics, difficult to isolate labor input specific ton energy innovation, particularly in diversified companies
Outputs	Publications	• Number of peer-review articles • Can be weighted by citations or impact factors • Can also include other research publications (reports, books, evaluation, etc.) • Workshops and conferences	• Readily available information, but English language bias. • Difficult to define clear systems boundaries for ETI: for example, should articles complementary technologies such as catalysts, material and control systems be included? • Useful metric for program evaluation if quality or impact-weighted
	Patents	• Number of patents filed or granted • Can be weighted by citations	• Similar issues to publications: readily available, but difficult to define system boundaries. Greatest validity if use at low level of aggregation • Biased toward industrialized countries, and toward industrial sectors with higher propensity to patent • Patents generally relate to R&D rather than later stage innovation activities, and are not necessarily good predictors of successful commercialization
	Technologies	• Number of technologies commercialized • Can be terms of plants, production, lines, product variants, process improvements, companies, turnover, etc.	• Most visible measure of ultimate success of innovation process • Difficult to define clear system boundaries for what constitutes a technology, particularly for complex multicomponent systems (e.g., aircraft) • Fails to capture increases in learning and know-how for technologies based on tacit or no codified knowledge (e.g., energy efficient building design)
	Technologies characteristics	• Ratios of technical to service characteristics	• Change in ratios of technical characteristics to performance or service characteristics indicate directionality and variety of innovations, as well as their proximity to the technological frontier

Metric		Description	Issues
			• Technology specific: not possible it use in meta-analyses
Outcomes	Market penetration	• Rate or extent of substitution into or capture of a market by innovation • Market share is alternative measure normalizing for size of market or economy	• Generally available data • Extensive empirical literature on diffusion dynamics, market penetration, and substitution effects • Bias toward ‘successful’ innovations that have diffused widely. Best suited to retrospective historical analysis
	Learning rates	• Rate of cost reduction of a technology • Conventionally measures as the % reduction in unit cost per doubling of cumulative production • Can be measured for productions plants, organizations, or technologies	• Learning rates emphasize the commercialization phase of a technology but substantive cost reductions may also occur in earlier innovations stages • Production and cost (on price) data generally available, and mechanisms for learning effects have been extensively researched • Learning rates can vary widely between variants of the same technology and between plants producing the same technology; learning rates are also to timing and data fitting issues
	Economic benefits	• Cost benefit analysis • Can be aggregated as net social benefit, or left disaggregated in multiple ‘accounts’ (e.g., labor, environment, knowledge, etc.)	• (Investment) costs generally easier to quantify than benefits which can include environmental and energy security externalities, knowledge stocks and spillovers, option values of technology portfolios, as well as more conventional net employment, tax, and consumer surplus benefits • Cost benefit analyses widely used as core component of program evaluations
	Energy/Emissions Intensity	• Primary energy (GJ), electricity (GWh), or emissions (e.g., tCO_2. tSO_X) per unit of GDP • Normalization can also be more tightly defined, for example, per sector, or per power plant	• Readily available data; meaningful as part of time series trend. • Aggregated impact of innovation only, and potentially confounded by structural changes to economic activity, nonprice induced changes, and inter-fuel substitution
	Project/program evaluation	• Size and number of programs in terms of employees, turnover, investment, outputs, etc.	• Difficult to assess quality, so need to complement with case study or survey research (see text) • Similar issues with tacit knowledge as for technologies (see above under outputs)

16.3.1 Processes underpinning innovation

16.3.1.1 Research and development

A primary source of innovation is research and development, that is the process of looking for new solution that could increase the efficiency of existing production methods or result in new product. The decision about the investment in search is taken by technology firms (e.g., the producers of capital good) and it is motivated by the desire to decreases the cost of production, increases the productivity of existing products or generates new good (Romer 1986, 1990; Aghion and Howitt 1992; Grossman and Helpman 2006; Young 2002). The research is performed by skilled labour. Thus firms decision about investment could depend on the equilibrium wage of this type of workers and availability of human capital in the economy (Romer 1990), (Aghion and Howitt 1992).

Technology firms finance their research with their monopoly rents. This implies that those firms will usually need to have some monopoly power. If a competitive firm with constant cost could decrease those costs by investment in R&D, then the profit maximization problem of that firm does not have a solution and equilibrium does not exist (Romer 1990).

The assumption on monopolistic competition between technology firms is frequently adopted in models designed to explore the prospects of green growth. For instance (Acemoglu et al. 2012) and (Greaker et al. 2018) assume that green innovation is generated by ‘researchers’ attracted to the 'green industries' by high profits. In other models, the innovation is generated directly by investment in R&D (Fisher-Vanden and Ho 2010).

Learning by searching is taken into account in some IAMs. These models assume that firms (or planners) could invest resources in research which leads to the accumulation of knowledge. The knowledge stock is then used as one of the factors driving down the costs of technology in the two factors learning curve (Klaassen et al. 2005; Söderholm and Sundqvist 2007) or as a factor that increase efficiency of energy use (Goulder and Schneider 1999; Popp 2004).

16.3.1.2 Learning by doing

Productivity could be increased and the cost of technology could be reduced by the accumulation of knowledge in the process of learning by doing (Arrow 1962). Arrow (1962) argues that the interaction of workers with new machines allows them to use them more efficiently. The higher is the stock of capital in the economy, the more intensive is the interaction with machines and the larger is the stock of knowledge and productivity.

The benefits of learning by doing are larger at the economy level than at the firms level (Arrow 1962). Every production and investment by firms is associated with the creation of knowledge. Since that knowledge is a non-excludable good its benefits are not internalized by firms making decisions. In contrast to learning by conducting research and development, learning by doing is not an outcome of a purposeful decision of a firm. Instead, it is rather a by-product of firms decision regarding production.

If learning by doing is necessary to drive the cost of technology down, there is a risk that this technology will not be adopted by the market even if its adoption could bring benefits to the society in the long run. Initially new technologies are often expensive and cannot compete with the incumbent technologies (Cowan 1990). Large number of adopters could potentially lower this cost via the learning by doing effect to the level that would allow the technology to beat the incumbent technology (Gruebler et al. 2012). However, no firm wants to be the first adopter and bear the high cost. If adopters are not able to coordinate, it will lead to situation of a lock-in with new technology not being able to compete with incumbent technologies even if the former could be superior in the long-run (Gruebler et al. (2012). This market failure could be however corrected by policies, such as subsidies for first adopters.

Although empirical data in energy technologies supports the negative correlation between cumulative deployment of and costs , the size of this correlation is not sufficient to estimate the causal effect of increase in deployment on cost reduction (Nemet 2006). The evolution of technology costs is not only a function of learning, but depends on many processes that are also taking place, including research and development (Klaassen et al. 2005), economies of scale (Arce 2014), learning by doing, and knowledge spillovers (Nemet 2012b), among others (Gruebler et al. 2012; Nemet 2006). In addition the relation could reflect reverse causality: increase in deployment is an effect (and not a cause) of a drop in price (Witajewski-Baltvilks et al. 2015) (Nordhaus 2014). However, in some applications, learning curves can be a useful proxy and heuristic (Nagy et al. 2013).

Researchers and policymakers alike are interested in using learning curves to determine what are the policies or actions that most cost effectively drive costs down. Over time there has been a growing amount of work trying to separate the influence of learning by doing versus other factors in explaining cost reductions specifically in energy technologies. This has led to some studies moving from the so-called "one-factor" learning curves (estimating the rate at which costs come down as a factor of deployment) to "two-factor" learning curves (e.g., Mayer, T., Kreyenberg, D., Wind, J. & Braun 2012; Bettencourt et al. 2013) which estimate the relationship between technology cost reductions and deployment and R&D investments in that energy technology. However, reliable information on public energy R&D investments in OECD countries is hard to obtain. In particular, private sector energy technology R&D investments and data from developing countries (both public and private) are hard to obtain in a comparable form (Verdolini et al. 2018). In addition, separating the contribution of R&D and deployment in a robust fashion is difficult and has led to some studies learning by research and learning by doing (e.g., (Qiu and Anadon 2012). Modeling based studies using cross sectional data, mainly focused on solar PV, have improved our understanding of the components of overall costs by breaking them down into factors such as labor and material costs, efficiency, scale, etc. (see for example (Goodrich et al. 2013; Kavlak et al. 2018; Nemet 2006), without linking such factors to particular market developments or policy incentives. In this sense, the attribution of cost reductions to different policies or processes beyond associations is an important area of research.

The literature analyzing learning by doing in energy technologies is large, with reviews collecting data for one-factor (and some two-factor) learning rates for electricity generation technologies (Rubin et al. 2015), for storage (Schmidt 2017) and for energy demand and energy supply technologies (Weiss, M., Junginger, M., Patel, M. K. & Blok 2010). Other work cutting across a wide range of industrial sectors (not just energy) has tried to relate cost reductions to different functional forms, including cost reductions as function of time (Moore's law) and cost reductions as a function of production or deployment (Wright's law) finding that those two forms perform better than alternatives combining different factors, with costs as a function of production (Wright's law) performing marginally better (Nagy, B., Farmer, J. D., Bui, Q. M. & Trancik 2013) . A systematic comparison using such empirical relationships of energy technology cost reductions as a function of time and expert estimates to forecast ranges of future costs have found that neither method is either more accurate on an equal basis or provides systematically more optimistic values for 2030.

In some cases technology costs increase with deployment or experience, at least in some countries (e.g., nuclear power in OECD countries (Lovering et al. 2016) and solar water heaters in the US (Nemet 2012a)), and it has been common to find that cost decreases are preceded by a short-term increases during the formative phase of the technologies (Dowlatabadi 1998; Rubin et al. 2015)

The negative relation between technology costs and technology deployment is frequently used in IAM to project to cost of renewable technologies in the future. While most models include a simple one-factor learning curve some recent studies use two-factor learning curve that takes into account the learning by searching (see for instance Emmerling et al. 2016 and Kouvaritakis et al. 2015). However, including an equation estimated with a simple regression in the model may lead to projection bias, because such specification does not take into account that the negative relation between costs and deployment might be partly due to reverse causality (Witajewski-Baltvilks et al. 2015).

The potency of learning by doing may depend on the size of research and development. Young (1993) postulates that learning-by-doing cannot continue forever and must be bounded by an upper physical limit of productivity of a given technology. However, this upper bound could be shifted by new inventions that could replace the existing technology with a new one. However, these inventions require R&D activity. A continuous growth of productivity requires both, investment in capital, which fuels learning by doing, and investment in R&D which fuels learning by searching. Shayegh et al. (2017) distinguishes between the effect of incremental and transformational innovations. The former has the same effect as movement along the curve: it produces knowledge that would have otherwise been gained through learning-by-doing. The transformational innovations result in improvements that would not have occurred through learning-by-doing.

Including learning by doing effect in models based on optimization is problematic. If a firm or a planner takes into account the learning effects, the positive feedback between technology deployment and cost reduction implies that the optimal choice involves the choice of only one technology in a short period of time. Including learning by doing could also lead to instability of models numerical solution and give rise to multiple equilibrium (Sue Wing 2006). The model by Young (1993) which introduce a bound on learning in each period mitigates this problem.

16.3.1.3 Spillovers

An unbounded and continuous technological progress requires the presence of knowledge spillovers (Rivera-Batiz and Romer 1991; Romer 1990). Every innovation and every addition to the knowledge stock gives an opportunity for others to create new innovations and increase the knowledge stock even further. The constant growth of knowledge stock translates into constant growth of productivity.

The spillover effect is an externality. A firm that maximize its profit does not take into account that its investment in R&D brings benefits for other firms. As a result the equilibrium level of R&D is lower than in the social optimum (Romer 1990; Young 2002). Kealey and Ricketts (2014) postulates that firms contributing knowledge to the common pool benefit from technology spillovers in different ways from non-contributors, providing them with incentives to share knowledge. This is supported by the finding that 23% of innovations came from swapping information between rival companies (Allen et al. 1983). This could lead to a ‘critical mass’ problem: researchers will contribute to knowledge only if others will contribute too (Kealey and Ricketts 2014).

The presence of spillovers related to energy and low-carbon technologies has been documented by a number of empirical studies (*high confidence*) (Popp 2002; Aghion et al. 2016); (Witajewski-Baltvilks et al. 2017; Verdolini and Galeotti 2011). Aghion et al. (Aghion et al. 2016) finds that intertemporal spillover results in path-dependency in auto industry: companies that patented more in combustion engines are more likely to patent in the same technology in the future.

The spillover effect has been integrated in several IAMs. For instance, Goulder and Schneider (Goulder and Schneider 1999) takes into account the spillovers between industries and (Emmerling et al. 2016) technological spillovers across countries.

The spillover effect associated with innovation in dirty technologies increases the costs of climate policy, and may lead to lock-in to fossil-fuel technologies. A continuous technological progress of dirty industry raises a bar for clean technologies: a larger drop in clean technologies is necessary to become competitive (Acemoglu et al. 2012; Aghion et al. 2016)

The spillover effect associated with innovation in clean technologies increases the role of climate policy in the short-run. A policy that encourages clean innovation leads to accumulation of knowledge in clean industry. On the one hand this decreases the cost of clean technologies, on the other hand it encourages further innovation in these industries. Once the stock of knowledge is sufficiently large, the value of clean industries will be so high, that technology firms will invest there their research effort even without policy incentives (Acemoglu et al. 2012)

In addition, the spillover of clean technological progress across regions could neutralize or even offset the carbon leakage after a unilateral effort to reduce in emissions in one region (*medium confidence*) (Gerlagh and Kuik 2014; Golombek and Hoel 2004). A carbon tax incentivises clean technological progress that increases the competitiveness of clean technologies not only locally, but also abroad. The size of this effect depends on the size of international spillover. If they are sufficiently strong, the negative effect of carbon tax on emissions abroad due to clean technological progress could be larger than the positive effect due to carbon leakage (Gerlagh and Kuik 2014).

The spillover effect can take a form of the recombinant innovation, when several components or technological solutions are combined to give raise to a new technological solution (Weitzman 1998; Fleming and Sorenson 2001; Olsson and Frey 2002; Tsur and Zemel 2007; Arthur 2009). The underlying idea is that experimenting with variations of existing technologies may contribute to knowledge creation, or combining different technologies can result in a new technological solution. It has been shown that 77 percent of all patents granted between 1790 and 2010 in the US are coded by a combination of at least two technology codes (Youn et al. 2015). In fact, many technologies considered to be ‘environmental’ innovations combine distinct technological options: a hybrid car combines a conventional engine with an electric propulsion system; a combined cycle gas turbine (CCGT) integrates gas and steam turbine technologies; or Integrated Solar Combined Cycle Power Plants (ISCCs) produce electricity by combining gas-turbine with a photovoltaic system.

Recombinant innovations have been shown to speed up technological progress by allowing for the emergence of technologies, which would be impossible only with incremental innovations (Frenken et al. 2012). Weitzman (Weitzman 1998) presents a formal model in which the number of new combinations is a function of the number of existing ideas. He shows that, if this number is the only limiting factor in knowledge production, super-exponential growth may result. However, maintaining the diversity of investments in different technologies is costly. In particular, it may involve the forgone costs of specialization and economies-of-scale from investing in only the most promising solutions (Safarzyńska and van den Bergh 2010; van den Bergh 2008).

Research trying to estimate knowledge spillovers from other areas relying on patent citations has found that compared to other technologies, energy technology patents that rely to a greater extent on knowledge from other technology areas (from patents in other areas) are more likely to be heavily cited (Nemet 2012b). An analysis of lithium ion battery patents in Japan over time breaking down the patents according to lithium ion battery architecture found that the contribution of patents from different sectors varied depending on the components of the technology and that over time spillovers had made greater contributions to the battery integration component (they were not present at the start of the technology) (Stephan et al. 2017).

The opportunity for the development of new technologies is sometimes created by the arrival of new General Purpose Technologies (GPTs). GPTs provide solutions that could be applied across sectors and industries (Goldfarb 2011). Historical examples of GPT include steam engine, electric dynamo and, more recently, the ICT. GPTs create technological platforms for a growing number of interrelated innovations. Each such innovation depends on the success of other innovations (Gruebler, A; Aguayo, F; Gallagher, KS; Hekkert, M; Jiang, K; Mytelka, L; Neij, L; Nemet, G; Wilson 2012). Examples of such dependencies include electric light and power (Du Boff 1984)and automobiles and complimentary services (Freeman and Perez 1988).

The growing complexity of technologies and global competition implies that the development of a technology is a truly international process that involves the flow of knowledge across borders. For instance, in production of electronics, Asian economies have captured co-location synergies and dominate production and assembly of products components, whereas American firms have adopted "design-only" strategies (Tassey 2014). In the context of renewable energy technologies, "green global division of labour" has been observed, with countries specializing in investments in R&D, manufacturing or deployment of renewable technologies (Lachapelle et al. 2017).

16.3.1.4 Determinants of technology costs unrelated to production technique

We now discuss two factors that could contribute to cost reductions or cost increases. One of them is materials costs and the other is financing costs. In terms of materials costs, in some cases, when the use of the material for the technology does not constitute the main market, such as steel, those building an energy technology relying on steel (like wind turbine manufacturers) may be able to take to some extent the cost of materials as exogenous. In other cases, when the use of the material for that technology is significant (such as in silicon for solar panels and lithium for batteries), firms manufacturing technologies as a whole and policies driving demand can shape the costs of the materials. Not surprisingly, some learning curves studies have begun controlling for key materials, costs, see for example (Qiu and Anadon 2012) accounting for steel costs for wind turbines, (Kavlak et al. 2018; Nemet 2006) accounting for Silicon costs, and (McNerney et al. 2011) including coal costs over time.

For technologies that have high capital costs when compared to fuel costs, such as renewable technologies, financing conditions are important determinants of overall costs. Recent work focussed on Germany found that financing conditions that are exogenous and apply to the overall economy played an important contribution in the cost of wind and solar over 18 years. But it also found that there had been learning in the renewable energy financing industry that significantly contributed to the sharp reductions in the levelized cost of electricity (LCOE) in those solar (5%) and wind (24%) (Egli et al. 2018). In short, learning in production and deployment is not the only learning taking place over time.

16.3.1.5 Technological diffusion

Market penetration (or technology diffusion) has been shown to proceed non-linearly in a characteristic logistic (S-shaped) curve used in the diffusion and technology substitution literature (Gruebler 1996). In this sense, the timeline associated with diffusion can range widely, with the formative phase (up to 2.5% of deployment) ranging between 5 years to over 200 years (Bento and Wilson 2016; Bento et al. 2018) with 5 to over 70 years for technologies getting from a 10 to 90% market share of saturation (Wilson 2012).

16.3.2 Drivers and enablers of the innovation processes

16.3.2.1 Market incentives and the direction of technological change

Technological progress is characterized not only with its speed, but also its direction. The early works that considered the role of technology on growth, such as (Solow 1957) or (Nelson and Phelps 1966) assumed that technology can move forward along only one dimension - every improvement lead to increase in efficiency and increase demand for all factors of production (this is also sometimes referred as Hicks neutral technological change). This view however ignores the potency of technological progress to alter the otherwise fixed relation between economic growth and the use of resources.

Technological change is biased if it saves relatively more of one input to production than another (Sue Wing 2006). In particular technological progress that is biased against carbon-intensive production could decouple growth and the use of fossil-fuels (Acemoglu et al. 2014; Hémous 2016; Acemoglu et al. 2012; Greaker et al. 2018). An alternative direction of technological change is the progress favoring carbon-intensive technologies. One must understand which type of innovation could lead to emission reduction and more broadly to sustainable development and under what conditions those innovations accelerate.

Technological change can change the relative demand by altering the efficiency of use of that input relative to other inputs (Acemoglu 1998). One could distinguish two cases. First, if a process that use dirty resource could be substituted with a clean process then increase of relative efficiency of a clean process decreases the demand for dirty resource (Acemoglu et al. 2012, 2014). This is the case of combustion engine cars which could be substituted with electric cars: progress of electric cars will reduce demand for oil (Aghion et al. 2016). Second, if there is no substitute and dirty resource is complimentary to other inputs, then increase in relative efficiency of the dirty resource will reduce the demand for dirty resource relative to the demand for other resources (Hassler et al. 2012; André and Smulders 2014; Witajewski-Baltvilks et al. 2017). Both, in the first and in the second case, number of innovations improving efficiency of dirty resource use will be larger than the number of innovations improving efficiency of other inputs if returns to the latter innovations are higher than returns to the former. Below we review how these returns depend on market conditions.

The returns to innovation improving the relative efficiency of one input depend on the relative prices. According to the price-induced technological change hypothesis (Hicks 1932; Samuelson 1965), firms will wish to invest in technology which allows them (or consumers) to economize of a factor which has become relatively expensive. For example, an increase in oil price will lead to development of fuel-saving technologies. Such strong response of technological change was evident during the oil-price shocks in the 1970s (Hassler et al. 2012). Presence of induced technological change allows for larger reduction in relative use of expensive input than if technology is fixed (Sue Wing 2006). Gerlagh and Kuik (2014) therefore notes that it could be modeled simply as an increase in elasticity of substitution between inputs. However an important distinction between substitution and induced technological change is a timing – while substitution within existing technological frame can take place in the short-run, the induced technological change will typically involve development of new techniques, diffusion and scale-up of operations (Sue Wing 2006), which can take place only in the long-run.

The hypothesis of induced technological change relies on the trade-off between improving efficiency on one input and other inputs (Acemoglu 2015; Samuelson 1965; Sue Wing 2006). A firm could buy an additional efficiency of energy use only at the expense of lower efficiency (or slower improvement) in efficiency of capital use. In the models of induced technological change this tradeoff is based on the ad-hoc assumption on the shape of the innovations possibility frontier. In the new directed technological change (DTC) literature, the trade-off is derived from the explicit representation of R&D sector (Acemoglu 2015) and results from the limited availability of research resources. The DTC literature could be divided into two strands described below.

The first strand shows that an increase in price of dirty input, such as carbon energy, incentivize R&D directed at increasing efficiency of that input, if that input complements other inputs in production and it cannot be substituted. This prediction has consequences for the growth that relies on the use of scarce resources. Since the price of scarce resources is expected to increase in the future, the long-run technological change is resource-saving (André and Smulders 2014). Similar prediction was derived for the case of energy: since energy is complementary to other factors of production, energy efficiency improvement induced by an increase in energy price leads to drop in demand for energy (Hassler et al. 2012; Witajewski-Baltvilks et al. 2017).

The second strand argues that an increase in price of dirty input will increase the market for clean technologies that could substitute that input. The increase in clean market size would then incentivize R&D directed at increasing efficiencies of clean technologies (Acemoglu et al. 2012). For example, increase in the price of oil will create incentives for firms to invest in development of technologies that does not require oil, for example, electric cars (Aghion et al. 2016). Also in this case the technological change induced by price increase of an input leads to drop in demand for that input. On the contrary, fall in oil price would hamper this development.

The direction of technological change depends also on the size of market for dirty technologies relative to the size of other markets. In theory a single region could design a blend of climate, industrial and trade policies that alters the size of that market and direction of technological change in other regions. If technologies can be traded then introduction of carbon tax in one region leads to a drop in the size of the carbon-intensive sector globally and push global innovation away from this sector. Consequently even a unilateral climate policy of one region will shift the direction of technological change towards clean goods (Maria and Van Der Werf 2008).

If technologies cannot be traded, but the output of the carbon-intensive sectors (e.g., chemicals or cement) can be traded, an introduction of carbon tax in one region leads to the expansion of carbon-intensive sector in the other region (carbon leakage). This increases the size of the market for dirty innovations and speeds up development of dirty technologies in the region with no climate policy (van den Bijgaart 2017; Hémous 2016). On the contrary, an introduction of carbon tax together with clean R&D subsidies and trade policies discouraging import of the carbon-intensive good decrease the size of the market for dirty innovation in the other region in the long-run (Hémous 2016). Global reduction of emissions is possible if one region could push the comparative advantage of the other regions to clean or carbon-neutral sectors and meanwhile develop technologies that could substitute the carbon-intensive goods. (van den Bijgaart 2017; Hémous 2016).

Greaker et al. (2018) notes that the value of the market for clean technologies is determined not only by a current but also by a future stream of profits. Consequently, climate policies of the future are able to redirect research effort today. Greaker et al. (2018)also notes that the firm receives the stream of profit only until another firm innovates and steals its market. If majority of technology firm works on clean technologies the successful innovator in clean market would enjoy its monopoly rent for a shorter period of time than a successful innovator in a dirty market since it is more likely that the clean market will be captured by another innovator soon. In this situation, the private return to clean innovation is smaller than social return and the free-market number of clean innovations is smaller than the social optimum. To correct this, a green R&D subsidy is needed in addition to carbon tax.

In the case of some energy related technologies, for example those related to electricity generation, liquid fuel production, and provision of transportation, firms may expect innovation to yield lower returns because of the incumbency of other technologies producing what is a commodity market. In other words, electricity and fuel markets, as currently established, may not offer sufficient incentive for firms to innovate, since electricity and fuels are considered to be commodities (unlike medicines for new illnesses or devices for new uses). A second reason why innovation in some energy technologies may be lower is the scale of the investment needed in a lot of the infrastructure, with many power plants being in the multibillion dollar range of capital investments (Koonin, SE, Gopstein 2011). A third factor shaping investment may be the longevity of many energy assets, which last for many decades, which means that the size of the market in industrialized countries may not be as high investments (Koonin, SE, Gopstein 2011).

The particular underinvestment in energy innovation in the private sector resulting from these factors is evidenced by two main facts. First, by the low R&D intensity of electric utilities, which spend 0.2% of their revenues on R&D (Battelle Memorial Institute 2011; Lester, R. 2012; NAS 2016) , a tenth of what other sectors spend, at least in the United States (Jones, C, Anadon, LD, Narayanamurti

2014; US NSF 2019). Without a price on carbon or pollution, electricity generation renewables that were comparatively expensive 20 years ago had to compete with cheaper electricity from coal and gas and were only able to do so with other types of government support, such as tax credits and feed-in-tariffs, as will be discussed in the policies part of the chapter.

The challenges of investing in innovation in energy when compared to other important areas, such as IT and medicine are also reflected in the trends in VC funding. Research found that early-stage investments in clean-tech companies were more likely to fail and returned less capital than comparable investments in software and medical technology (Gaddy, BE, Sivaram, V, Jones, TB, Wayman 2017), which led to a retreat from investors from hardware technologies required for renewable energy generation and storage to software based technologies and demand-slide solutions (Bumpus, A, Comello 2017).

The preference for particular types of investments in renewable energy technologies depends on investors attitude to risk (Mazzucato and Semieniuk 2018). Some investors invest in only one technology, others may spread their investments, or invests predominantly in high-risk technologies. The distribution of different types of investors will affect whether finance goes to support deployment of new high-risk technologies, or diffusion of more mature, less-risky technologies characterized by incremental innovations, which may affect not only energy production but also the financial system in the long run.

The financial system might be affected by the low carbon transition due to high initial costs of investments in renewable energy. First, too rapid investments in deployment of renewable energy can render substantial losses for the investors holding assets of fossil fuel companies (Campiglio et al. 2018). Although the direct exposure of assets hold by companies in various sectors to the fossil fuel industry is small, it can reach almost 40% if indirect effects via financial counterparties are taken into account (Battiston et al. 2017). Second, if investments in renewable energy are financed with loans, the degree of concentration of loans to energy companies will affect the distribution of risk in the banking sector. If such loans are concentrated in few large banks, this may undermine stability of the financial system compared to the situation when risk is spread more evenly (Safarzyńska and van den Bergh 2017). Third, innovations in renewable energy are typically financed by different types of investors, including public and private entities.

As previously indicated, the literature on technological innovation in sustainability, and in particular the literature on the multilevel perspective (Geels 2002) highlights the importance of small niche markets that allow for experimentation and for a higher willingness to pay. One prominent example was the role that space exploration and remote power generation had in the early development of solar PV technologies (Nemet 2019a). Another example is lithium ion batteries, which initially entered the market not for storing electricity in transportation or grid uses, but instead for camcorders, that were able to charge more money.

Market forces alone can fail to induce development of disruptive technologies that allows for global reduction of emissions. The first and second welfare theorem in microeconomic theories states that the free-market economy with no policy interventions (other than redistributive policies) brings the best possible outcome from the point of view of society (including optimal level of investment in new technologies) providing, among other conditions, that private return from investing or using each technology reflect the social benefits of this action (i.e., there are no externalities) (Mas-Colell et al.). This condition is likely to fail in the case of disruptive clean technologies. R&D in clean technologies generate knowledge that could be used by other researchers to build further progress of those technologies (see the spillover effect; see also the discussion in 16.3.2.3); their production and deployment generates knowledge that lower cost of production for other firms (see the learning -by doing effect discussed in section 16.3.2.2).

There is a mixed evidence whether the industrial policies should explicitly support clean technologies. Nordhaus (2011) separates the problem of imperfect property rights from the problem of greenhouse emissions: once the intellectual property rights are in place, a price on carbon that corrects the emission externality is sufficient to induce optimal level of green technological change. Acemoglu et al.(2012) demonstrates that subsidizing clean technologies (and not dirty ones) is necessary to break the lock-in of dirty technological progress. Bijgaart (van den Bijgaart 2017) and Hemous (Hémous 2016) show that clean innovation subsidies in the coalition of environmentally concerned regions are necessary to induce global emission reduction if other regions are not willing to collaborate in setting climate policies.

16.3.2.2 Institutional and infrastructural constraints

The well-established term 'carbon lock-in', originally defined by Unruh (2000), refers to "the tendency for certain carbon-intensive technological systems to persist over time, 'locking out' lower-carbon alternatives, and owing to a combination of linked technical, economic, and institutional factors. These technologies may be costly to build, but relatively inexpensive to operate and, over time, they reinforce political, market, and social factors that make it difficult to move away from, or 'unlock' them. As a result, by investing in assets prone to lock-in, planners and investors restrict future flexibility and increase the costs of achieving agreed climate protection goals" (Erickson et al. 2015). Infrastructure and technological lock-in occurs when the economic, institutional and social barriers to switching to an alternative competing infrastructure and technology may be prohibitive (Unruh 2000).

Collectively, these types of lock-in mechanisms tend to hinder efforts to implement greenhouse gas-saving measures; effectively perpetuating fossil fuel-based infrastructures in spite of their known environmental externalities and the apparent existence of cost-neutral, or even cost-effective remedies (Arvesen et al. 2011). Despite growing evidence of substantial environmental risk, these forces can create pervasive market, policy and organizational failures toward the adoption of mitigating policies and technologies (Unruh 2000). Klitkou et al (Klitkou et al. 2015) demonstrate that infrastructure lock-in reinforces certain pathways of economic, technological, industrial and institutional development and can lead to path-dependency. The characteristics of existing regimes set the preconditions for the development of new transition pathways (Klitkou et al. 2015).

A prime example of carbon-intensive technology lock-in is coal and gas-fired power, "for which plants are costly to build, but relatively inexpensive to operate and, over time, they reinforce political, market and social factors that make it difficult to move away from, or 'unlock' them" (Erickson et al. 2015).

Another widely acknowledged case in point is the global car industry and its many associated supply chains comprising; the car maintenance and distribution network; the global oil industry and the associated infrastructure of oil wells, pipelines, refineries, distribution networks and fuel stations; the road infrastructure and traffic system; the patterns of land use that have developed around that road infrastructure, including amenities and workplaces that are only accessible by car; the multiple institutions, regulations and policies associated with the production and use of cars; the engineering skills and knowledge built up over decades in a variety of domains; the political power of relevant interest groups; the daily travel routines, behaviour and expectations of millions of car owners; and the symbolism and cultural norms that have become associated with car-based mobility ('car culture'). These different elements act together to shape the level and pattern of personal mobility and hence the energy use for that mobility.

While carbon lock-in provides a conceptual basis for understanding macro-level barriers to the diffusion of carbon-saving technologies, it also generates questions for standard economic modeling approaches that do not consider technological and institutional evolution in their elaboration (Unruh 2002). Models that do account for lock-ins bring different predictions than those that don't. For instance, models accounting for lock-in predict that temporary measures, such as temporary subsidy for green technologies, could lead to permanent redirection of R&D resources towards the development of low-carbon technologies (Acemoglu et al. 2012).

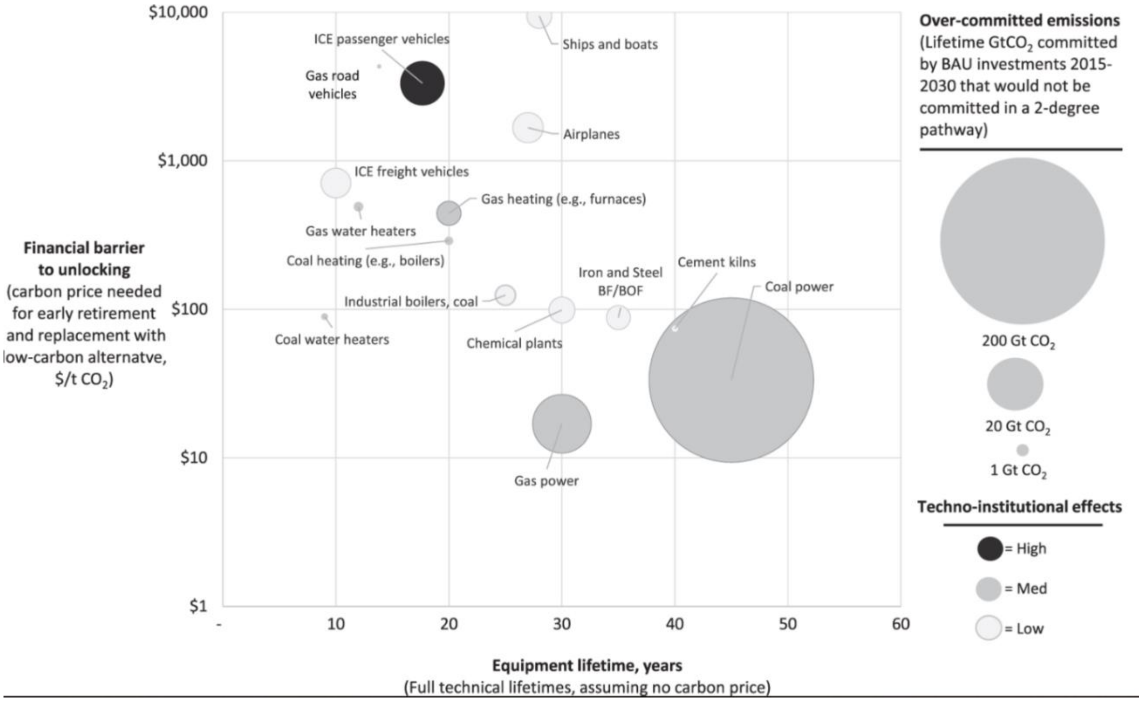


Figure 16.1 Financial barrier to unlocking vs equipment lifetime

16.3.2.3 Innovative and absorptive capacity

A unilateral effort to reduce emission (via a combination of climate, industrial and trade policies) in a coalition of regions that are technology leaders will reduce cost of clean technologies, which will have a negative effect on emissions in the countries outside the coalition (Di Maria and Smulders 2005; Golombek and Hoel 2004; Maria and Van Der Werf 2008; Hémous 2016; van den Bijgaart 2017). The literature suggests various mechanisms leading to this result. Di Maria and van der Werf (Maria and Van Der Werf 2008) argues that the effort to reduce emission in one region reduces global demand for dirty good. This will redirect global innovation towards clean technologies, leading to drop in cost of clean production in every region.

The models in Hemous (Hémous 2016) and Bijgaart (van den Bijgaart 2017) predict that the coalition could induce acceleration of clean technological progress with a mix of carbon tax, clean R&D subsidies and trade policies in that region leading to reduction of cost of clean production inside the coalition. In the model by Hemous (Hémous 2016) export of goods produced with clean technologies to a region outside the coalition reduces demand for dirty good in that region. In the model by Bijgaart (van den Bijgaart 2017) local advancements of clean technologies by a coalition with strong R&D potential are imitated outside the coalition. Furthermore, advancements of clean technologies will incentivise future clean R&D outside the coalition due to intertemporal knowledge spillovers. In Golombek and Hoel (Golombek and Hoel 2004) increase in environmental concern in one region increases abatement R&D in that region. Part of this knowledge spills over to other regions, increasing their incentive to increase abatement too, providing the latter regions did not invest in abatement before.

However, this chain breaks if the regions that are behind technological frontier (i.e., technological followers) are not able to absorb the solutions developed by regions at the frontier. New technologies might fail due to deficiencies of political, commercial, industrial, and financial institutions. For instance, countries might not benefit fully from international knowledge spillover due to insufficient domestic R&D investment (Mancusi 2008; Unel 2008; Gruebler, A; Aguayo, F; Gallagher, KS; Hekkert, M; Jiang, K; Mytelka, L; Neij, L; Nemet, G; Wilson 2012), since local knowledge is needed to determine the appropriateness of technologies for the local market, adapting them, installing and using effectively (Gruebler et al. 2012). Some technologies might require experience with the organization and management of large-scale enterprise or financial markets capable of mobilizing capital for individual firms at large scale (Abramovitz 1986; Aghion et al. 2005). Other obstacles to change include vested interests and customary relations among firms and between employers and employees (Olson 1982; Abramovitz 1986). From the policy perspective this implies that simple transfer of technologies could be insufficient to guarantee adoption of new technologies (Gruebler, A; Aguayo, F; Gallagher, KS; Hekkert, M; Jiang, K; Mytelka, L; Neij, L; Nemet, G; Wilson 2012).

Emmerling et al. (Emmerling et al. 2016) made an attempt to condition technological diffusion on the absorptive capacity in the IAM. In their framework, they proxy for adaptive capacity with the distance (measured in terms of productivity) between technological leaders and followers. The distance becomes simultaneously an opportunity as well as an obstacle to catch-up. Understanding when one effect will dominate the other requires further theoretical and empirical work.

Research relying on patent citations has indicated that Foreign Direct Investment (FDI) is a mechanism for firms to both contribute to the recipient country's innovation output as well as benefitting from the recipient country both in industrialized countries (Branstetter 2006) and in developing countries (Newman et al. 2015). However, insights specific for energy or climate change mitigation areas are not available, nor is there much information about how other innovation metrics may react to FDI.

Finally, technologies could be not efficient in developing countries even if they are efficient in countries at the technological frontier. For instance, technologies that are highly capital intensive will be efficient in countries where costs of capital are low. The same technology could be less efficient than previous labour-intensive technologies in countries where cost of labour is low relative to the cost of capital. Similarly, technologies which require large number of skilled labour will be more competitive in a country where skilled labour is abundant (and hence cheap) than where it is scarce (Basu and Weil 1998; Caselli and Coleman 2006).

When it comes to building a domestic industry (as opposed to getting a new technology penetrating the market), five key resources have been identified from a literature review and a detailed interview based case study of the development of the solar PV manufacturing industry in China: knowledge (tacit and codified), markets (commodification and niche markets), financing investments (Venture Capital and government subsidies), and technology legitimacy (institutional embedding and technology certification standards) – see table 16.2 (Binz and Anadon 2018).

Table 16. 2 System resources for industry formation in second countries. From: Binz and Anadon (2018)

Key system resources for industry formation.

Resources	Sub-dimensions	Streams of literature	Key references	Basic argumentation
Knowledge	Codified knowledge (Know-what)	Economic Geography	(Asheim an Coenen, 2005; Bathelt an Glückler,	In a knowledge-based globalizing economy, knowledge (codified and tacit)

	Tacit knowledge (Know-how)	Innovation studies	2005; Crevoisier and Jeannerat, 2009; Freeman, 1987; OECD, 1996)	is a key resources for any innovative activity.
Markets	Commodification	Social construction of markets	(Dewald and Truffer, 2012; Fligstein and Zhang, 2011)	In newly emerging industries, commoditized products and protected niche markets are not given, but actively created by early entrepreneurs, user groups, and/or government intervention
	Niche markets	Transition studies		
Financial investment	Venture capital, banks, equity and institutional investors	Management, entrepreneurship and business literature	(Gustafsson et al., 2016; Surana and Anadon, 2015; Teppo, 2006; van den Bergh, 2013)	Entrepreneurial actors in a latecomer region need to mobilize various forms of financial investments to keep their new ventures in business and growing.
	Government subsidies			
Technology Liegitimacy	Institutional embedding	Institutional Sociology	(Johnson et al., 2006; Suchman, 1995; Zelditch, 2001)	New technologies that have no precedent in the social order are confronted with high scepticism by users, investors, and policy makers. They thus have to be aligned with the relevant (normative, regulative and cognitive) institutional structures
	Technology certification, standards		(Aldrich and Fiol, 1994; Rao, 2004)	

16.3.3 Main insights guiding innovation policy and practice

During the 20th century, the innovation agenda was dominated by a science-driven, technology-mediated change. Its contributions to economic growth and competitiveness have made a point of interest to policymakers. This has led to a further institutionalisation of a science and technology-centred innovation policy paradigm. During this period, associating innovation with technological novel was institutionalised via patent laws and development of R&D departments and laboratories. Science and technology policies were heavily influenced by the linear model of innovation often relying on supply-push mechanism or top-down centralised approach for R&D (Mazzucato 2018; Jong Tsong Chiang 1991). The focus is mainly on scientific and technological knowledge production. Nuclear energy and space programmes are the examples of such science and technology policy which is also known as mission-oriented innovation policies. However, such a supply-push mechanism created market failures whereby supply is greater than demand. Following that, the Apollo Program and the Manhattan Project came about with well-defined objectives that would guide scientific and technological research in a clearer direction. They were solely government-funded and dependent on a relatively small number of direct stakeholders.

In the last decades of the 20th century, the linear model of innovation policy has lost its influence as it was seen as overly simplistic and unfit for the transition towards sustainability (Fagerberg 2018). The linear model was criticised not only for producing disappointing direct results but also for failing to provide indirect broader structural support and mechanism for the diffusion of innovation. Therefore, science and technology policy, a policy for knowledge production, was slowly shifted to innovation system policy paying extra attention on the ability and capability of countries to diffuse innovation successfully in everyday practice. A more systemic or holistic view laid the ground for innovation system policy. It provides a complementary way of framing innovation through national (Bengt-Ake Lundvall 1992), regional (Koh and Lim 2010), sectoral (Malerba, F. 2002) or technological systems. This provides a powerful framework for policymakers to start applying the systems of innovation heuristic in order to generate a set of policy recommendation such as well-functioning patent laws, intellectual property rights, good infrastructure, access to finance and a healthy entrepreneurial climate. Innovation systems policy can be seen as one that broadly accommodates since most academics are more involved in academia-industry relations or engage in the triple helix of academia, industry and government. Other sources of contributions further open the innovation system to a broader variety of innovative actors such as entrepreneurs, users and citizens. Innovation systems policy mostly shies away from mission-oriented approaches and focuses more on creating enabling framework conditions for any innovation to happen in real life. Therefore, there is less room for strategic priorities, national prestige or broader societal issues to set the agenda.

The economic policy agenda has dominated over 30 years of uncontested hegemony, in which a shift towards a broader societal policy agenda becomes noticeable since mid-2000. Two of the key societal challenges are climate change and resource scarcity. Hence, the focus is not only directed on innovation policies that can optimise the innovation system to improve economic competitiveness and growth but also policies that can induce strategic directionality and guide processes of transformative changes towards desired societal objectives (Mitcham C 2003; Steneck 2006). Therefore, a wide variety of actors and ideas are aimed to connect innovation policy with societal challenges and transformative changes. In other words, this new policy paradigm is opening up a new discursive space for actors to move into and shape policy outcomes. Therefore, this is giving rise to the emerging paradigm of transformative innovative policy (Diercks et al. 2019; Fagerberg 2018).

Transformative innovative policy has a broader coverage of the innovation process with a much wider participation of actors, activities and modes of innovation. It is often expressed as social-technical transitions (Boelie Elzen, Frank W. Geels 2005; Edquist 2019) or societal transformations (Ian Scoones, Melissa Leach 2015; Roberts et al. 2018). The transformation innovation policy encompasses different ideas and concepts that aim to address the societal challenges involving a variety of discussions including social innovation (Mulgan 2012), complex adaptive systems (Lance H. Gunderson 2002), eco innovation (Kemp 2011) and framework for responsible innovation (Stilgoe et al. 2013), value-sensitive design (Friedmann. 1996) and social-technical integration (Fisher, E., Mahajan, R., Mitcham, C. 2006).

16.4 Role of innovation, technology development, diffusion and transfer in the context of mitigation pathways

Reaching the Paris Agreement target of limiting mean global temperature increase to 2C degrees with respect to 1900 levels (IPCC 2018) is strongly dependent on what actions are taken in the years to come at the local, regional and global level in all economic sectors, and of the timing of such action [AR6 Chapters 3, 4, 5 through 11 and 12]. The most ambitious pathways target the 1.5C degree limit; the least ambitious ones are consistent with the commitments that have been made through the Nationally Determined Contributions (NDCs), which are consistent with an increase of global mean temperature of above 3C degrees.

One of the key differences across the alternative pathways explored in the literature, either through top-down long-term IAMs [Chapter 3], through bottom up models [Chapter 4] or through any other analytical approach [ref. chapters 5 through 11 and 12] is the nature and timing of innovation, technology diffusion and transfer overall and across different sectors of the economy. Note that innovation and technological diffusion also play a role in supporting the achievement of sustainable development goals, but trade-offs between decarbonization and broader sustainable development need to be appropriately managed (IPCC 2018; McCollum et al. 2018a) [see section 16.2 in this Chapter].

16.4.1 The speed and depth of technical change in mitigation pathways and comparison with historically observed transformations

National and global IAMs show widespread agreement across several the high-level characteristics of mitigation pathways (IPCC 2018; Barker et al. 2009) (IPCC. Working Group III on Climate Change Mitigation 2014). For instance, to increase the chance attaining stringent climate targets such as 2°C or 1.5°C, economic growth should decouple from GHG emissions as soon as possible through the deployment of low-carbon technologies. There is also widespread agreement that such decoupling will not happen unless strong policy signals are put into place. In addition, the energy sector is consistently projected as decarbonizing first under any climate policy scenario. Models also indicate that climate targets will be attainable only if all other sectors of the economy decarbonize (such as transport, industry, buildings and agriculture). These dynamics are true at the aggregate level, as well as for specific countries which chose to delay climate action (Kriegler et al. 2015; Napp et al. 2019; Krey et al. 2019; Vrontisi et al. 2018). Importantly, available analyses show that the commitments implied by the Nationally Determined Contributions will not ensure the attainment of climate targets (Fragkos et al. 2018). Finally, the economic costs of mitigation associated with the 1.5°C target are significantly higher than those associated with the 2°C target, but a more stringent climate targets reduces significantly the risks associated with climate change (IPCC 2018).

Technological innovation and diffusion are the major drivers of emissions reductions in mitigation pathways which allow to achieving such large-scale, deep energy transition. In the context of the pathways, technological change includes the development of low- and zero-carbon energy options, but also investments for increased energy efficiency and negative emissions technologies.

An increasingly rich literature explores the extent to which the underlying technological trajectories of mitigation pathways are consistent with previously observed historical rates of technological innovation and deployment. Indicators informing on the rate of technological change include additional capacity installed, RD&D investments or emission trends, both in absolute values and normalized to account for the future system growth (i.e., by total capacity or GDP). As many modelling exercise recognize, the technically feasible chance identified by models does not necessarily factor in all non-technical constraints, such as economic, financial, institution or behavioural hurdles, which may impede the diffusion of low- and zero-carbon technologies [see more detailed discussion in Section 16.4.2]. Indeed, as illustrated in Chapter 2, and discussed in AR5 Chapter 5, historical observation suggests that technological development has increased, rather than decreased, fossil emissions. This may be due to dynamics associated with rebound effects (see section 16.2). Note that upward emissions trends also characterize more recent times, when low carbon energy technologies accounted for an increasingly large scale of energy generation. Indeed, between 2014 and 2017 global CO_2 emissions seemed to have stabilized. Yet, in 2018 and 2019 they started to increase again, indicating the economic growth has yet to decouple from the use of fossil resources [see Chapter 2 this report]. Finally, note that there is the distinct possibility that technological change in fact favours non-mitigation issues over reducing GHG emissions (as discussed in AR5 and in Section 16.4.3.2).

Regarding pathways for 2°C degrees climate targets, insights on the consistency of modelled rates of change with historical observations are ambiguous. Absolute near-term (2030) rates of change, whether measures as capacity, emissions or size of investments, vary in their consistency with historical observations. As shown in 2, while until mid-century several indicators appear as being broadly in line with what historically observed, the speed of technological development foreseen between 2030 and 2050 rumps up to unprecedented levels (van Sluisveld et al. 2015). Yet, normalizing all indicators for system growth, future change appears to be broadly within observed ranges (van Sluisveld et al. 2015). Yet, regional differences, for instance with respect to the financial investments needed to support the energy transition, are significant, with developing countries having a much higher average investment intensity (3.5%) as opposed to developed countries (1.3%) (McCollum et al. 2018b).

Table 16. 3 [Placeholder name of table]. Consistency of predicted rates of change with historical estimates for the energy sector. Source: (van Sluisveld et al. 2015).

			Absolute growth			Normalized growth		
			Baseline	Reference	2 Degree	Baseline	Reference	2 Degree
2010-2030	Average annual capacity additions	Fossil	🟥	🟥	🟦	🟩	🟩	🟦
		Non-fossil	🟦	🟦	🟦	🟩	🟩	🟦
	Average annual emission decline rates	System	🟩	🟩	🟦	🟦	🟦	🟦
	Average annual supply-side investments	System	🟩	🟥	🟥	🟩	🟩	🟩
2030-2050	Average annual capacity additions	Fossil	🟥	🟥	🟦	🟩	🟦	🟦
		Non-fossil	🟦	🟦	🟥	🟩	🟩	🟦
	Average annual emission decline rates	System	🟩	🟦	🟥	🟦	🟦	🟥
	Average annual supply-side investments	System	🟥	🟥	🟥	🟩	🟩	🟩
	Technology diffusion	Tech-specific				🟩	🟩	🟩

	Not applicable
🟩	Below historical growth frontier for corresponding technology
🟦	Below historical growth frontier for any technology
🟥	Above historical growth for any technology

Notes: while until mid-century several indicators appear as being broadly in line with what historically observed, the speed of technological development foreseen between 2030 and 2050 rumps up to unprecedented levels. Yet, normalizing all indicators for system growth, future change appears to be broadly within observed ranges.

Yet, comparability with historical rates may be not appropriate in the case of low carbon technologies (Verdolini et al. 2018), especially under more stringent climate policies, which provide much higher incentives for innovation than previously observed. In this respect, it is worth noting that recent technological developments in certain energy technologies, such as solar and batteries, have surpassed both predictions based either on historical or on expert elicitations methods, as illustrated in Figure

16.2 (Verdolini et al. 2018). Yet, while the penetration of solar energy in the energy mix is speeding up, the penetration of electric vehicles is lagging behind in most countries. This once more indicates that low technology costs are not per se a sufficient condition for technology diffusion. Additional non/technical barriers exist, as discussed in Section 16.4.2.

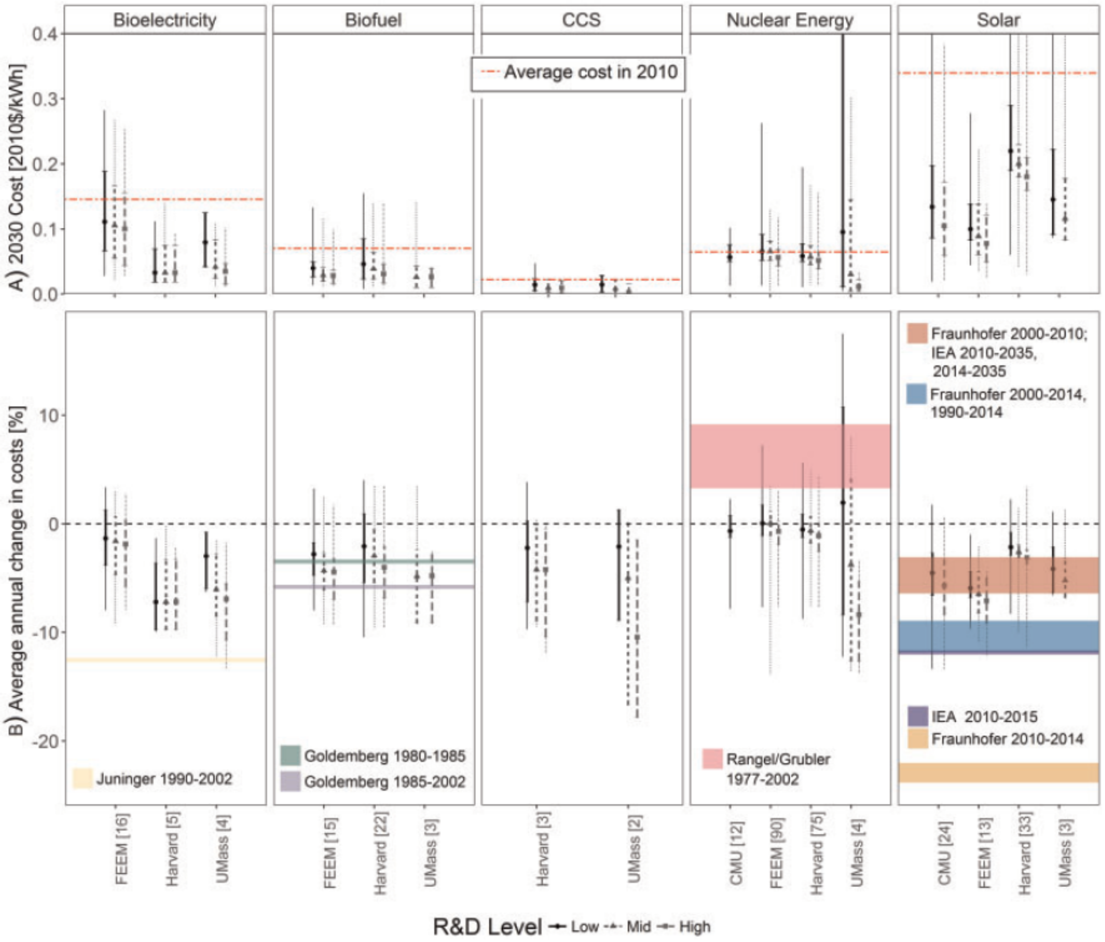


Figure 16. 2 [placeholder name of figure] Comparison of expert elicitations cost estimates with historical trends and model forecasts. Source: (Verdolini et al. 2018)

16.4.2 The role of non-technical barriers: assessing assumptions on the innovation process in future pathways for the low-carbon transition

Integrated Assessment Models (IAMs) are based on (energy) engineering principles and neo-classical economics. While such models may differ greatly with respect to the modelling approach they implement, they generally assume that choices regarding investment in the different (low-carbon) technologies are determined by pure economic considerations, i.e. they are made by comparing relative prices of different technological options (Iyer et al. 2015). Yet, an increasingly rich literature shows that the process of technological change is strongly influenced by a number of other key factors, currently not well accounted for in IAMs. For instance, the benefit associated with adopting a new low-carbon technology may depend on the number of users. In this case, the "network externalities" generate mutual dependence among actors, and either promote technological change or slow it. Their overall impact may be positive if they reduce the risk of technology adoption, but also negative, if users delay the decision to adopt until a certain number of other users also decides to adopt. Similarly, factors such as the co-evolution of technology clusters over time ("path dependence"), infrastructure externalities, the risk-aversity of users, personal preferences and perseptions and lack of adequate institutional frameworks constrains may negatively influence the speed of (low-carbon) technological innovation and diffusion (van Sluisveld et al. 2018). Another important aspect governing low-carbon innovation is uncertainty around the presence and the level of environmental policies. This gives rise to an "option value", namely users have incentives to postpone the adoption of new technology to the future if they are not certain on the presence and level of environmental policy (Iyer et al. 2015).

The fact that IAMs do not depict all these dynamics and factors has two important implications for technological change and diffusion dynamics. On the one hand, scenarios emerging from cost-optimal integrated assessment models may be too optimistic regarding the timing of action, or the availability of a given technology and its speed of diffusion. The presence of non-cost, non-technological barriers regarding behaviours, society and institutions may slow technology diffusion even if low-carbon technologies are cost-competitive with fossil technologies, and also in the presence of strong climate policies. If such constraints were to be factored into the analysis, the resulting decarbonisation pathways will give rise to significantly different (and slower) patters of low-carbon technology innovation and diffusion (Clarke et al., 2009; Edmonds, Clarke, Lurz, & Wise, 2008; Stocker, 2013). This would lower the probability of attaining even the less stringent climate targets. Overall the literature argues that introducing and sustaining lifestyle change is not as straightforward as a (prescriptive) modelling approach may suggest. The design of a successful policy strategy requires knowledge of all these factors that determine and sustain changes in specific behaviors.

On the other hand, IAM may be too conservative because they leave out a particular set of mitigation options since they cannot appropriately portray mitigation channels such as lifestyle changes. Indeed, the literature evaluating the potential implications of modelling such dynamics is only limited (see for instance Roy et al. 2000). A few analysis provide evidence that demand-side actions, such as behavioural changes, can make a discrete difference in demand sector (consumers), with reductions potential of roughly 15-20% in the residential (Dietz et al. 2009) sector and of roughly 20-35% in the transport sector (Iyer et al. 2015). Evidence for industrial sectors is more scarce and suggests that measures targeting lifestyle changes may not provide mitigation opportunities unless accompanied by short term radical changes in energy infrastructure. Effectively, this suggests that mitigation opportunities in hard-to-decarbonize sectors may be unlocked only by pre-emptively reducing energy demand and transitioning to electricity-driven end-use sectors, (van Sluisveld et al. 2016).

The negative effect of non-technical factors is particularly crucial if policy action is delayed by a few decades, as they negatively impact the feasibility (or, alternately, on the mitigation costs) of achieving stringent climate stabilization targets. Conversely, if stringent environmental policies are implemented without delay, non-technical factors play a less critical role. Moreover, non-technical constraints to technology innovation and diffusion are particularly important if the diffusion of multiple technologies is jointly constrained (Iyer et al. 2015).

Another key aspect of decarbonisation regards issues of acceptability and social inclusion in decision-making. Participatory processes involving stakeholders can be implemented using several methods to incorporate qualitative elements in model-based scenarios on future change (Schmid et al. 2016; Salter et al. 2013; van Sluisveld et al. 2018).

16.4.3 Key role of new disruptive technologies

16.4.3.1 New low and zero-carbon disruptive technologies

An important result emerging from the comparison of different mitigation pathways is that the more we delay mitigation effort, the more we will need to rely on disruptive, backstop negative and zero-emission technologies to achieve a given climate target (Luderer et al. 2018). Table 16.4 provides examples of incremental, transformative a mitigation options for different sectors [to be completed]. Table 16.4 shows the increasing importance of incremental, transformative and disruptive technologies as a function of the timing of climate action.

As an illustrative example, we note that 2°C degrees climate scenarios characterized by delayed action the forecate particularly steep declines of emissions in the second half of the century. To achieve this, they rely on large-scale deployment of carbon dioxide removal (CDR) technologies, which raise major concern not only in terms of technical feasibility but also, and most importantly, in terms of sustainability. Conversely, ambitious near term mitigation significantly decreases CDR requirements to keep reach stringent climate targets (Strefler et al. 2018).

Table 16.4 Examples of mitigation opportunities for several key sectors and degree of transformation required. Sources:

Mitigation options	Incremental	Transformative	Disruptive
	Energy sector		
Energy generation	- Increase penetration of traditional renewable technologies (solar PV, onshore wind, hydro) - biofuels - use of forestry products for bioenergy to replace fossil fuel use	- Smart grids and prosumers - Energy storage - CCS - Geothermal - Offshore wind - Solar CSP	- Hydrogen from renewable sources
Negative emission technologies	- Afforestation - reforestation; - forest management - reduced deforestation - harvested wood product management	- Direct Air Capture	- Ocean alkalinization
	Industrial sector		
Production	- Energy efficiency - Industrial automation - Zero-waste production	- Electrification (e.g., electric arc furnace) - Circular economy - Bio-based plastics	- 3D printing - Industry 4.0 - Beyond the plant fence - Air-to-material
Chemical	- Energy efficiency	- Bio-based chemicals - Nanotechnologies	- Synthetic fuels
	Transport sector		
Passenger travel and freight	- Car sharing - Mass transport - Hybrid vehicles	- Self-driving vehicles - Electric vehicles	- Mobility as a service - Drone delivery
Air travel	- Reduction in demand for air travel	- Bio jet fuel	- Electric planes
	Building sector and energy demand		
	- Efficient lighting and daylighting	- passive and active solar design for heating and	

	- More efficient electrical appliances and heating and cooling devices - improved cook stoves, improved insulation	cooling - alternative refrigeration fluids	
Agriculture & Husbandry			
Food production	- Farm level mitigation options for crop and livestock production -	- Novel feeds (algae, insects, food waste) - Gene editing - Bio-refineries - Rooftop greenhouse - Indoor farming - Biochar	
Emerging Food Products and production systems	- Plant-based meat replacements	- Bio-refineries - Insects - Myco-proteins	- Laboratory haem, milk and eggs proteins
Meat Production	- Reduced meat demand	- Change in livestock feeding to reduce methane emissions	- Cultured meat

16.4.3.2 Other disruptive technologies, including digitalization

Digitalization is profoundly reshaping economies and societies; it will also affect decarbonisation. Digitalization will impact decarbonisation through several channels. Digital technologies consume large amounts of energy. They also contribute to (energy) efficiency in economic and human systems through material input savings and increased coordination. Furthermore, the digital transformation will have profound distributional effects (i.e., it will affect competitiveness, trade, and employment because of increased automation).

Lastly, digitalization may influence mitigation potential, making it easier and cheaper (or harder and costlier) to implement stringent climate policies across sectors and countries (i.e., enhancing policy enforcement). Yet, the (IEA 2017) shows that the magnitude of potential impacts – and associated barriers – of digitalization in transport, buildings and industry varies greatly depending on the particular application. (Horner et al. 2016) show that uncertainty persists in understanding the net energy effects of ICT. Results of indirect energy effect studies are highly sensitive to scoping decisions and assumptions made by the analyst. Uncertainty increases as the impact scope broadens, due to complex and interconnected effects. However, there is general agreement that ICT has large energy savings potential, but that the realization of this potential is highly dependent on deployment details and user behaviour.

16.5 National and subnational innovation policies and activities

National policies play a key role for the redirection and acceleration of technological innovation (Rogge and Reichardt 2016) (Anadon et al. 2016b) (Anadón et al. 2017)(Roberts et al. 2018)(Åhman et al. 2017) *(robust evidence, high agreement).*

This section (1) offers a set of frameworks for understanding the role of government policies at a national level that shape the development and diffusion of technologies that can advance climate change mitigation and adaptation; (2) includes a classification of policies that are relevant for technology innovation in technologies for climate change mitigation and adaptation; (3) takes stock of the overall empirical and theoretical evidence that has emerged regarding the relationship between those policies and (primarily) innovation outcomes; and (4) reviews literature on the role of different actors conducting technology innovation in technologies relevant for climate change mitigation, including universities, firms, national labs, start-ups, and users.

This section and chapter do not select or prioritize the technologies or sets of technologies that need to be developed, improved and/or deployed to best advance climate change mitigation. Many considerations are needed to conduct such selection or prioritization to maximize the synergies and minimize the trade-offs with other Sustainable Development Goals (McCollum et al. 2018a; Fuso Nerini, Francesco; Tomei, Julia; To, Long Seng; Bisaga, Iwona; Parikh, Priti; Black, Mairi, Borrion, Aiduan; Spataru, Catalina; Castán Broto, Vanesa; Anandarajah, Gabrial; Milligan, Ben; Mulugetta 2018). Many such considerations need to be considered at a national or local level.

When relevant, this section on policies highlights examples of policies or initiatives that delve more deeply into the main high-level sectors: power, transport, industry, buildings, and AFOLU.

Finally, when possible, this section also discusses issues in policy selection, design, and implementation that have been identified as more relevant in developing countries and emerging economies.

16.5.1 Frameworks for studying the determinants of technological innovation

The role of the state shaping the advancement of science, technology and innovation to improve health, national security and public welfare goals became very visible after World War II,Vannebar Bush (Bush 1945). The need to better understand the factors driving technological innovation and economic growth emerged from the observation in the 1970s that while some countries had industrialized rapidly (e.g., the Asian Tigers), others had not, and the United States and Europe were believed to be slowing down (Nelson 1993a). Investigating the role of national level actors and institutions (including policies) was prominent from the start.

In the broader innovation literature, there are several frameworks for understanding how technologies are invented, developed and adopted as well as the role of different actors and institutions, with the literature including a greater range of actors over time.

The first framework is that of *national innovation systems*, which highlights the importance of national and regional relationships for determining the technological and industrial capabilities and development of a country when compared to international connections and processes (Nelson 1993b; Freeman 1995). Later a similar concept was developed to account for differences across industrial sectors. The second framework is that of *sectoral innovation systems*, which emphasizes the need to study the “set of agents carrying out market and non-market interactions for the creation, production and sale of [those] products” with interactions that are “shaped by institutions” (Malerba, F. 2002). Sectoral innovation systems, importantly, did not just include technologies, actors and policies, but also the knowledge base, inputs and demand (Malerba, F. 2002). The third , more recent framework, is that of *technology innovation systems* which focuses on explaining what accelerates or hinders the development and diffusion of a technology or set of technologies (more narrowly or broadly defined in different cases) as the unit of analysis (Hekkert, MP; Suurs, RAA; Negro, SO; Kuhlmann, S; Smits 2007; Binz C, Truffer B 2014).

This framework identifies seven functions (or processes) that are important for ‘well performing innovation systems’ and takes a dynamic view including (for example) guidance of search, entrepreneurial networks, and experimentation (Hekkert, MP; Suurs, RAA; Negro, SO; Kuhlmann, S; Smits 2007). A significant fraction of analysis of technology innovation systems relying on this framework focussed on technologies related to pollution abatement, climate mitigation (e.g., (Hekkert, M.P. & Negro 2009), or the energy transition (mostly based on qualitative case studies) focussed on technologies. More recent work explains how some of the sectoral, geographical and political dimensions intersect with technology innovation systems (Bergek et al. 2015). The fourth framework, referred to as the *multilevel perspective* (Geels 2002), also focusses on technologies and has had a particular focus on technologies with impact on environmental outcomes, but studies the evolution of such technologies in particular in relation to the incumbent technologies in the sector and the overall economy.

Overall, technology innovation takes place in the context of "innovation systems," which can be thought of as the connected set of actors (including researchers, firms, consumers, the finance community, policy makers and other groups) and institutions that shape innovation processes with different speed and level of complementarities across technologies and sectors ((Lundvall 2010; R Nelson 1993; Anadon, LD; Chan, G; Harley, A; Matus, K; Moon, S; Murthy, S; Clark 2016; Bergek et al. 2015; Geels 2004, 2002) often across different spatial scales (Binz C, Truffer B 2014; Binz and Anadon 2018) (*robust evidence, high agreement*).

Because of the multiple market, system and institutional failures that are associated with the energy system, a range of policy interventions are usually required to enable the development and introduction of new technologies in the market (Rationales for additional climate policy instruments under a carbon price 2012; K.M. Weber 2012; Negro et al. 2012; Jaffe et al. 2005; M.J. Bürer 2009) and used in what is termed as policy mixes (Rogge and Reichardt 2016). Empirical research shows that when in the energy and environment space new technologies were developed and introduced in the market, it was usually at least partly as a result of more than one policy (i.e., of a range of policies) that shaped the socio-technical system (Nemet 2019b; Bunn et al. 2014; Bergek et al. 2015; Rogge and Reichardt 2016) (*robust evidence, high agreement*).

There are many definitions of policy mixes from various disciplines (Rogge et al. 2017), including environmental economics (Lehmann 2012), policy studies (or public policy)(Kern and Howlett 2009) and innovation studies. Generally speaking, a policy mix can be characterized by a combination of building blocks elements, processes and the characteristics of such elements and processes set in different policy, governance, geography and temporal contexts (Rogge and Reichardt 2016). The building block elements include the policy strategy with its objectives and principal plans and the mix of policy instruments, the policy processes that led to the creation of such mix of policies. These elements are the result of policy processes. Both elements and processes can be described by their characteristics in terms of the consistency of the elements, the coherence of the processes, and the credibility and comprehensiveness of the policy mix (Rogge and Reichardt 2016). In addition, many have argued the need to craft policies that affect different actors in the transition, some supporting and some 'destabilizing' (see e.g., (P. Kivimaa 2016; Geels 2002).

Overall, the literatures on innovation systems, complex systems, and socio-environmental systems show that innovation systems are: (a) characterized by linked innovation activities and feedbacks, positive and negative impacts and potential for non-linear impacts; (b) shaped by the interactions of social and technological factors; and (c) guided by institutions that tend to embody the goals of those that are in powerful roads more so than those of the poor, marginalized or `future populations, although these institutions can be reshaped by different actors (Anadon, LD; Chan, G; Harley, A; Matus, K; Moon, S; Murthy, S; Clark 2016) (*medium evidence, high agreement*).

The diffusion of renewable energy is one example in which the novel technology has been hindered by the actions of powerful fossil energy incumbents, displaying the power imbalance between incumbent powerful actors, economies of scale, powerful incumbent firms, a long history of incremental technological improvement, and the long life of physical and institutional supporting infrastructure have given economic and political advantages to incumbent technologies, (Unruh 2002; Supran and Oreskes 2017; Hoppmann et al.) (*robust evidence, high agreement*).

The development and diffusion of less polluting and more fuel-efficient cookstoves is another example of the power imbalance mostly taking place in the developing world. The use of inefficient biomass stoves contributes to local deforestation, as well as climate change, and is a major public health threat in the developing world because of the negative health impacts caused by products of incomplete combustion from cooking. Because these problems could be reduced by using more fuel efficient cookstoves, their development has attracted attention for decades (World Bank. 2008). However, many efforts to develop them did not yield lasting results, because the needs of the (often marginalized) users were not taken into account. More recent efforts in technology development have tried to incorporate these needs (e.g., (Booker et al. 2012)(Booker et al. 2012) (*robust evidence, high agreement*).

Overall, the direction and pace of technology innovation is shaped by a wide range of actors and is disproportionately shaped by those that are most powerful and organized. The particularities of innovation depend on local context, institutions, geography, as well as on the characteristics of the sector and the technology (*robust evidence, high agreement*).

16.5.2 Frameworks for identifying barriers to innovation in climate related technologies

This section focuses on frameworks to understand the relationship between barriers to innovation in environmental or climate related technologies and possible (often national- or regional-level) policies to address such barriers.

16.5.2.1 Different frameworks for identified barriers to innovation for policy design purposes

One such effort used renewable energy technologies as a case study of novel technologies trying to disrupt incumbents. This study combined an inductive analysis of renewable energy case studies across a range of countries with various literatures to classify barriers into hard and soft institutions, market structures, capability problems, knowledge and physical infrastructure, too weak and too strong interactions, and physical infrastructure (Negro et al. 2012) (Bergek et al. 2008) (see Table 16.5 below). Importantly, this analysis identifies knowledge and physical infrastructure as one of the key barriers, highlighting the importance of domestic capabilities.

Table 16.5 Categorization of systemic problems preventing different types of renewable energy technologies from reaching their potential. The table includes detail of the number of case studies in which the particular 'systemic problem' was identified. Source: (Negro et al. 2012).

Allocation scheme of systemic problems.

Systemic problems	Empirical sub categories	No. of cases
Hard institutions	1. 'Stop and go policy': lack of continuity and long-term regulations; inconsistent policy and existing laws and regulations 2. 'Attention shift': policy makers only support technologies if they contribute to the solving of a current problem 3. 'Misalignment' between policies on sector level such as agriculture, waste, and on governmental levels, i.e. EU, national, regional level, etc. 4. "Valley of Death": lack of subsidies, feed-in tariffs, tax exemption, laws, emission regulations, venture capital to move technology from experimental phase towards commercialisation phase	51

Market structures	1. Large-scale criteria Incremental/near-to-market innovation Incumbent’s dominance	30
Soft institutions	1. Lack of legitimacy Different actors opposing change	28
Capabilities/capacities	1. Lack of technological knowledge of policy makers and engineers Lack of ability of entrepreneurs to pack together, to formulate clear message, to lobby to the government Lack of users to formulate demand Lack of skilled staff	19
Knowledge infrastructure	- Wrong focus or not specific courses at universities knowledge institutes - Gap/Misalignment between knowledge produce at universities and what needed in practice	16
Too weak interactions	- Individualistic entrepreneurs - No networks, no platforms - Lack of knowledge diffusion between actors - Lack of attention for learning by doing	13
Too strong interactions	- Strong dependence on government action or dominant partners (incumbents) - Networks allows no access to new entrants	8
Physical infrastructure	- No access to existing electricity or gas grid for RETs - No decentralised, small-scale grid - No refill infrastructure for biofuels, ABG, H2, biogas	2

While the Negro et al (2012) framework sets out factors that need to be addressed by policy from a systems perspective inductively from a range of cases, work published by the Organization for Economic Cooperation and Development (OECD) frames the barriers in terms of market failures (OECD 2011), a commonly used terminology in economic and policy circles.

The OECD framework, which also builds on an extensive literature in economics, indicates that across a range of sectors, the incentives for firms and other actors to invest in ‘green’ activities, including in innovation in ‘green’ technologies stem from various factors.

First, low economic returns resulting from inertia in across various societal sectors, particularly in sectors that are commoditized, leading to low R&D intensity levels in (for example) regulated utilities, at the same time, restructuring electricity markets were associated with even lower R&D investments given the lower ability to invest for the longer term (Sanyal and Cohen 2009a). This inertia can come from the inability to reap the returns from R&D (something that can be shaped by existing regulations, incentives and norms), network effects which favour incumbent technologies), barriers and competition and norms and habits of consumers and decision makers.

A second factor that reduces incentives to invest in green innovation is referred to as ‘low social returns’ and it includes difficult related to inadequate infrastructure, low human capital, poor institutional quality, etc.

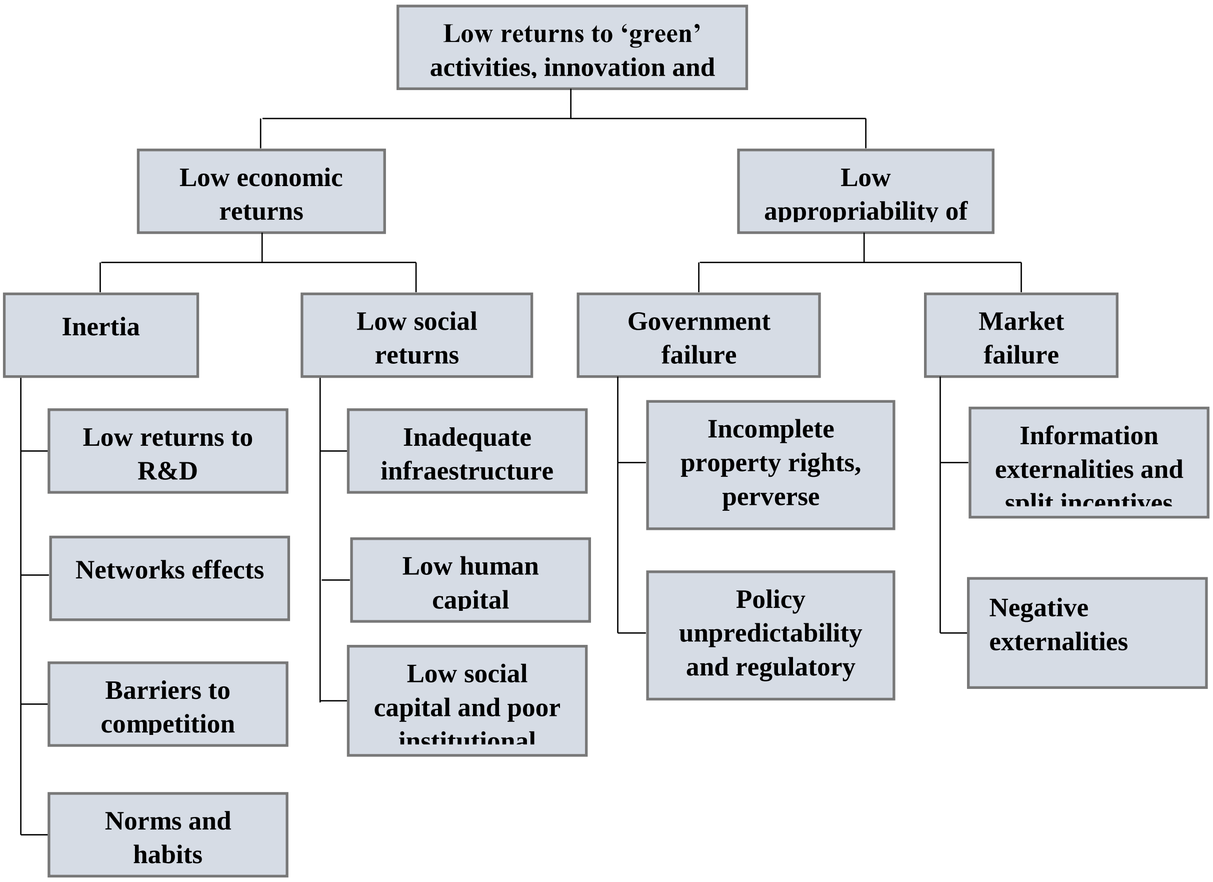


Figure 16. 3 Overview of drivers of low returns to green activities, innovation and investment. Source OECD (2011)**, based on** (Hausmann, R, Velasco, A, Rodrik 2008).

16.5.2.2 Evidence on low green innovation activity in the private sector

Many sectors crucial for climate mitigation, among which industrial metals and mining, electricity, construction and materials, oil & gas producers, forestry and paper, gas, water and multi-utilities, and industrial transportation, and banks, among the industries in the low R&D intensity category, namely investing less than 1% of sales in R&D include. With and without deregulation, the variety of incentives for traditional electricity utilities in Europe and the U.S. has traditionally led to low R&D investments in electric utilities (Sanyal and Cohen 2009b; Jamasb and Pollitt 2005).

The venture capital financing model, which has been used in the biotech and IT space, is not have been as suitable for hardware startups in the energy space: the percentage of exit outcomes in clean-tech startups was almost half of that in medical startups and less than a third of software investments (Gaddy, BE, Sivaram, V, Jones, TB, Wayman 2017). Complementary research documents the 'valley of death' in hardware energy technologies indicating that the current VC model and other private finance does not sufficiently cover the need to demonstrate technologies at scale (Nemet et al. 2018; Anadon 2012). Similarly, data on venture capital and private equity finance for renewable energy technologies, which typically aims at relatively innovative technologies (after R&D but generally before large scale deployment) (UN Environment; Frankfurt School; Bloomberg New Energy Finance 2019) shown in Figure 16.5, indicates that this greater difficulty in growing in the market compared to other sectors may have contributed to a reduction in private equity and venture capital finance for renewable energy technologies after the boom of the late 2000s.

Overall, evidence shows that some of the industrial sectors that are important for meeting climate goals (electricity, agriculture and forestry, mining, oil and gas, and other energy intensive industrial sectors)(European Commission 2015; Gaddy, BE, Sivaram, V, Jones, TB, Wayman 2017; National Science Board 2018; American Energy Innovation Council 2017; Jamasb and Pollitt 2005; Sanyal and Cohen 2009b) are investing, because of the existing incentives, relatively small fractions of sales on R&D (*medium evidence, high agreement*).

The role of governments setting incentives and supporting research is particularly important (Weyant 2011; Anadon 2012; Anadón and Nemet 2011; Nemet et al. 2018) (*medium evidence, medium agreement*).

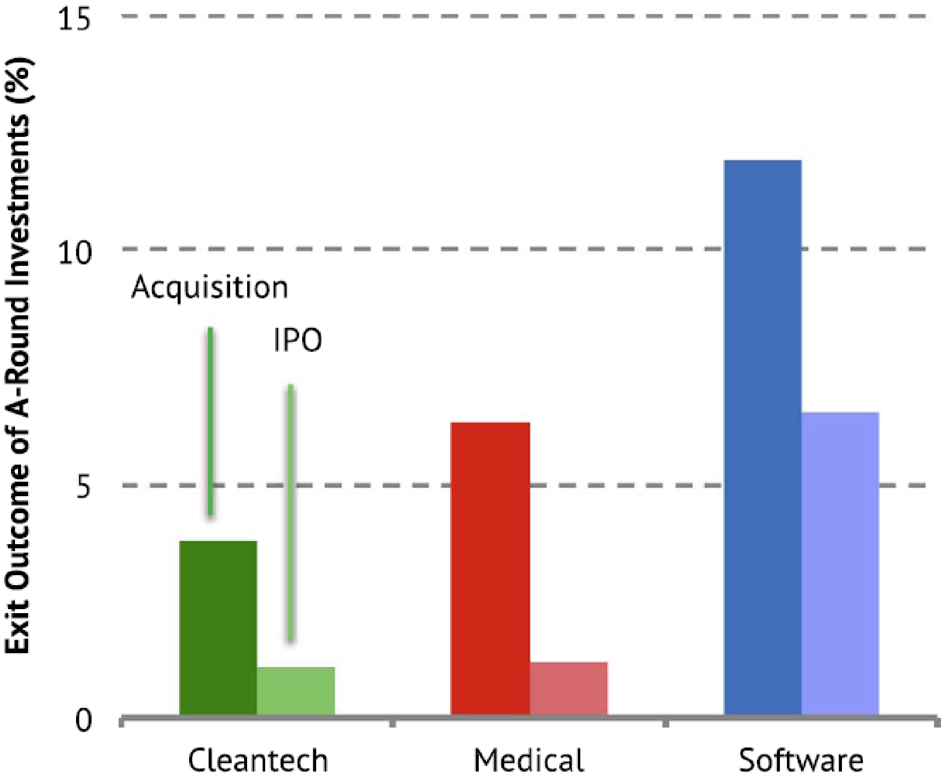
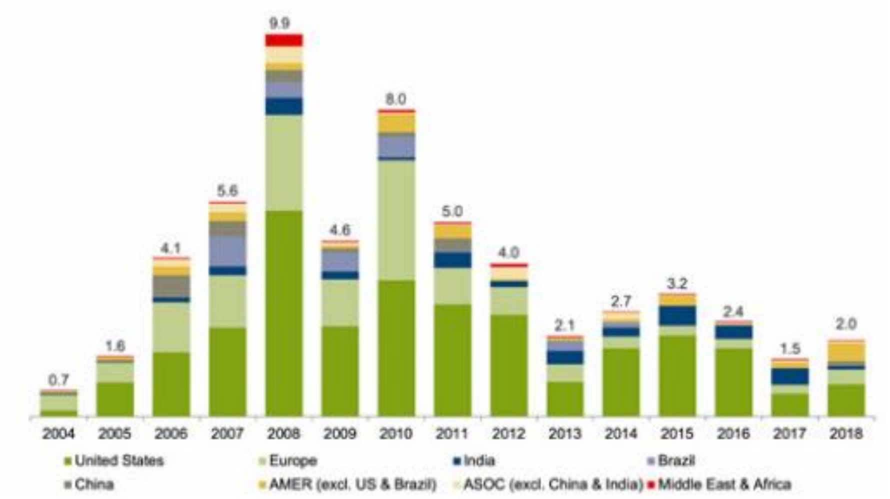


Figure 16. 4 Percentage of exit outcomes for investors in cleantech, medical or software companies between 2004 and 2014. Outcomes are shown as the percentage of companies receiving A-round in each sector that exited through an IPO or acquisition. Source: (Gaddy, BE, Sivaram, V, Jones, TB, Wayman 2017).



Buy-outs are not included as new investment. Total values include estimates for undisclosed deals.
Source: UN Environment, Frankfurt School-UNEP Centre, BloombergNEF

Figure 16. 5 Evolution of global venture capital and private equity investment in renewable energy by region 2004-2018 in billions of US$. Source: (UN Environment; Frankfurt School; Bloomberg New Energy Finance 2019)

16.5.2.3 Summary of barriers to climate-related technology innovation for policy design

The barriers highlighted in both the TIS and OECD frameworks for identifying barriers that should be considered by policy makers when designing policies to promote innovation in climate, green or environmental technologies, as well as the evidence available on private R&D and early funding for climate-related technologies suggest that the following are key high-level issues that national policy makers should consider for promoting innovation (*robust evidence, high agreement*):

- low economic returns to activities in these areas because of environmental and other impacts
- market structures favorable to incumbents, including barriers to competition
- low returns to R&D and valley of death questions
- policy unpredictability (stop and go policy) and uncertainty
- poor or inadequate physical infrastructure
- low human capital among policy makers and other actors
- lack of networks or missing or weak interactions between different actors
- norms and habits and lack of legitimacy of new players

16.5.3 Typology of policies shaping technology innovation in climate-related technologies

The literature on environmental policy evaluation focusses on different subgroups and uses different terminologies, including energy technologies, environmentally sound technologies, low-carbon technologies, etc. Broader economic literature typically classifies public policy instruments in three broad categories (HA De Bruijn 1998; John 2011; Borrás and Edquist 2013; Rogge and Reichardt 2016): regulatory instruments, economic instruments and soft instruments, with a couple of exceptions, one of which is focussed on digital technologies (Linder 1998; Hood 2007). Conversely, the literature on the economics of innovation classifies policies as technology push and market pull policies (Mowery and Rosenberg 1979). This high-level classification into push and pull has been further developed in research focussed on the energy sector by providing examples of technology push policies (including direct R&D funding, education policies, demonstration projects, R&D tax credits, and funding for R&D partnerships) and market pull policies including deployment incentives, standards, or prices (Anadon and Holdren 2009).

More detailed classifications have been proposed over the years specifically for policy instruments designed to support decarbonisation, such as, for example, the ones developed by the IEA, the OECD, or IRENA among others largely build on the regulatory, economic and soft instrument typology from the literature (Penasco, C., Anadon, Laura Diaz, Verdolini 2019). Building on these previous efforts, Penasco et al (2019) developed a three-tiered classification of policy instruments available to support the low-carbon transition in Table 16.6 below with a focus on technology innovation. At the highest level of aggregation, this policy instrument categorization is divided into regulatory, economic and financial, and soft instruments. These high-level categories are complemented with two more granular levels. This classification is broadly aligned with the typology used in Chapter 13: National and sub-national policies and institutions.

In short, policy instruments shaping innovation can largely be characterized as economic and financial instruments (including subsidies, carbon markets, carbon prices, public procurement, loans, taxes, and direct funding for R&D and demonstration or innovative partnerships), regulatory instruments (including performance, technology, fuel, or other standards) and soft or information instruments (including performance labels, voluntary standards and behavioural policies). While other policies (such as monetary, banking and trade policies, for instance) also shape innovation, most activity and action has focussed on the previously mentioned policy instrument categories (*robust evidence*, *high agreement*).

Table 16. 6 Types of policy instruments for the decarbonisation shaping innovation in the regulatory instrument and economic instrument categories. Source: From (Penasco, C., Anadon, Laura Diaz, Verdolini 2019) based on IEA classification (IEA 2008; IRENA 2015; ILO 2011). Broadly aligned with the Policy Typology in Chapter 13.

<table>
<tr><th colspan="5">Regulatory instruments</th></tr>
<tr><td colspan="3">Codes/ standards / mandates</td><td colspan="2">Obligation schemes / quotas</td></tr>
<tr><td>Building codes and standards</td><td>Product standards</td><td>Vehicle-fuel economy and emissions standards</td><td colspan="2">Renewable Energy obligation schemes</td></tr>
<tr><th colspan="5">Economic and Financial instruments</th></tr>
<tr><td colspan="2">Direct investment</td><td colspan="2">Fiscal / Financial incentives</td><td>Market-based instruments</td></tr>
</table>

<table>
<tr><td>Government Procurement</td><td>RD&D funding</td><td>Feed-in tariffs / premium</td><td>Auctions</td><td>Taxes-tax relief / exemption</td><td colspan="2">Grants and subsidies</td><td>Loans and soft loans</td><td colspan="2">User chargers</td><td colspan="2">GHG emissions allowance trading schemes</td><td>Green certificates</td><td>White certificates</td></tr>
<tr><td colspan="14">Soft Instruments</td></tr>
<tr><td colspan="2">Performance labels</td><td colspan="4">Information campaigns</td><td colspan="8">Voluntary approaches</td></tr>
<tr><td>Comparison Labels</td><td>Endorsement labels</td><td colspan="4">(by energy agencies, energy suppliers, etc…)</td><td colspan="3">Negotiated agreements (Public-private sectors)</td><td colspan="2">Public voluntary schemes</td><td colspan="3">Unilateral commitments (private sector) / Environmental Management Systems (EMSs)</td></tr>
</table>

[As it will be discussed later, different literatures aim to link the factors that limit innovation in Table 16.6 and Figure XX.]

Table 16. 7 Policy taxonomy from Chapter 13. Note that both taxonomies are quite aligned, but this chapter relies on the Table 16.6 taxonomy because it provides more detail on policy instruments that are more often explicitly focussed (at least partly) on advancing innovation in climate related or clean technologies.

Suggested Revised Taxonomy	**Notes**
Economic or market-based instruments	Overarching category
Taxes	Not just carbon taxes; also refers eg to energy taxes, congestion taxes etc
Permit trading	
Other trading mechanisms	Includes eg tradable performance standards. Eg energy efficiency (White Certificates), emissions intensity in power and industry, renewable energy shares in power supply (Renewable Portfolio Standards) etc.
Hybrid instruments	Typically a quantity-based instrument with a price override, or vice versa, eg a trading scheme with a floor price and ceiling; can apply to other trading mechanisms too
Offset systems	Domestic and international offset schemes
Subsidies	A relatively large share of policies in buildings and services/demand fall in this category

Direct regulation	Overarching category
Technology standards	
Performance standards	
Other direct regulation	To cover specific policies that are not readily classified as performance standard or technology standard
Other policies	Overarching category
Information programmes and policies	
Government provision of public goods, services and infrastructure	
Voluntary agreements between govts and private firms	
Behavioural change programmes and policies	This is separate and distinct from information programmes

There have been some attempts to link the barriers to green innovation in section 16.4 to a lists of high-level policies such as that listed in Table 16.4. In particular, Table 16.4 links the different barriers to green innovation listed in Table 16.3 with a selected set of policies that at least theoretically could (if they are adequately designed and implemented) address the barrier.

Table 16. 8 Selected set of possible policies to address green growth constraints in Figure 16.5. Source: **(OECD 2011)**.

Green growth constraints	Policy options
Inadequate infrastructure	• Taxes • Tariffs • Transfers • Public-private partnerships
Low human and social capital and poor institutional quality	• Taxes • Subsidy reform/removal
Incomplete property rights, subsidies	• Review and reform or remove
Regulatory uncertainty	• Set targets • Create independent governance systems
Information externalities and split incentives	• Labelling • Voluntary approaches • Subsidies • Technology and performance standards
Environmental externalities	• Taxes • Tradable permits • Subsidies
Low returns on R&D	• R&D subsidies and tax incentives

	• Focus on general-purpose technologies
Network effects	• Strengthen competition in network industries • Subsidies or loan guarantees for new network projects
Barriers to competition	• Reform regulation • Reduce government monopoly

Yet, governments also need to reduce policy costs, improve competitiveness, and ensure energy security, affordability, and fairness while pursuing all the Sustainable Development Goals.

16.5.4 Rationales for and politics of national policies in the climate change mitigation and adaptation space

In contrast with earlier periods, at the start of the 21st century different governments around the world increasingly implemented innovation policies with the aim of simultaneously advancing environmental and industrial policy (or competitiveness) goals ((Anadon 2012).see for example,(Surana and Anadon 2015; Meckling et al. 2017; Matsuo and Schmidt 2019). Access and distributional fairness has also been an important consideration in many countries and it is emerging as a stronger factor (*medium evidence, medium agreement*).

Co-benefits, including innovation and competitiveness can therefore be important drivers of climate mitigation policy in the innovation sphere (Deng et al. 2017). This was the case for climate and air pollution policies with local content requirements for different types of renewable energy projects in places including China (Lewis 2014; Qiu and Anadon 2012), India (Behuria 2020)b, South Africa (Kuntze et al. 2013), and Canada (Vanier 2014) (*robust evidence, medium agreement*).

Most of the analysis concerned with the politics driving national policies related to promoting the development and diffusion of climate-related technologies, focuses on renewable energy technologies. One can identify three phases of politics in the development of policies to meet climate and industrial objectives (Hanna Breetz 2018).

In the first phase of 'niche market diffusion', the politics of more sustained support for a technology or set of technologies become possible after a group of economic winners and 'clean energy constituencies' are created (Meckling, J., Kelsey, N., Biber, E., and Zysman 2015). When technologies grow out of the niche (second phase), they pose a more serious competition to incumbents who may become more vocal opponents of additional support for innovation in the competing technologies (Stokes 2016; Geels, F. W., Tyfield, D., and Urry 2014). In a third phase, path-dependence in policymaking and lock-in in institutions need to change to accommodate new infrastructure, the integration of technologies, the emergence of complementary technologies and of new regulatory regimes (Aklin, M. and Urpelainen 2013; Levin, K., Cashore, B., Berstein, S., and Auld 2012). As novel technologies are becoming cost-competitive, policy makers must navigate the growing opposition of incumbents in the second phase, as well as the dangers of lock-in that can be posed by the new winner, and this involves adapting policy (*robust evidence, high agreement*).

16.5.5 Assessment of innovation and other impacts of policies shaping innovation

16.5.5.1 Outcomes to assess policies with multiple missions and goals, trade-offs and/or co-benefits

Policy instruments shaping innovation with potential to foster a zero carbon future need to be evaluated in relation to their impact on the whole socio-technical system (Neij, L., Åstrand 2006) and a wide range of goals, including distributional impacts and competitiveness and jobs (Stern, N. 2006). It is important to understand the (mainly) *ex post* evidence linking particular policies and some of the innovation metrics (particularly the inputs and outputs) discussed in Chapter 16, section 3.1, Penasco, C., Anadon, Laura Diaz, Verdolini (Penasco, C., Anadon, Laura Diaz, Verdolini 2019) present a typology of outcomes, and indicators to systematically review the evidence on the impact of each of the 21 policies listed in Table 16.4 on the 7 outcomes (i.e., environmental effects, technological effects, cost, innovation incentives, distributional effects and other socio political effects) listed in Table 16.9.

Table 16. 9 Criteria, outcomes, and indicators to evaluate the impact of policies shaping innovation to foster carbon neutral economies. Source: From (Penasco, C., Anadon, Laura Diaz, Verdolini 2019) based on EC, 2015; IPCC, 2007; IRENA, 2014; Neil and Astranj, 2006; Kondari and Mavrakis, 2007; Del Rio et al., 2014; Scheneider and Wagner, 2002; Spree, 2013, Field and Olewiler, 2011.

Effectiveness		**Efficiency**		**Relevance**	**Socio-political acceptability**		**CRITERIA**
Environmental effect	**Technological effect**	**Cost-effectiveness**	**Innovation incentives**	**Competitiveness**	**Distributional effects**	**Other socio-political impacts**	**OTUCOMES**
GHG emissions reductions (tCO_2e) Meeting targets Total energy savings	Installed capacity RE Electricity generated with RE Deployment of EE systems buildings Number electric vehicles	Cost installed capacity RE Total costs indicators \$/avoided tCO_2e \$/saved kWh Difference cost to comply with targets with and without policies	Tie series cost-effectiveness indicators Patents Learning rates Reduction technology abatement costs	Industry creation Net job creation Export of RE technology equipment Economic growth (GDP, GNP) Productivity Investments	Incidence of support costs Change in spending on electricity as a % of total household spending Participation of stakeholders International equity (tCO_2e/capita)	Social barriers and drivers Not in my backyard syndrome (NIMBY)	**INDICATORS**

The framework used to evaluate the impact of 10 of the policies (i.e., building codes and standards, renewable obligation schemes, government procurement, RD&D funding, auctions, feed-in-tariffs, taxes or exemptions, emissions trading schemes, tradeable green certificates, and white certificates) on the innovation incentive, the competitions and the distributional outcomes.

Results show that indirect policy instruments (most policy instruments reviewed except for R&D funding) had some negative impacts on outcomes at least in some instances, crucially, on some aspects of competitiveness and distributional outcomes (Penasco, C., Anadon, Laura Diaz, Verdolini 2019) (*medium evidence, medium agreement*).

Yet, this does not imply that the benefits are smaller than the negative impacts of the policies in those cases in which some negative impacts were identified. Rather, it suggests that there are some negative impacts of the implementation of some of the policies in some cases and that future policies should consider and try to address such negative impacts.

16.5.5.2 Assessment of the impact on innovation of policy instruments with a direct focus on fostering innovation: public RD&D investments, R&D tax credits, and innovation procurement

From the policy categorization above, the policies in the economic and direct investment categories are the ones that are typically associated with a direct focus on technological innovation. These policies are R&D grants, R&D tax credits, prizes, national laboratories, technology incubators (including support for business development, plans), novel direct funding instruments (e.g., ARPA-E), and innovation procurement.

It is perhaps not surprising that, research on the impact of direct RD&D funding on innovation generally concludes that the impact is positive. Penasco et al. (2019) indicate that there is a high level of agreement in the literature of 34 evaluations explicitly looking and the link between direct R&D policies in energy and environmental technologies and increased innovation, as measured by patents, publications, cost reductions and spinoffs, although cost effectiveness in terms of a full benefit analysis are lacking. 76% of the evaluations conclude that the impact of RD&D funding on innovation outcomes is positive, while 24% were not able to detect an impact. Of the 34 evaluations assessing the impact of RD&D on innovation, 76% use quantitative methods, and the remaining 24% use theoretical ex ante approaches (see Table 16.10). Public RD&D investments have been found to have a positive impact on innovation in energy and climate related technologies (*robust evidence, high agreement*).

We now turn to the evidence on innovative procurement. A smaller number of evaluations (in this case 20) have assessed, using qualitative research methods, the relationship between government procurement in energy related technologies and innovation. In this case, all the analysis conclude that the impact of procurement on innovation is positive. We find that existing experience points to the potential for innovative public procurement has the potential to stimulate business innovation by creating a demand for innovative products or services and helping innovative firms bridge the pre-commercialisation gap for their innovative products or services by awarding contracts for pre-commercial innovations (Guerzoni and Raiteri 2015; Aschhoff and Sofka 2009). Many OECD countries have shown a growing interest in public procurement policies in recent years. Public procurement can provide critical support to investments in R&D activities. However, it is not the most widespread innovation policy instrument among both developing and developed countries (Fernández-Sastre and Montalvo-Quizhpi 2019).

The results indicate that public procurement does not induce firms to invest in R&D activities in developing countries. However, providing innovation support programs do induce firms to invest in R&D activities in many developing countries. This is because most firms lack of sufficient capabilities to perform R&D activities, any useful innovation policy instruments are normally designed to add to the knowledge and capabilities of the firms. Overall, public procurement has high potential to incentivize innovation in climate technologies (Henderson and Newell 2011; ICLEI 2018;

Baron 2016a), but the evidence is mixed , particularly in developing countries (*medium evidence, medium agreement*).

Table 16. 10 Impact of direct innovation policies (public RD&D funding and innovation procurement) on innovation outcomes. Source of data: Penasco et al. (2019)

Policy	**Number of evaluations of impact on innovation outcomes**	**% Positive impact on innovation**	**% Negative impact on innovation**	**% Negligible impact on innovation**	**Research method employed**
R&D funding	34	76%	0%	24%	95% quantitative methods 5% theoretical ex ante assessment
Government procurement	20	100%	0%	0%	100% qualitative methods

16.5.5.3 Assessment of the impact on competitiveness of policy instruments with a direct focus on fostering innovation: public RD&D investments, R&D tax credits, and innovation procurement

When it comes to the industrial development or ‘competitiveness outcome’, R&D in the energy, renewables, environment space are generally associated with positive impacts, but in a smaller number of cases they were associated with negligible and in one case negative impacts on competitiveness. There is a relatively large evidence of the impact of RD&D on innovation, when compared to other policies, although the majority of papers trying to isolate the impact of a policy on the competitiveness outcome have focussed on taxes and emissions trading schemes review (Penasco, C., Anadon, Laura Diaz, Verdolini 2019). Public RD&D investments are associated with improved innovation and competitiveness outcomes (*robust evidence, medium agreement*).

Table 16. 11 . Impact of direct innovation policies (public RD&D funding and innovation procurement) on competitiveness outcomes. Source of data: Penasco et al. (2019)

Policy	**Number of evaluations of impact on competitiveness outcomes**	**% Positive impact on competitiveness**	**% Negative impact on competitiveness**	**% Negligible impact on competitiveness**	**Research method employed**
R&D funding	11	74%	10%	16%	74% quantitative methods 26% theoretical ex ante assessment
Government procurement	4	25%	25%	50%	75% qualitative methods 25% quantitative methods

The amount of evidence assessing the impact of policies directly supporting innovation in climate or energy technologies on distributional outcomes is much more limited. Penasco et al. (2019) identify three evaluations of the impact of RD&D funding on distributional outcomes (two using quantitative methods and one ex ante theoretical methods) and one of procurement on distributional outcomes (relying on qualitative analysis). All four evaluations point to a positive impact of R&D and procurement policies on distributional outcomes (*limited evidence, high agreement*).

16.5.5.4 Assessment of the design of different public RD&D funding strategies on innovation and competitiveness

Research has also shed light into how the design of R&D policy instruments for allocating public R&D investments in energy relates to improving innovation and competitiveness outcomes. Most of this research on the relative performance of the policy depending on policy design focus on measuring innovation and competitiveness respectively using patents and publications and follow-on private financing, firm growth and survival, respectively. Most evidence available has generally focussed on the energy sector and draws heavily on US experience and thus, extrapolating to emerging economies and low-income countries is difficult. There is very limited evidence analysing the impact of different ways of allocating public energy RD&D investments in the context of developing countries.

One mechanism for conducting and allocating public R&D funds are national research laboratories, which conduct at least 30% of all research in 68 countries around the world (Anadon et al. 2016a). An analysis of the national labs from the US Department of Energy finds that having some funds with a greater flexibility to deploy funds quickly can help improve research productivity measured by patents, indicating that it is important for national labs to have some funds that can be quickly deployed for high risk projects (Anadon et al. 2016a). Research focussed on Japan that is not specific to energy or climate technologies comparing the novelty of R&D funds allocated competitively versus through block funding showed that while for researchers of a ‘high status’ competitive funds result in more novel research, for lower status researchers block funding was associated with research of higher novelty (Wang et al. 2018). Block funding, which tends to be more flexible, can lead to research that is more productive or novel, but this is mediated by various factors, including status and gender (*limited evidence, medium agreement*).

Another approach for allocating public R&D funds in energy involves relying on active program managers. This approach can be exemplified by a relatively new energy R&D funding agencies in the US, ARPA-E, which was created in 2009. ARPA-E was modelled on the experience of DARPA (a US government agency funding high risk high reward research in defuse related areas) has showed that this more ‘actively managed’ R&D funding program that may yield greater patenting than other US energy R&D funding programs and a greater or similar rate of academic publications when compared to other public funding agencies in energy in the US, ranging from the Office of Science, the more applied Office of Energy Efficiency and Renewable Energy or the small grants office (Goldstein and Narayanamurti 2018) (*limited evidence, medium agreement*).

A growing body of work has assessed the role of public energy R&D funding dedicated to private firms. It suggests that small firms (which tent do have more cash constrains) in the energy space in the US (and firms more broadly in the UK), conduct additional innovation activities with more direct support for R&D. The evidence for US small US firms suggests that energy R&D funding for small firms yields to more innovation measured by patents and financing when provided with either cash incentives for R&D in the form of grants (Howell 2017). Evidence from small firms across a range of sectors in the UK suggests that, unlike large firms, when provided with additional R&D tax credits small firms conduct ‘additional’ R&D (Pless 2019). And evidence again from US clean-tech startups shows that when such firms partner with government partners for joint technology development or licensing partnerships they are associated with more patents and follow on financing (Doblinger et al. 2019). In summary, research shows that public financing for R&D and research collaboration in the energy sector is important for small firms, at least in industrialized countries, and it does not seem to crowd out private investment in R&D (*medium evidence, high agreement*).

Research on other direct incentives for R&D, such as innovation prizes for achieving particular missions (e.g., a prize for the firm or research group capable of building a new electric vehicle meeting the performance standards set by those organizing the prize) shows that such direct policy instrument for R&D can bring in new players, although there are considerations that must be made in their design (Murray et al. 2012) (*limited evidence, low agreement*).

Overall, the body of literature on public R&D funding design in energy and climate related technologies provides some high-level guidance on how to make the most of these direct RD&D investments in energy technologies in the climate change mitigation space, including: giving researchers and technical experts autonomy and influence over funding decisions; incorporating technology transfer in research organizations; focussing demonstration projects on learning; incentivizing international collaboration in energy research; adopting an adaptive learning strategy; and making funding stable and predictable (Gabriel Chan et al. 2017). (Narayanamurti, V; Odumosu 2016; Chan, G; Goldstein, AP; Bin-nun, A; Anadon, LD; Narayanamurti 2017; Narayanamurti et al. 2009) (*medium evidence, high agreement*).

16.5.5.5 Assessment of the impact on innovation of policy instruments with a more indirect direct focus on fostering innovation

When it comes to other policies in the market pull category (such as tradeable green certificates, taxes, or auctions, for instance), the literature indicates in some cases evidence of no impact or positive impact in the case of auctions in some cases negative, in some cases, positive and in some cases no impact on innovation (see Table 16.12).

For example, most research on feed-in tariffs concludes that they have a positive impact on innovation (73% of the analysis yield positive results, and 27% negligible impact). However, about 23% of the assessments evaluating their impact on competitiveness find a negative impact on at least some players, with 55% of the studies finding a positive impact and 18% no impact. The results on distributional impacts for feed in tariffs are more negative, with 8% finding no impact and 91% finding at least some negative distributional impacts.

Research has found that the same policy instrument is associated with positive impacts in some cases and negative in others, differences in the impact. In some cases due to the method used in the evaluations (Penasco, C., Anadon, Laura Diaz, Verdolini 2019) , and in others in differences in the details of policy design (e.g., the level and the rate of decrease of the tariff) (Hoppmann et al. 2014), the policy mixes (Rogge et al. 2017), the technologies targeted and their stage of development (Huenteler et al. 2016), as well as the spatio-temporal context of where the policy was put in place. Thus, the design of feed in tariffs must account for the fact that, in spite of the generally positive impacts on innovation, the specifics of the country, the technology and the policy could result in negative distributional and (to a lesser extent) competitiveness impacts. Many factors affect the impacts of feed in tariffs on outcomes other than innovation (*robust evidence, high agreement*).

The importance of policy design, domestic capacity, the technology and the industry maturity is also apparent in research on the impacts of auctions for renewable energy. As shown in Table 16.12, in 59% of the evaluations they were associated with positive innovation outcomes, although in 23% of the evaluations the impacts were negligible and in 18% of the cases some negative innovation outcomes were found. However, when looking at competitiveness outcomes, the literature was more limited: there were just 6 evaluations, compared with 54 evaluations for of the impact of auctions on innovation outcomes. In addition, in around 80% of evaluations there were at least some negative the competitiveness impacts, with the remaining 20% of the evaluations reporting positive impacts (Penasco, C., Anadon, Laura Diaz, Verdolini 2019). Interestingly, all the negative impacts on competitiveness from outcomes were emerging from qualitative studies. In this case there has been work focussing on emerging economies that reinforces the conclusions regarding the factors that shape policy impacts beyond innovation for feed in tariffs, mainly in industrialized countries.

For example, work comparing the approaches to renewable energy auctions of Mexico and South Africa found that prioritizing low-cost renewable energy generation can result in a greater reliance on existing foreign value chains and capital, and thus in lower or negative impacts on domestic competitiveness. Some approaches can lead to not building the local capabilities that could result in greater long-term benefits domestically (Matsuo and Schmidt 2019). Other work with a greater focus on developing countries indicate that local and absorptive capacity also play an important role in particular on the ability of policies to contribute to competitiveness or industrial policy goals (e.g., Binz and Anadon 2018). Research comparing China's and India's policies and outcomes on wind also suggest that policy durability and systemic approaches can affect industrial outcomes (Surana and Anadon 2015). Policy design, policy mixes, and domestic capacity and infrastructure are important factors determining the extent to which economic policy instruments in industrialized countries and emerging economies can also lead to positive (or at least not negative) competitiveness outcomes and distributional outcomes (*medium evidence*, *medium agreement*).

Table 16. 12 Summary of analysis of indirect policies on innovation outcomes. Source of data: Penasco et al. (2019) and other literature reviewed by Ch16 authors.

	Policy	**Number of evaluations of impact on innovation outcomes**	**% Positive impact on innovation**	**% Negative impact on innovation**	**% Negligible impact on innovation**	**Methods**
Economic or financial instruments	Feed in tariffs (or premiums)	52	73%	0%	27%	58% quantitative; 28% theoretical ex ante; 14% qualitative
	Renewable energy auctions	54	59%	18%	23%	80% qualitative; 20% theoretical ex ante
	Emissions trading scheme	60	47%	0%	53%	44% quantitative; 23% theoretical ex ante; 33% qualitative
	Taxes/tax relief	24	50%	0%	50%	100% quantitative methods
Regulatory policies	Tradeable green certificates	58	17%	27%	56%	18% quantitative; 12% ex ante'; 70% qualitative
	White certificates	29	75%	0%	25%	25% quantitative; 75% ex ante

						theoretical
	Renewable portfolio standards (electricity)	54	23%	0%	77%	37% quantitative methods; 33% ex ante; 30% qualitative methods
	Building codes (building efficiency codes)	0	N/A	N/A	N/A	N/A
	Fuel efficiency standards	Placeholder TO COMPLETE BEFORE SOD				
	Appliance standards	Placeholder TO COMPLETE BEFORE SOD				
Soft instruments	Comparison labels	Placeholder TO COMPLETE BEFORE SOD				
	Endorsement labels	Placeholder TO COMPLETE BEFORE SOD				
	Voluntary approaches	Placeholder TO COMPLETE BEFORE SOD				

The record of these policies with a more indirect focus on innovation when it comes to the competitiveness outcome (at least in the short term) is more mixed (see Figure 16.6).

The disagreements in Figure 16.5 regarding the positive, negative or no impact of a policy on competitiveness or other outcomes (see Figure 16.6) can be explained by differences in policy design, differences in geographical or temporal context (since the review included evidence from countries from all over the world), or on how policy mixes may have affected the ability of the research design of the underlying papers to separate the impact of the policy under consideration from the others (Penasco, C., Anadon, Laura Diaz, Verdolini 2019).

The review excluded soft policy instruments (such as voluntary labels) because of their lower relevance for stringent climate targets such as the ones promoted by the Paris Agreement (Hertin, J., Berkhout, F.G.H., Wagner, M., Tyteca 2008) (Hertin, J., Berkhout, F.G.H., Wagner, M., Tyteca 2008).

16.5.5.6 Trade instruments and their impact on innovation

There has been a long interest on the impact of Foreign Direct Investment (FDI) on domestic capacity on innovation and on environmental outcomes.

A recent student indicates that for countries with high environmental performance FDI has a negligible impact on environmental performance, while on the lower end of the spectrum (countries with a lower environmental performance) may benefit from FDI in terms of their environmental performance (Li et al. 2019). Other work on China links FDI not just with improve environmental performance but also innovation outcomes in general (Gao and Zhang 2013). Other work links FDI with increased productivity across firms (not just those engaged in climate-related technologies) through spillovers (Newman et al. 2015). Overall, research indicates that trade can facilitate the entrance of new technologies, but the impact on innovation is less clear (*limited evidence, low agreement*).

16.5.5.7 Intellectual property rights, legal framework and the impact on innovation

Intellectual property (IP) regimes in different countries and regions are institutions that aim to incentivize innovation by allowing inventors to exclude others from using patented technology for a fixed period, during which they can charge monopoly prices for patented products or earn revenues from licensing (Anadon et al. 2016b). Although IP protections provide incentives to invest in innovation, it has the double effect of restricting the use of new knowledge by raising prices or blocking follow-on innovation (Stiglitz JE 2008; Wallerstein M, Mogee M, Schoen R 1993). Because of this, it has been argued that the increasingly globalized IP regime through initiatives like the TRIPS agreement will diminish prospects for technology transfer and competition in developing countries, particularly for several important technology areas related to meeting sustainable development needs (Maskus KE 2004).

(Hall and Helmers 2010) have argued that the limited existing empirical evidence on intellectual property right and technology transfer suggests that there are two groups of developing countries. One group includes emerging economies, such as Brazil, China, India, and Mexico, and the second group a larger number of less-developed countries. While for the first group the available evidence suggests that a strengthening of intellectual property rights for emerging economies may have a positive impact on the domestic development of technology, the evidence for least developed countries is more negative. This review concluded that patent protection in a host country may encourage technology transfer to that country but that the impact of patent protection on innovation and development outcomes, which are harder to measure, is more ambiguous (*low evidence, low agreement*).

16.5.5.8 System-oriented policies and instruments

Although previous sections summarized the research disentangling the role of individual policies in advancing or hindering innovation (as well as impacts on other objectives), other research has tried to characterize the impact of a policy mix on a particular outcome. Although the outcome studied was not innovation, but diffusion (technology effectiveness is in the set of criteria outlined above), it seems relevant to discuss overall findings.

Using renewable energy policies in nine OECD countries, research concludes that over time they have a significantly broad set of policies in renewable energy, a similar balance of policies (defined as dispersion of policy instruments across different instrument types). This research also identifies a significant negative association between the balance of policies in renewable energy and the diffusion of total renewable energy capacity but no significant effect of the overall intensity (coded as the weighted average of six indicators) on renewable capacity (Schmidt and Sewerin 2018), indicating that a neural conception of balance across all possible policies may not be desirable and that policy mix intensity by itself does not explain technology diffusion.

16.5.6 National public investments in energy R&D

Given that public R&D investments in technologies that can be used for climate mitigation and adaptation are the most direct policy in the space, and the indicated underinvestment in the area, this section summarizes the data available on public energy RD&D investment. The data for agriculture is not available to the best of our knowledge.

Figure 16.6 from the IEA (2019) shows that across OECD countries, over time, a greater fraction of public energy R&D budgets is being devoted to energy efficiency, renewable energy and cross cutting, to the detriment of nuclear power R&D. The fraction of public energy R&D devoted to nuclear power has decreased over time in OECD countries, with a growing share of R&D funding for cross-cutting technologies, renewables and efficiency research (*limited evidence, high agreement*).

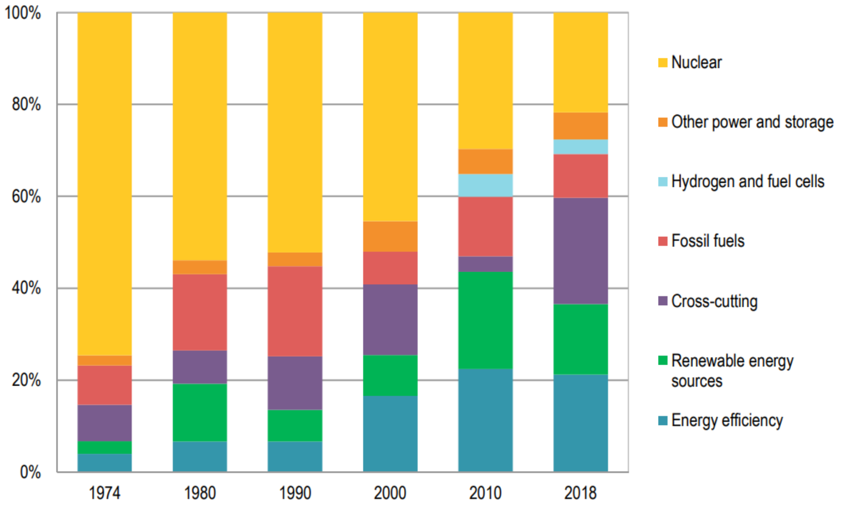


Figure 16.6 Fraction of public energy RD&D by technology over time for IEA (largely OECD) countries between 1974 and 2018. Sources: IEA RD&D Database, 2019.

Data collected by the IEA also shows that, since 2014, the contribution of China to public energy R&D has increased. It must be noted that the data on the "Rest of the World' is limited.

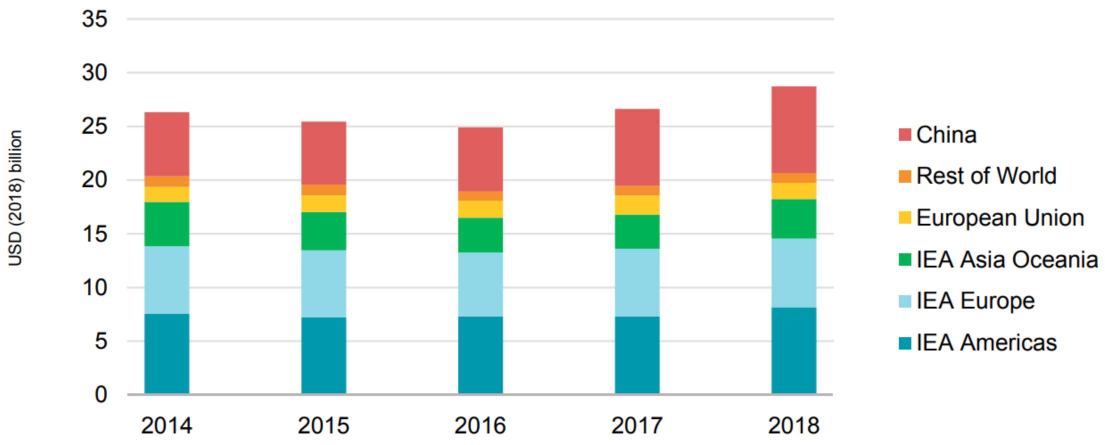


Figure 16.7 Global public energy RD&D budget by region/country (2014-2018) in billions of 2018 USD.. Sources: IEA RD&D Database, 2019.

While data on public energy RD&D from non OECD countries has been traditionally limited, recent data collected allows a comparison over the evolution of public energy RD&D budgets by technologies in OECD regions compared to India and China.

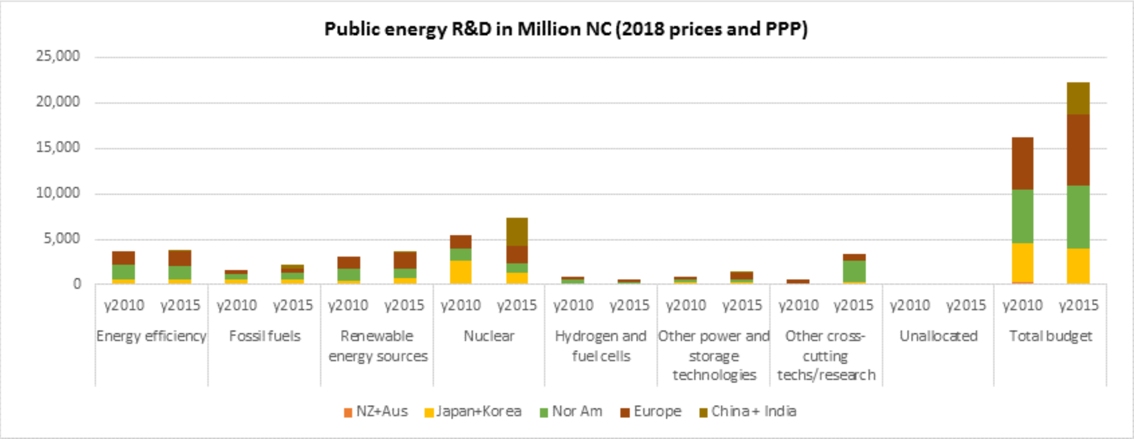


Figure 16.8 Public energy RD&D investment by region (note that not all regions include data on all countries) for 2010 and 2015 by technology area. Sources: IEA RD&D Database, 2019.

16.5.7 Regional innovation policies

[Placeholder, to be completed for the SOD]

16.5.8 Key insights on national and regional policies impact on technology innovation

[Placeholder, to be completed for the SOD]

16.5.9 Government procurement

The purchase of products, services and works by government, is acknowledged as a vital mechanism for bringing low-carbon innovative solutions to the market. Public procurement has accounted for 13 % of gross domestic products in OECD in 2013 and much more in some emerging and developing economies (Baron 2016b). The main objective of public procurement is to determine and purchase products or services for the betterment of public services, infrastructures and facilities. It is important to implement several instruments in the public procedure to improve the transparency in order to minimise waste, fraud and corruption of public fund, ranging from the assessment of a need, issuance of a tender to the monitoring of delivery of the good or service.

There is evidence to indicate that innovative public procurement has the potential to stimulate business innovation by creating a demand for innovative products or services and helping innovative firms bridge the pre-commercialisation gap for their innovative products or services by awarding contracts for pre-commercial innovations (Guerzoni and Raiteri 2015; Aschhoff and Sofka 2009). Many OECD countries have shown a growing interest in public procurement policies in recent years. Public procurement can provide critical support to investments in R&D activities. However, it is not the most widespread innovation policy instrument among both developing and developed countries (Fernández-Sastre and Montalvo-Quizhpi 2019). The results indicate that public procurement does not induce firms to invest in R&D activities in developing countries. However, providing innovation support programs does induce firms to invest in R&D activities in many developing countries. This is because most firms lack of sufficient capabilities to perform R&D activities, any useful innovation policy instruments are normally designed to add to the knowledge and capabilities of the firms.

The transfer of low-carbon technological innovations can be hindered by a number of external factors such as lack of financiers to enter competition, technology lock-in, capacity constraints in term of human capital and facilities as well as the problems of the inventors to appraise the value of their inventions (Polzin 2017). A range of policies restore the innovative capability of an economy, starting from competition to environmental policies and dedicated innovation policy. Innovation policy includes technology push (the supply-side of innovation including the support to research institutions and private R&D sectors), demand-side innovation as well as measures to build innovation networks and cooperation.

The public procurement plays an important role in improving the efficiency and quality of implementing low-carbon technologies while addressing the climate change issue as being one of the major society challenges. Public procurement can be used for different innovation purposes such as pre-commercial procurement (PCP) and public procurement of innovative solutions (PPI). Pre-commercial procurement (PCP), is a practice in many developed and developing countries which is also known as contract research for providing research grants to the institution of higher education and private sectors of R&D. In PPI, procurement is used to diffuse an innovation products and services that have been used in other regions. North-South technology transfer and cooperation (NSTT) for low-carbon energy technology has been implemented for decades. However, South-South technology transfer and cooperation (SSTT) and South-North technology transfer and cooperation (SNTT) have only recently emerged (Kirchherr and Urban 2018). The strengths and weaknesses of different methodological approaches for the effective NSTT, SSTT and SNTT are identified as shared in (Pueyo et al. 2012). Governmental procurement, which is one of the government policies, is found to be one of the main drivers as well as by international firms that are interested in expanding their markets in overseas. However, the inhibitors include a non-existent market in the host countries, a weak investment climate as well as the abundance of cheap fossil fuel resources.

The Clean Development Mechanism (CDM) is one of the flexible mechanisms defined in the IPCC 20117 that provides for emissions reduction projects that generate certified emission reduction units for trading in emission trading schemes. The countries listed in Annex 1 of the industrialized countries can meet part of their emission reduction commitments by buying Certified Emission Reduction Units from CDM emission reduction projects in developing countries. In addition, the Global Environment Facility (GEF) was established to unite 183 countries in collaboration with international institutions, civil society organisations and the private sectors to address global environmental issues. Since 1992, the GEF has provided over $17 billions in grants for financing more than 4000 projects in 170 countries. CDM and GEF are the two examples of the government procurements to foster the transfer and development of low-carbon technologies in developed and developing countries.

16.5.10 Case studies covering country experiences

16.5.10.1 Case Study 1: Korea's Green Public Procurement and Lessons Learned

The government of Korea implemented its green public procurement programme in 2005 by making sure that the central and local governments as well as public organisations to report on the implementation of their green procurement plans (Ko and Office; Huh and Kim 2018). The programme was launched together with the Korea Eco-label and Good Recycled Marks that cover appliances, officer supplies, furniture and construction materials. The labelling system is intended to save time and administrative costs. Since 2005, any public institutions have purchased eco-products when they intend to purchase any product under the Act. The heads of public institutions shall aggregate purchase records of green products pursuant and submit such purchase records to the Minister of Environment. Green purchases grew substantially from 2005 to 2012. However, the amount is only equated to 5 to 6% of public purchases by 2012. Among the problems in the increasing green purchases are the high prices and the complaints on quality. Procuring organisations are also subject to other overlapping criteria such as energy efficiency or social responsibility.

16.5.10.2 China's Implementation of Environmental Labelling Products.

In 2006, the Chinese Ministry of Finance and the former State Environmental Protection Administration issued recommendations on the implementation of Environmental Labelling Products in government procurement. The recommendations were accompanied by the Government Procurement List for Environmental Labelling Products, including 14 product categories and were accessible by the general public. The list of products is certified based on environmental performance, technological advancement and market considerations. According to the recommendation, listed products with similar performance, technology and service attributes but lower environmental impacts should be preferred. Reliance on the list is entirely voluntary however. The list of certified products has grown significantly from 800 to 37953. Categories including cars, home and office appliances, cement concrete products and construction materials, windows and plastic products. However, monitoring and evaluating green public procurement has been difficult due to the decentralised nature of public procurement and the many organisations involved. In addition, green public procurement was seen to lack a powerful legal basis. Furthermore, the environmental awareness of purchases is limited, despite evidence that such awareness increases the environmental performance of procurement organisations in the country.

16.5.10.3 Dutch's Efforts of Lowering the Carbon Footprint of Infrastructures

The Department of Public Works of the Dutch Ministry of Infrastructure and the Environment (Rijkswaterstaat, hereafter RWS) has developed an approach to encourage the minimisation of environmental impacts related to infrastructure building. The policy direction was given by the House of Commons, asking that public procurement be 100% sustainable by 2015 – that is the inclusion of green criteria in all tenders. RWS works from the Most Economically Advantageous Tender (MEAT) methodology which includes both price and quality attributes. In RWS tenders, however, quality attributes are fully monetised in the quoted price; the contract is awarded to the bidder with the lowest adjusted price. From the RWS staff perspective, DuboCalc has been effective in facilitating the introduction of low-carbon materials for public infrastructure. This is an example of adaptive innovation – that is the diffusion of environmentally-friendly products (e.g., low-clinker cement) that are already available, rather than driving breakthrough innovation. A more integrated set of policy instruments is needed to achieve more ambitious reductions in the carbon footprint of materials such as cement. At the initiative of industry, a Green Deal policy framework is in development with RWS with the aim of bringing breakthrough innovations seen as beyond the reach of public procurement.

16.5.10.4 Procuring the World's First Electric Ferry by the Norwegian Government

In 2010, the Norwegian Ministry of Transport launched a competition for an energy efficient and low-emission car ferry to link two villages in the Sognefjord. The successful bidder would be awarded a ten-year concession contract. The Norwegian Public Roads Administration, in charge of the competition, required a minimum 15-20% improvement in energy efficiency over that of the existing diesel-powered ferry. The winning consortium, which gathered Norled, a ferry operator, the Fjellstrand shipyard and Siemens, proposed Ampere, the world's first electric car ferry. Ampere offers a 37% reduction in energy use per passenger car-km, a 60% reduction in total energy use, the elimination of NOx emissions and an 89% reduction in CO_2, accounting for the electricity mix in Scandinavia's NordPool. Unlike most others, the ferry is made of aluminium and is therefore lighter than steel-made vessels. A catamaran (i.e., two slim hulls instead of one), it also offers less resistance than traditional ferries, allowing total engine power to be cut by half. The charging system brought another innovation: batteries are replaced at each pier, saving the higher voltage necessary for a single battery onboard and the time it would take to recharge it. The 80-meter long ferry, which can transport 120 cars in 34 daily trips across the Sognefjord, is now in operation. Making all future ferries low-carbon is now under discussion. Tenders opened recently for second electric ferry and an unspecified zero or low-carbon emissions ferry which could run on biogas, biofuel, electricity or any combination thereof. The procurement of the Ampere ferry clearly triggered these opportunities and helped to launch the market for low-carbon ferries.

16.6 International cooperation

[Placeholder introductory paragraph to the section]

16.6.1 Modes of international technology transfer and technology cooperation

Motives for technology transfer and cooperation in climate change could include access to financial instruments under the UNFCCC as well as promotion of domestic industry on the part of the developed country (Huh and Kim 2018). Activities include informational contacts, research activities, consulting, education & training and activities related to technical facilities (Huh and Kim 2018).

Increasingly, both in literature and in UNFCCC deliberations, South-South technology transfer is highlighted (Khosla et al. 2017), linked to the level of innovation capabilities in China (Urban 2018), although (Wu 2016) argues that China agreed to commitments in part because it relies on developed countries for technology transfer.

16.6.2 What is the role for international cooperation in new disruptive technologies?

(Yan et al. 2017) indicate that between 1990 and 2012, the gap in low-carbon technology innovation between countries has possibly only been reducing for OECD countries, and recommend continued promotion of technology transfer to countries with low levels of technological development.

(Gross et al. 2018) argue that the development timescales for new energy technologies can extend from 20 to 70 years, even within one country, and recommend that innovation efforts be balanced between commercializing already low-emission technologies in the demonstration phase, and diffusing them globally, and early-stage R&D spending.

There is a handful of papers that conduct game-theoretic analysis on technology cooperation, sometimes as an alternative for cooperation on emission reductions. (Rubio 2017; Narita and Wagner 2017)(Bosetti et al. 2017; Verdolini and Bosetti 2017)

(McGee and Wenta 2014) argue that the post-2009 UNFCCC discussions on technology have moved to the more fundamental issue of ‘the extent to which redistributive claims are allowed to shape institutions of global climate governance”.

16.6.3 What can be the role of international technology cooperation to address sustainable development in developed and developing countries, including in emerging economies and LDCs?

(Vega and Mandel 2018) argue that ‘long-term economic relations’, for instance being part of a customs union, affects technological diffusion between countries for the case of wind energy, and indicate that for this, low-income countries have been largely overlooked.

(Khosla et al. 2017) suggest that low-carbon technology deployment in developing countries could be enhanced by (1) technology development and transfer collaboration on a need-driven' approach, (2) development of the specific types of capacity required across the entire innovation chain and (3) domestic strengthening of the coordination and agendas across and between governance level.

There are also other views. (Glachant and Dechezlepretre 2017) indicate that technology transfer of low-carbon technologies to emerging economies has been strong but that low-income countries are lagging behind. They indicate that this due to their lack of participation in economic globalisation and that the role of the climate negotiations for technology transfer to those countries should be the creation of demand for low-carbon technologies through stronger emission targets.

16.6.4 Assessing gaps in resources and capacity for transformative change

16.6.4.1 Technological gaps

[Placeholder to be completed for SOD]

16.6.4.2 Capabilities for innovation, engineering

Not just technical characteristics, but also mutual learning on how to address common problems of electricity access and poverty, was suggested as an important condition for successful South-South technology transfer between India and Kenya (Ulsrud et al. 2018). An econometric analysis lend quantitative credibility to the often-stated conclusion that a technology skill base is a key determinant of technological diffusion in wind energy globally (Halleck-Vega et al. 2018). (Hsu 2017) argues that human capital should be at the focus of international climate negotiations as well as national climate policy , as it could change the political economy in favour of climate mitigation and the transformation needs to happen so fast that developing such capabilities in advance would be required.

Specifically for Africa, (Olawuyi 2018) discussed the capability gap in Africa, despite decades of technology transfer efforts. He suggests that barriers need to be resolved by African countries themselves, in particular inadequate access to information about imported climate technologies, weak legal protection for imported technologies, lack of domestic capacities to deploy and maintain imported technologies, the weak regulatory environment to stimulate clean technology entrepreneurship, and the absence or inadequacy of climate change laws.

16.6.4.3 Governance

(Ramos-Mejía et al. 2018) indicate that developing countries exhibit a "mixture of well- and ill-functioning institutions, in a context of market imperfection, clientelist and social exclusive communities, patriarchal households and patrimonial and/or marketized states", which affects the governance of low-emission technology transfer.

(Boyd 2012) indicates, based on a case study of biogas in South Africa, that both national and international engagement is needed to address the needs for technology transfer to developing countries.

16.6.4.4 R&D cooperation

[Placeholder to be completed for SOD]

16.6.4.5 Deployment incentives

[Placeholder to be completed for SOD]

16.6.5 Assessment and outcomes of international institutions, partnerships and cooperative approaches for capability development and technology development and transfer

(Huh and Kim 2018) discuss two 'knowledge and technology transfer' projects that were eventually not pursued through beyond study due to cooperation and commitment problems between national and local governments and highlight the need for ownership and engagement of local residents and recipient governments.

(Gross et al. 2018) caution against too much focus on R&D efforts for energy technologies to address climate change, including Mission Innovation. They argue that given the timescales of commercialization, developing new technologies now would mean they would be commercial too late for addressing climate change.

(Sarr and Swanson 2017) model that, due to the rebound effect, technology development and transfer of resource-saving technologies may not lead to envisioned emission reductions.

16.6.5.1 Cross border initiatives in climate innovation

All the publications have in common is the emphasis on participative social innovation as a replacement of the expert-led technological change. A broad transformative agenda therefore proposes that contemporary societal challenges are wider in the scope and are often more difficult to be clearly defined and will require the actions of a broader and more diverse set of actors to both formulate and address the policy. Social, institutional and behavioural changes as well as technological innovations are the possible solutions (Geels 2004). Societal challenges are viewed as more than just a market failure that requires incentives to attract the academia and industry to come up with technological solutions. The commercialisation of science through a linear model of innovation is no longer an emphasis, resulting in the supply-side activities to be considered as unlikely to suffice.

The Global Covenant of Mayors for Climate and Energy (Energy 2019) is one of the initiatives of the transformative innovation policy that is a highly prominent innovation-oriented global policy initiative accompanied by the adoption of the Paris Agreement at the 21st Conference of the Parties of the United Nations Framework Convention on Climate Change in 2015. Its vision is to accelerate ambitious, measurable climate and energy initiatives that lead to a low emission and climate resilient future, thus helping to meet and exceed the Paris agreement objectives. It has the three main characteristics of a transformative innovation policy. The first characteristic is that it aims to drive purposive and directional innovation; the second is that it is derived from outside the traditional innovation policy domain and the third is that it aspires to set new modes of global collaboration for innovation.

The Mission Innovation (Innovation 2019) is another global initiative consisting of members of 23 countries and the European Commission working together to reinvigorate and accelerate global clean energy innovation with the objective to make clean energy widely affordable with improved reliability and secured supply of energy. The goal is to accelerate clean energy innovation in order to limit the rise in the global temperature to well below 20°C. These 24 members are committed to seek and increase public investments in clean energy R&D with the engagement of private sectors. MI also seeks to foster international collaboration amongst its members.

16.6.6 Assessment of how international initiatives are fulfilling roles

(Brook et al. 2016) argue that the UNFCCC mechanisms for technology are insufficiently fulfilling the needs of low-emission technologies, supported by (de Coninck and Puig 2015) who assessed the UNFCCC instruments specifically for technology transfer to developing countries and indicate that knowledge development, market formation and legitimacy are functions that are currently poorly addressed in developing countries' low-emission technological innovation systems. (Ockwell and Byrne 2016) argue that a role for the UNFCCC could be to support climate relevant innovation-system builders in developing countries, institutions locally that develop capabilities that "form the bedrock of transformative, climate-compatible, technological change and development".

16.7 Knowledge gaps

[Placeholder section to be completed for SOD]

Limited evidence with respect to the role of disruptive general purpose technologies on the framework conditions in which decarbonization pathways will have to be pursued. This includes, for example, the role of digitalization in promoting not only low carbon technologies/energy systems, but also green jobs, industrial competitiveness in the green economy and so on.

More evidence is needed with respect to the specificities of technological change dynamics in different regions of the world, and particularly in developing countries and smaller countries. Some evidence is being produced for major developing economies, but many knowledge gaps remain for large areas such as Africa, Asia and Latin America.

More evidence is needed for the role and dynamics of low carbon transformations in hard-to-decarbonize sectors, such as industry, transport, buildings and agriculture. Unless these sectors fully decarbonize in the next few decades, stringent climate targets will be unattainable.

Frequently Asked Questions

[Placeholder section to be completed for SOD]

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